CHANNEL AVAILABILITY AND QUEUING AWARE EARLIEST DEADLINE FIRST SCHEDULING ALGORITHM IN COGNITIVE RADIO NETWORK

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I dedicated this

To my truly loved parents: Omar and Sirad

To my supportive aunts: Shamso and Seynab

To my beloved brothers: Mohamed and Yahye

To my beloved sisters: Najmo,Seynab and Maryan

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ABSTRACT

Cognitive Radio Networks (CRNs) provide a solution for the spectrum scarcity problem facing modern wireless communications. However, compared with the traditional networks, cognitive radio networks exhibit some distinct features, which result in necessity of further research in the resource allocation and scheduling that have been solved for the traditional networks. The basic concept of CRNs relies on utilizing the unused spectrum of a primary network, without interfering with the activity of primary users (PUs). Therefore, an effective scheduling algorithm is needed in order to manage the opportunistically available resources and provide the necessary Quality of Service (QoS) for different traffic classes for secondary users. In this work, we focus on link queue aware earliest deadline first scheduling in a single cell cognitive radio system. The purpose of this work is to investigate how CAQA-EDF algorithm satisfies the QoS for various secondary user traffic. A buffer selection criterion is introduced together with the channel availability to adjust the priority of different cognitive radio user traffic to be selected for service. Extensive simulations have been carried out and important performance metrics are investigated in the simulation, such as the system throughput, fairness and sevice delay time and are quantified by the impact of PU channel availability. Simulation result shows that all traffics are scheduled before missing their deadline, despite giving rtPS default scheduling, nrtPS and BE are served before their deadline. In terms of throughput, PU activity effect the overall throughput, the result shows that lower PU active period and high probability of detection with lower false alarm increases the throughput. Finally, fairness is achieved for all traffic and no starvation happened during packet transmission.

ABSTRAK

Rangkaian Radio Kognitif (CRNs) menyediakan satu penyelesaian untuk masalah kekurangan spektrum menghadapi komunikasi tanpa wayar yang moden. Bagaimanapun, berbanding dengan rangkaian tradisional, rangkaian radio koginitif mempamerkan beberapa ciri-ciri yang berbeza, dimana menghasilkan keperluan untuk kajian lanjutan dalam peruntukan sumber dan penjadualan telah diselesaikan untuk rangkaian tradisional. Konsep asas bagi CRN bergantung kepada penggunaan spektrum yang tidak digunakan daripada suatu rangkaian utama, tanpa menganggu aktiviti bagi pengguna utama(PUs). Oleh itu, suatu algoritma penjadualan yang effektif adalah diperlukan untuk menguruskan peluang sumber sedia ada dan menyediakan keperluan kualiti perkhidmatan (QoS) bagi kelas trafik yang berbeza untuk CRU. Dalam kerja ini, kami fokus kepada ketersediaan saluran dan penjadualan pertama bagi tarikh akhir yang teratur dalam satu sel sistem radio kognitif. Tujuan kerja ini adalah untuk menyiasat bagaimana CAQA-EDF algoritma memenuhi QoS untuk pelbagai trafik CRU. Suatu kriteria pemilihan buffer adalah memperkenalkan bersama dengan ketersediaan saluran untuk menyesuaikan keutamaan bagi trafik pengguna radio kognitif yang berbeza dipilih untuk perkhidmatan. Simulasi yang meluas telah dijalankan dan kepentingan prestasi metrik telah dikaji dalam simulasi, seperti hasil sistem, kesamaratаan dan penangguhan masa perkhidmatan dan kuantiti, kesan daripada ketersediaan saluran PU. Keputusan simulasi menunjukkan bahawa semua trafik adalah dijadualkan sebelum ketinggalan tarikh akhir,walaupun diberi penjadualan lalai bagi rtPS, nrtPS dan BE berkhidmat sebelum tarikh akhir. Dalam bentuk hasil, aktiviti PU memberi kesan kepada keseluruhan hasil, keputusan menunjukkan bahawa tempoh aktif PU yang rendah dan keberangkalian yang tinggi bagi pengesanan dengan keberangkalian yang rendah bagi penggera kesalahan akan meningkatkan hasil. Akhirnya, kesamarataan telah dicapai untuk semua trafik dan tiada ketidakcukupan yang berlaku semasa penghantaran paket.

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BE	-	Best Effort
BS	-	Base Station
CAQA	-	Channel Availability and Queuing Aware
CBR	-	Constant Bit Rate
CCTT	-	Channel Closing Transmission Time
CDT	-	Channel Detection Time
CID	-	Connection Identifier
CMT	-	Channel Move Time
CP	-	Cyclic Prefix
CPE	-	Customer-Premises Equipment
CR	-	Cognitive Radio
CRBS	-	Cognitive radio base station
CRN	-	Cognitive radio network
CRU	-	Cognitive radio user
CTMC	-	Continuous Time Markov Chain
DFS	-	Dynamic Frequency Selection
DL	-	Downlink
DSA	-	Dynamic Spectrum Access
DSM	-	Dynamic Spectrum Management
DSS	-	Dynamic Spectrum Sensing
EDD	-	Earlier Due Date
EDF	-	Earlier Deadline First
ertPs	-	Extended Real Time Polling Service
FCC	-	Federal Communication Commission

FIFO	-	First In First Out
FFT	-	Fast Fourier Transforms
FTP	-	File Transfer Protocol
FUSC	-	Fully Used Sub Channel
HTTP	-	Hyper Text Transfer Protocol
IDT	-	Incumbent Detection Threshold
ISI	-	Inter-Symbol Interference
MAC	-	Medium Access Control
NPEDF	-	Non-Preemptive Earliest Deadline First
nrtPs	-	None Real Time Polling Service
OFDM	-	Orthogonal Frequency Division Multiplexing
OSA	-	Opportunistic Spectrum Access
PEDF	-	Preemptive Earliest Deadline First
PP	-	Poisson Process
PU	-	Primary user
QAM	-	Quadrature Amplitude Modulation
QoS	-	Quality of Service
QPSK	-	Quaternary Phase Shift Keying
RR	-	Round Robin
rtPs	-	Real Time Polling Service
SCH	-	Superframe Control header
SDR	-	Software defined radio
SF	-	Service Flow
SFID	-	Service Flow Identification
STE	-	Shortest Time to Extinction
SU	-	Secondary user
UGS	-	Unsolicited Grant Service
VBR	-	Variable Bit Rate
VC	-	Video Conference
VoIP	-	Voice-Over- IP
WFQ	-	Weighted Fair Queuing
WRAN	-	Wide Range Area Network

CHAPTER 1

INTRODUCTION

1.1 Motivation and Background

With the increasing number of wireless users, scarcity of the electromagnetic spectrum is obvious. Taking this into consideration, the Federal Communications Commission (FCC) which was created by the US Congress in 1934 published a report prepared by Spectrum Policy Task Force (SPTF) [1]. This report recommends certain rules and regulations for the efficient use of radio spectrum and the ways to improve the existing spectrum usage. Moreover, its responsibilities are the management and licensing of the electromagnetic spectrum within the United States and its possessions. For example, it licenses very-high frequency (VHF) and ultra-high frequency (UHF) broadcast television (TV) stations and enforces requirements on inter-station interference.

The main reason for such a step is the underutilization of the spectrum. It can be seen in Figure 1.1 that a large portion of the assigned spectrum is used scantily and utilization ranges from 15% to 85% [2]. In relation to the spectrum utilization this report illustrates that there is a significant inefficient spectrum utilization than the actual spectrum scarcity due to the legacy system and the rules imposed by the FCC. Most of the allotted channels are not in use most of the time; some are partially occupied while others are heavily used.

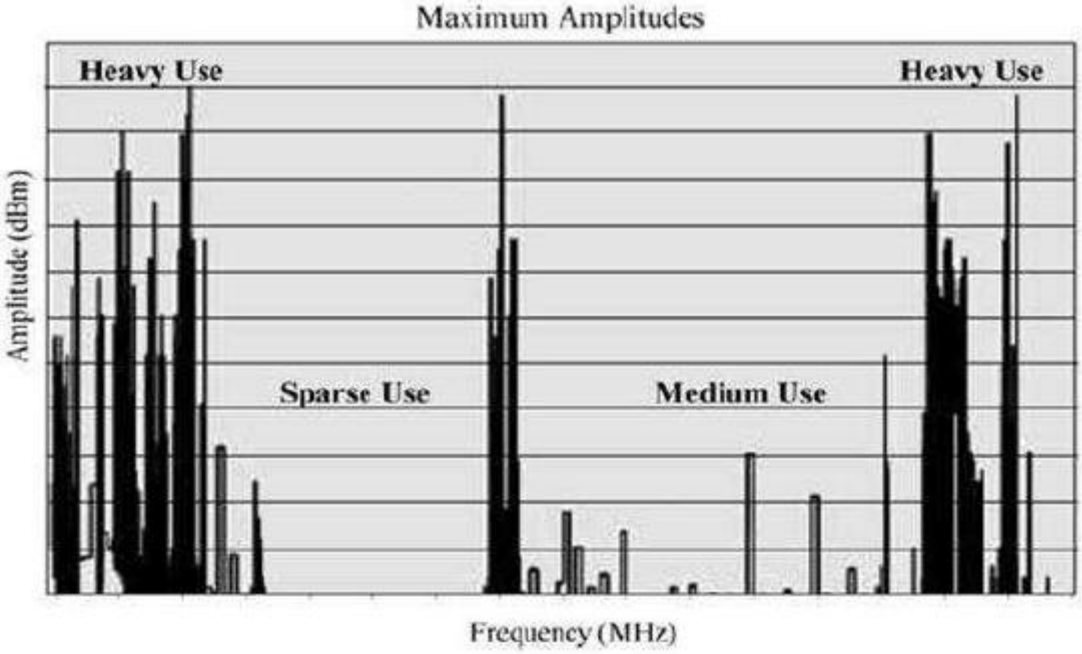

Figure 1.1 Spectrum utilization [2]

The 21st century has seen an explosion in personal wireless devices. From mobile phones to wireless local area networks (WLAN), people want to be perpetually networked no matter where they are. Services like mobile phone and global positioning system (GPS) use frequencies licensed by the FCC, while others like WLAN and Bluetooth use unlicensed bands.

The most popular unlicensed bands are the Industrial, Scientific and Medical (ISM) bands at 900 MHz, 2.4 GHz, and 5.8 GHz. While setting up a home wireless network to access your broadband Internet connection does not fall within the original “ISM" definition, lack of general use of these bands prompted the FCC to loosen restrictions. Within these frequency ranges, anyone can transmit at any time, as long as their power does not exceed the band's regulatory maximum.

Innovative techniques are required that can handle spectrum underutilization and exploit the currently available spectrum. The dynamic spectrum access (DSA) policy involves assigning different frequency bands to different wireless networks only when a need arises. The concept of licensed or primary user (PU) and unlicensed or secondary user (SU) emerge in this process. PU has the priority or legal right on the usage of the designated spectrum. SU uses the licensed frequency bands without causing any interference to the licensed users. Such vacant bands are called spectrum holes or white spaces. A spectrum hole is a band of frequencies assigned to a primary user, but at a particular time and specific geographic location, the band is not utilized by the user. Spectrum underutilization can be subsided if the spectrum holes can be utilized by a set of SU transceivers at the appropriate time and place. Cognitive Radio Network (CRN) is wireless communication concept which is capable of utilizing the unused spectrum opportunistically with the least interference to the existing users.

Twenty years ago, the FCC was primarily concerned with long-distance telecommunications. Managing spectrum resources typically involved guaranteeing minimal interference levels between spectrum licensees, including radio stations, broadcast television stations, and telecommunications providers. To accomplish this, FCC manually survey each area and select power, frequency, and bandwidth parameters for everyone that minimizes overall interference.

Mitigating interference in this new wave of personal wireless devices is a much more difficult problem. Certainly individually licensing every person's home Wi-Fi network would help cut down on interference, but it would by no means be a scalable solution. Rather than manually, static spectrum allocation, the FCC needs an automatic, distributed, and dynamic approach to managing radio frequencies in order to enable better spectrum sharing.

Such a scheme would define at least two classes of spectrum users. The first would be primary users who already possess an FCC license to use a particular frequency. The second would be secondary users consisting of unlicensed users. Other classes could also be defined, prioritizing users' access to the frequency band. Primary users would always have full access to the spectrum when they need it. Secondary users could use the spectrum when it would not interfere with the primary user.

IEEE 802.22 is the first worldwide cognitive radio based standard [3]. The development of the IEEE 802.22 WRAN standard is aimed at using cognitive radio techniques to allow sharing of geographically unused spectrum allocated to the television broadcast service, on a non-interfering basis, to bring broadband access to hard-to-reach low-population-density areas typical of rural environments, and is therefore timely and has the potential for wide applicability worldwide. IEEE 802.22 WRANs are designed to operate in the TV broadcast bands while ensuring that no harmful interference is caused to the incumbent operation (i.e., digital TV and analog TV broadcasting) and low-power licensed devices such as wireless microphones.

WRAN network is heterogeneous traffic wireless network that involves different users wired or wireless, from a real-time, data, voice users, to higher speed users and so on. The IEEE 802.22 standard [3] have identified and classified the heterogeneous traffics expected in WRAN into five service flows: Unsolicited grant service (UGS), Real time polling service (rtPS), non-real time polling service (nrtPS), best effort (BE) and extended real time polling service (ertPS). These traffics have different QoS and arrive to the network in Poisson process, from random locations within the coverage area of network. Thus, an efficient scheduling algorithm in cognitive radio is needed.

1.2 Problem Statement

As mentioned before, CRN is considered as a promising solution for addressing the spectrum scarcity problem by using an opportunistic spectrum access approach, where frequency bands that are not used by their licensed users, such as the TV users, can be utilized by cognitive radios. Making efficient use of the radio resources is becoming a very challenging task due to the scarcity of radio resources, time-varying channel conditions, and very diverse quality of service (QoS) requirements. However, availability of a channel for secondary users depends on whether the primary user is occupied or not which is opportunistic scenario.

Scheduling policy design is a part of the spectrum sharing and plays a crucial role in the network performance. How to design a scheduling scheme to efficiently and fairly allocate the available spectrum(s) or channel(s) is a challenging and fundamental issue in CRNs. Users in a wireless scenario may have different channel conditions. The selection of a CRU to use an available spectrum at any time should take into consideration the balance between the current possible throughput and fairness. If a user with the highest priority is chosen at each slot, then other users with lower priority will be starved and such an allocation scheme would be considered unfair. Fair scheduling can provide better opportunity to the users with lower priority but will reduce the overall maximum possible throughput. Therefore, how to improve the resource utilization to get a high throughput and make a compromise between the system throughput and fairness is an important issue. Moreover, we need to carefully consider the medium access control frame structure when designing a scheduling scheme because of the unique features of the CRNs. As such, we are motivated to investigate scheduling algorithms that address the distinct characteristics of CRN environments while finding a balance between fairness and system throughput.

1.3 Project Objectives

The objective of this study are as follows:-

1) To investigate channel availability and queuing aware scheduling algorithm in cognitive radio network.
2) To evaluate the secondary user traffic QoS in terms of throughput, delay and fairness.

1.4 Scope of the Project

The scope of this work will be on scheduling algorithm in cognitive radio networks based on Earliest Deadline First scheduling to preserve the QoS of all types of Secondary User traffic. In cognitive modeling, primary user activity is modelled by using ON/OFF Markov model. The research focuses on downlink scheduling for transmission from the BS to SUs. The basic allocated resource unit is a time-frequency block (using the OFDMA access technique).

The secondary user traffic that we will consider in the work is the Real Time Polling Service (rtPS) traffics, Non Real Time Polling Service (nrtPS) traffics and Best Effort (BE) traffics. In simulation MATLAB tools will be used.

1.5 Thesis Organization

This thesis is structured into six chapters.

Chapter 1 focuses on introduction, problem definition, research objective and scope of the work.

Chapter 2 introduces a cognitive radio spectrum sharing technology. We define cognitive radios in a very broad sense with the capability to share the available channel, also the important features of IEEE 802.22 WRAN are presented. In this chapter, we also provide literature reviews on scheduling policies in wireless networks and related work on scheduling in cognitive radio network.

Chapter 3 consists of the system design and framework of cognitive radio network. The primary user activity model is presented. Channel availability model for cognitive radio networks is described. Furthermore, the secondary user traffic generation is highlighted.

Chapter 4 presents channel availability and queuing aware scheduling algorithm in CRN. The technique used to differentiate services for QoS provisioning in the algorithm together with the CRN features is explained. Buffer management strategies in the algorithm are also highlighted.

Chapter 5 Simulation results are presented to evaluate the performance of the scheduling algorithm. Simulations in different performance metrices like throughput and fairness are discussed

Chapter 6 describes the summary of the work, conclusion and suggestions for future work.

REFERENCES

[1] Federal Communications Commission, "Spectrum Policy Task Force " Rep. ET Docket no. 02-135, Nov. 2002.

[2] I. F. Akyildiz, *et al.*, "Next generation dynamic spectrum access/cognitive radio wireless networks: A survey," *Computer Networks,* vol. 50, pp. 2127-2159, 2006.

[3] "IEEE Draft Standard for Information Technology -Telecommunications and information exchange between systems - Wireless Regional Area Networks (WRAN) - Specific requirements - Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Policies and procedures for operation in the TV Bands," *IEEE P802.22/D2.0, February 2011,* pp. 1-698, 2011.

[4] J. Mitola, III and G. Q. Maguire, Jr., "Cognitive radio: making software radios more personal," *Personal Communications, IEEE,* vol. 6, pp. 13-18, 1999.

[5] J. Mitola, "The software radio architecture," *Communications Magazine, IEEE,* vol. 33, pp. 26-38, 1995.

[6] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *Selected Areas in Communications, IEEE Journal on,* vol. 23, pp. 201-220, 2005.

[7] I. Akyildiz, *et al.*, "AdaptNet: an adaptive protocol suite for the next-generation wireless Internet," *Communications Magazine, IEEE,* vol. 42, pp. 128-136, 2004.

[8] I. F. Akyildiz, *et al.*, "A survey on spectrum management in cognitive radio networks," *Communications Magazine, IEEE,* vol. 46, pp. 40-48, 2008.

[9] F. F. Digham, *et al.*, "On the energy detection of unknown signals over fading channels," in *Communications, 2003. ICC '03. IEEE International Conference on*, 2003, pp. 3575-3579 vol.5.

[10] A. Sahai, *et al.*, "Fundamental design tradeoffs in cognitive radio systems," in *Technology and Policy for Accessing Spectrum* 2006.

[11] M. Kaplan and F. Buzluca, "A dynamic spectrum decision scheme for heterogeneous cognitive radio networks," in *Computer and Information Sciences, 2009. ISCIS 2009. 24th International Symposium on*, 2009, pp. 697-702.

[12] P. Lassila and A. Penttinen, "Survey on performance analysis of cognitive radio networks," presented at the COMNET Department, Helsinki University of Technology, 2009.

[13] S. Enserink and D. Cochran, "A cyclostationary feature detector," in *Signals, Systems and Computers, 1994. 1994 Conference Record of the Twenty-Eighth Asilomar Conference on*, 1994, pp. 806-810 vol.2.

[14] B. Canberk, *et al.*, "A QoS-aware framework for available spectrum characterization and decision in Cognitive Radio networks," in *Personal Indoor and Mobile Radio Communications (PIMRC), 2010 IEEE 21st International Symposium on*, 2010, pp. 1533-1538.

[15] L. Won-Yeol and I. F. Akyldiz, "A Spectrum Decision Framework for Cognitive Radio Networks," *Mobile Computing, IEEE Transactions on,* vol. 10, pp. 161-174, 2011.

[16] H. Arslan, *Cognitive Radio,Software Defined Radio, and Adaptive Wireless Systems*: Springer, 2005.

[17] R. Dubey and S. Sharma, "Distributed Shared Spectrum Techniques for Cognitive Wireless Radio Networks," in *Computational Intelligence and Communication Networks (CICN), 2010 International Conference on*, 2010, pp. 259-264.

[18] A. W. Min, *et al.*, "Opportunistic spectrum access for mobile cognitive radios," in *INFOCOM, 2011 Proceedings IEEE*, 2011, pp. 2993-3001.

[19] J. Mehdi, *Stochastic Models in Queueing Theory*: Academic Press, 2002.

[20] M. Raspopovic, *et al.*, "Performance models for wireless spectrum shared by wideband and narrowband sources," in *Military Communications Conference, 2005. MILCOM 2005. IEEE*, 2005, pp. 1642-1647 Vol. 3.

[21] X. Yiping, *et al.*, "Dynamic spectrum access in open spectrum wireless networks," *Selected Areas in Communications, IEEE Journal on,* vol. 24, pp. 626-637, 2006.

[22] C. Chun-Ting, *et al.*, "What and how much to gain by spectrum agility?," *Selected Areas in Communications, IEEE Journal on,* vol. 25, pp. 576-588, 2007.

[23] F. Capar, *et al.*, "Comparison of bandwidth utilization for controlled and uncontrolled channel assignment in a spectrum pooling system," in *Vehicular Technology Conference, 2002. VTC Spring 2002. IEEE 55th*, 2002, pp. 1069-1073 vol.3.

[24] T. Pak Kay and C. Yong Huat, "On the Modeling and Performance of Three Opportunistic Spectrum Access Schemes," *Vehicular Technology, IEEE Transactions on,* vol. 59, pp. 4070-4078, 2010.

[25] H. Senhua, *et al.*, "Opportunistic Spectrum Access in Cognitive Radio Networks," in *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*, 2008, pp. 1427-1435.

[26] C. Stevenson, *et al.*, "IEEE 802.22: The first cognitive radio wireless regional area network standard," *Communications Magazine, IEEE,* vol. 47, pp. 130-138, 2009.

[27] Carlos Cordeiro, *et al.*, "Cognitive PHY and MAC layers for dynamic spectrum access and sharing of TV bands," in *Proceedings of the 1st international workshop on technology and policy for accessing spectrum (TAPAS)*, Boston, 2006.

[28] Z. Ping, *et al.*, "Scheduling Model for Cognitive Radio," in *Cognitive Radio Oriented Wireless Networks and Communications, 2008. CrownCom 2008. 3rd International Conference on*, 2008, pp. 1-6.

[29] J. Zhang, *et al.*, "Uplink Scheduling for Cognitive Radio Cellular Network with Primary User's QoS Protection," in *Wireless Communications and Networking Conference (WCNC), 2010 IEEE*, 2010, pp. 1-5.

[30] M. E.Khedr, *et al.*, "Adaptive QoS Contrained Priority Scheduling for Cognitive Radio Systems," *European Journal of Scientific Research,* vol. 82, pp. 227-247, 2012.

[31] C. Yaxin and V. O. K. Li, "Scheduling algorithms in broadband wireless networks," *Proceedings of the IEEE,* vol. 89, pp. 76-87, 2001.

[32] M. Torabzadeh and W. Ajib, "Packet Scheduling and Fairness for Multiuser MIMO Systems," *Vehicular Technology, IEEE Transactions on,* vol. 59, pp. 1330-1340, 2010.

[33] H. Anh Tuan and L. Ying-Chang, "A Two-Phase Channel and Power Allocation Scheme for Cognitive Radio Networks," in *Personal, Indoor and Mobile Radio Communications, 2006 IEEE 17th International Symposium on*, 2006, pp. 1-5.

[34] H. Anh Tuan and L. Ying-Chang, "Maximizing Spectrum Utilization of Cognitive Radio Networks Using Channel Allocation and Power Control," in *Vehicular Technology Conference, 2006. VTC-2006 Fall. 2006 IEEE 64th*, 2006, pp. 1-5.

[35] L. Jianying*, et al.*, "Adaptive Packet Scheduling Algorithm for Cognitive Radio System," in *Communication Technology, 2006. ICCT '06. International Conference on*, 2006, pp. 1-5.

[36] V. K. Tumuluru*, et al.*, "An Opportunistic Spectrum Scheduling Scheme for Multi-Channel Cognitive Radio Networks," in *Vehicular Technology Conference Fall (VTC 2010-Fall), 2010 IEEE 72nd*, 2010, pp. 1-5.

[37] R. Urgaonkar and M. J. Neely, "Opportunistic Scheduling with Reliability Guarantees in Cognitive Radio Networks," *Mobile Computing, IEEE Transactions on,* vol. 8, pp. 766-777, 2009.

[38] R. Hassan*, et al.*, "Priority-Based Scheduling for Cognitive Radio Systems," in *International Conference on Information and Network Technology (ICINT 2012)*, Singapore, 2012, pp. 145-150.

[39] M. Wellens*, et al.*, "Modelling Primary System Activity in Dynamic Spectrum Access Networks by Aggregated ON/OFF-Processes," in *Sensor, Mesh and Ad Hoc Communications and Networks Workshops, 2009. SECON Workshops '09. 6th Annual IEEE Communications Society Conference on*, 2009, pp. 1-6.

[40] L. Won-Yeol and I. F. Akyildiz, "Optimal spectrum sensing framework for cognitive radio networks," *Wireless Communications, IEEE Transactions on,* vol. 7, pp. 3845-3857, 2008.

[41] M. D. Felice*, et al.*, "Modeling and performance evaluation of transmission control protocol over Cognitive Radio Ad HoC Networks," in *Proc. of ACM MSWIM* Tenerife, Spain, 2009, pp. 1-12.

[42] D. S. Shu'aibu, "Radio Resource Management For Mobile WIMAX Network," Ph.D, Universiti Teknologi Malaysia, Johor, 2012.

[43] X. Li, *et al.*, "Cross-layer optimal spectrum sensing duration and scheduling in cognitive networks," presented at the Proceedings of the 3rd ACM workshop on Cognitive radio networks, Las Vegas, Nevada, USA, 2011.

[44] K. Ali and Z. Weihua, "Link-Layer Resource Allocation for Voice Users in Cognitive Radio Networks," in *Communications (ICC), 2011 IEEE International Conference on*, 2011, pp. 1-5.