UNIVERSITI PUTRA MALAYSIA

DYNAMIC APPROACHES FOR SPECTRUM CONTROL IN COGNITIVE RADIO NETWORKS

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By

AHMED MOHAMEDOU

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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DEDICATION

To my parents.
Without them, this was impossible.

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

DYNAMIC APPROACHES FOR SPECTRUM CONTROL IN COGNITIVE RADIO NETWORKS

By

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October 2015

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Cognitive Radio is an innovative wireless engineering paradigm which promises to mitigate spectrum scarcity problem. It provides wireless systems with capabilities of manipulating their transmission parameters to achieve the highest possible spectrum utilization. This is done by allowing secondary users (unlicensed users) to access licensed spectrum if the primary user (licensed user) is not using it. One necessary condition has to be satisfied. Secondary users have to guarantee that no harmful interference is caused to the primary user.

Three important challenges arise when developing such cognitive radio systems. First, electromagnetic spectrum used for wireless communication is very large. Looking for unused channels (sensing channels to figure out their status) is a very expensive operation. Any effective cognitive system has to implement efficient sensing order scheduler to reduce spectrum probing cost. The second and the third challenges arise from the coexistence of heterogeneous secondary users. These users have to share the unused spectrum fairly. Also, they must access the medium in an organized fashion to minimize collisions overhead.

This research investigates these three challenges extensively. It models the first problem as *Multi-Arm Bandit* problem and *Regret* concept is used to evaluate sensing order scheduling performance. Two artificial intelligence techniques are utilized which are *Fuzzy Inference* and *Bayesian Inference*. To optimize *Fuzzy Inference* scheduler, *Genetic Algorithm* is used. Compared to fixed sensing order, this proposed technique managed to achieve an outstanding performance in term of channel utilization. Another two solutions are proposed to solve problem of co-existing heterogeneous secondary users. The first solution can be used in centralized fashion where a central entity exists which decides transmission power for all secondary users. This solution has one objective which is to minimize the time required by secondary users to clear their queues. *Interior-Point*

Method is used to find the best spectrum sharing and medium access policy to achieve this objective. The second solution assumes the autonomy of secondary users where the decision to update transmission power is distributed among users. Dynamical system approach is used to model system behavior and a forecasting engine based on *Deep Neural Network* is proposed. This engine gives secondary users the ability to acquire useful knowledge from surrounding wireless environment. As a result, better transmission power allocation is achieved. Evaluation experiments have confirmed that adopting *Deep Neural Network* can greatly improve the performance.

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

KAEDAH DINAMIK UNTUK KAWALAN SPEKTRUM DALAM RANGKAIAN RADIO KOGNITIF

Oleh

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Radio kognitif adalah paradigma kejuruteraan tanpa wayar yang inovatif dan berjanji untuk mengurangkan masalah spektrum kekurangan. Ia menyediakan sistem tanpa wayar dengan keupayaan memanipulasi parameter penghantaran untuk mencapai spektrum penggunaan tertinggi. Ia berfungsi dengan membenarkan pengguna sekunder (pengguna tidak berlesen) untuk mengakses spektrum berlesen jika pengguna utama (pengguna berlesen) tidak menggunakannya. Dengan memenuhi satu syarat. Pengguna sekunder perlu menjamin tidak akan menyebabkan gangguan yang memudaratkan kepada pengguna utama.

Tiga cabaran penting timbul semasa membangunkan sistem radio kognitif seperti ini. Pertama, spektrum elektromagnet yang digunakan untuk komunikasi tanpa wayar adalah sangat besar. Mencari saluran yang tidak digunakan (mengimbas saluran untuk mengetahui status mereka) adalah operasi yang sangat mahal. Sistem kognitif yang berkesan perlu melaksanakan penjadual susunan sensing yang cekap untuk mengurangkan kos pengimbasan spektrum. Cabaran yang kedua dan yang ketiga timbul daripada kewujudan bersama pengguna sekunder heterogen. Pengguna ini perlu berkongsi spektrum yang tidak digunakan dengan adil. Selain itu, mereka mesti mengakses medium tersebut dengan cara yang teratur untuk mengurangkan perlanggaran overhed.

Kajian ini menyiasat tiga cabaran ini secara meluas. Ia modelkan masalah pertama sebagai masalah Penyamun Multi-Lengan dan konsep Penyesalan digunakan untuk menilai prestasi penjadualan susunan sensing. Dua teknik kecerdasan buatan yang digunakan adalah *Kesimpulan Fuzzy* dan *Kesimpulan Bayesian. Algoritma Genetik* digunakan untuk mengoptimumkan penjadual *Kesimpulan Fuzzy.* Berbanding dengan susunan sensing tetap, teknik yang dicadangkan ini berjaya mencapai prestasi cemerlang dari segi penggunaan saluran. Dua lagi penyelesaian dicadangkan untuk menyelesaikan masalah dari peng-

guna sekunder heterogen yang wujud bersama. Penyelesaian yang pertama boleh digunakan dengan fesyen berpusat di mana entiti pusat diwujudkan untuk membahagikan kuasa penghantaran untuk semua pengguna sekunder. Penyelesaian ini mempunyai satu matlamat iaitu untuk mengurangkan masa yang diperlukan oleh pengguna sekunder untuk mengurangkan barisan giliran mereka. Kaedah *Interior-Titik* digunakan untuk mencari perkongsian spektrum yang terbaik dan dasar akses medium untuk mencapai matlamat ini. Penyelesaian kedua mengiktiraf autonomi pengguna sekunder di mana keputusan untuk mengemaskini penghantaran kuasa diedarkan di kalangan pengguna. Pendekatan sistem dinamik untuk memodelkan tingkah laku sistem dan ramalan enjin berdasarkan Rangkaian Neural Dalam dicadangkan. Enjin ini memberikan pengguna sekunder keupayaan untuk memperoleh pengetahuan yang berguna dari persekitaran tanpa wayar sekitar. Oleh itu, peruntukan kuasa penghantaran yang lebih bagus dicapai. Eksperimen Penilaian telah mengesahkan bahawa pengunaan Rangkaian Neural Dalam banyak meningkatkan prestasi.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy.

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LIST OF ABBREVIATIONS

AI	Artificial Intelligence
ANN	Artificial Neural Networks
BI	Bayesian Inference
BSS	Bayesian Sensing Scheduler
CI	Convergence Indicator
CMSA	Centralized Medium Sharing and Access
CR	Cognitive Radio
CRN	Cognitive Radio Network
CSI	Channel State Information
DAE	Deep Auto Encoder
DBN	Deep Belief Network
DL	Deep Learning
DMSA	Distributed Medium Sharing and Access
DNN	Deep Neural Network
ECMA	European Computer Manufacturers Association
ETSI	European Telecommunications Standards Institute
FIS	Fuzzy Inference System
GA	Genetic Algorithm
GFSS	Genetic-Fuzzy Sensing Scheduler
LTE-A	Long Term Evolution Advanced
MAC	Medium Access Control
ML	Machine Learning
OFDMA	Orthogonal Frequency Division Multiple Access
PU	Primary User
QoS	Quality of Service
RRS	Reconfigurable Radio Systems

SINR	Signal to Interference Noise Ratio
SU	Secondary User
WLAN	Wireless Local Area Networks
WRAN	Wireless Regional Area Networks

CHAPTER 1

INTRODUCTION

1.1 Overview

Cognitive Radio (CR) (Mitola and Maguire, 1999) is a modern technique in wireless technologies which provides wireless devices with the ability of re-configuring their transmission parameters based on their surrounding environment. This reconfigurability feature is essential to solve the widely noticed underutilized and unfair spectrum resources assignment. In general, these resources are very limited and they are in high demand due to the exponential increase of data traffic. According to Juniper Research (Juniper, 2011), it is expected that by 2015 sixty percent of global traffic will be transferred through femtocells and WiFi. In addition, a white-paper published by Cisco Systems (Cisco, 2011) showed that the mobile data traffic has tripled every year between 2008-2010. These facts indicate an increasing usage of bandwidth for wireless communication. Ironically, the most used technologies (such as wireless LAN (WiFi) and mobile telecommunication systems) are suffering from spectrum scarcity while there is a lot of spectrum assigned to other technologies (such as TV broadcasting systems) which is underutilized (Staple and Werbach, 2004). Here, CR comes to rescue these suffering technologies (i.e. WiFi and femtocells) by providing them with the ability to exploit the underutilized spectrum. These technologies can expand their transmission bandwidth into underutilized spectrum as long as no harmful interference is suffered by the official spectrum owner (i.e. TV broadcaster).

According to CR terminology, the spectrum owner is called Primary User (PU) while the wireless station trying to utilize the spectrum is called Secondary User (SU). The highest motivation for SU to utilize PU spectrum is to increase its own data rate. Therefore, every SU will try to find as much as obtainable underutilized spectrum to achieve the highest possible throughput. This will lead to a situation where the SU should compromise between exploring new portions of PU spectrum and exploiting the existing portions. This is due to the fact that wireless stations usually have only one set of radio front (transmission components such as antenna and signal processor). Therefore, a wireless station can either explore spectrum by sensing it which means it cannot transmit any data; or it can use the existing spectrum for communication by transmitting data. The trade-off between exploring and exploiting is very tricky. Each channel of spectrum has its own utilization behavior depending on its primary user and other surrounding secondary user's activities. In addition, from each SU perspective, each channel has different significance subject to many factors such as shadowing, fading and bandwidth. As a result, one of the most important problems faced by secondary users is to find the best exploration strategy that achieves the optimal exploitation. In addition, during the exploitation phase, all co-existing secondary users should shared the available spectrum in wise way which increases their performance and decreases collisions among them when they try to access the available spectrum.

1.1.1 Cognitive Radio and Sensing Order

The prime condition for a transmission to occur in Cognitive Radio Network (CRN) is all secondary users must not cause any interference to the primary user transmission. Consequently, any secondary user has to sense the considered channel before transmitting to see if the primary user is using the channel (busy) or if the channel is free (idle). Sensing multiple channels in a row defines the exploration process of secondary users. This process can be performed either periodically or on-demand. Depending on the utilization approach, two policies can be recognized. First, One-Channel policy (Niyato and Hossain, 2008c) where the secondary user is using only one channel as long as it is idle and this user will explore for new channels only when the channel under usage is reclaimed by the primary user. The second policy is Multiple-Channels (Liang et al., 2008) usage where the secondary user is periodically looking for new underutilized channels to increase its data rate. In both policies, the order of sensing channels to know their primary user status has massive impact on the total system efficiency.

Here, it is assumed that channels are not homogeneous in sense that they have different bandwidth and PU occupancy activities. This assumption is necessary to achieve the highest degree of spectrum utilization by allowing heterogeneous secondary users to access all possible spectrum. Intuitively, the most efficient SU is the one that always sense channels which are idle and have attractive characteristics such as large bandwidth and long idle time. For example, if there are three channels (Ch_1, Ch_2, Ch_3) to be explored and Ch_2 has the highest probability of being idle (free), then Ch_2 should be sensed first. In addition, if Ch_1 and Ch_3 have the same idle probability but Ch_1 has the larger bandwidth, then Ch_1 should be sensed second and Ch_3 should be sensed the last (or it should be skipped to start exploiting Ch_2 and Ch_1). In this simple example, the best **Sensing Order** strategy is (Ch_2, Ch_1, Ch_3).

1.1.2 Cognitive Radio and Spectrum Management

Generally, spectrum management is a key challenge in cognitive radio technologies. One important aspect of spectrum management is spectrum sharing. There are two types of spectrum sharing. First, primary-secondary sharing where the primary users allow secondary users to use their spectrum under some conditions. This first type is divided into two categories which are primary-secondary Underlay sharing and primary-secondary Overlay sharing (Srinivasa and Jafar, 2007). In underlay paradigm, secondary user operates on primary user channel with promise of not causing interference higher than some threshold. In overlay paradigm, primary users allow secondary users to use their channels in return for some service such as relaying.

Second type of spectrum sharing is secondary-secondary sharing where the primary user is assumed to be absent and secondary users utilize the vacant spectrum based on some sharing policy (Hwang and Yoon, 2008). Literature lacks the needed research to tackle the second type (secondary-secondary) of spectrum sharing. Most of works on second type assume the homogeneity of secondary users and the homogeneity of idle primary channels. Recently, some works tried to handle heterogeneous cognitive radio settings. However, these works assumed some sort of cooperation among secondary users. These facts motivated this research to investigate second type of spectrum sharing and medium access control in harsher wireless environment. In this environment, secondary users are assumed to be totally heterogeneous without any cooperation among them. In addition, primary user channels are assumed to be heterogeneous as well; where they have different bandwidth and channel characteristics (e.g. fading and shadowing).

1.2 Problem Statement

Perfect sense order strategies are impossible to achieve. The main reason is the extreme shortage of knowledge about behavior of channels utilization. In addition, usually, channel utilization behavior is changing from time to time and from place to place. Adding to the problem complexity, the rate of changing is different from channel to channel. These obstacles decrease the possibility of having an efficient secondary user which can sense the channels in near optimal order. Developing good sensing order mechanism is very problematic issue but at the same time it is a very important step towards providing wireless stations with cognitive capabilities.

In addition, all co-existing cognitive radio systems (secondary users) should exploit spectrum opportunities and they should try to use the underutilized spectrum to improve their performance. However, a serious problem will arise if naive policy of unorganized attempts by multiple cognitive systems to utilize the same spectrum is adopted by these systems. This naive way of utilizing idle spectrum will lead to chaos and high competitive situations among cognitive radio systems. In addition, other resources will be wasted such as power and computation time. Hence, secondary users should figure out a way to share the underutilized spectrum without introducing more problems to each other.

There is an extreme need to properly address both of sensing order and coexistence of heterogeneous wireless stations problems. These problems are elementary in Cognitive Radio. If the cognitive wireless station does not have an efficient sensing order mechanism, it will not be able to efficiently find free and idle wireless channels to utilize. At the same time, cognitive wireless station without effective policy of coexistence with other neighboring wireless stations will not be able to operate on free and idle wireless channels without causing harmful interference to its neighbors. Hence, properly addressing these problems is essential for Cognitive Radio to become a reality. This research developed solutions to mitigate the negative impact of these problems on Cognitive Radio operations.

In addition, the possibility and applicability of utilizing Artificial Intelligence and Machine Learning techniques in developing solutions for Cognitive Radio processes need to be investigated. The main hypothesis of this research is based on the fact that operations of wireless communications are conducted in compact format. For example, most of interference experienced by wireless stations is caused by other wireless stations implementing the same wireless technology.

It is obvious that manifestations of wireless operations (such as interference) is generated due to structured dynamics (i.e. wireless technology standard). Therefore, this research hypothesize that Artificial Intelligence and Machine Learning techniques will be a great tools to tackle wireless communication problems.

Most works in literature do not provide analytical analysis which introduces uncertainty about these works reliability. Solid justifications for any developed solution in this thesis based on analytical tools should be provided. This is needed due to the reality that interactions among cognitive wireless stations can lead to very complex behaviors and phenomena. In addition, Artificial Intelligence and Machine Learning techniques can be very complicated as well. This complexity is magnified by the fact that this research is restricting number of assumptions incorporated in any modeling processes to be as small as possible. As a result, there is an extreme need to analytically justify any developed solution. Keep in mind, any adopted assumption is widely accepted in literature.

1.3 Research Objectives

The aim of this research is to developed solutions for sensing order and heterogeneous coexistence problems in cognitive radio networks. These solutions are developed using Artificial Intelligence techniques to prove these techniques ability in addressing cognitive radio problems. The main goal of proposed solutions is to effectively increase utilization of free wireless channels. To achieve this aim, this research has the following main objectives:

1. To develop sensing scheduler based on Fuzzy Inference and Genetic Algorithm for sensing order problem so that high utilization is achieved.
2. To develop sensing scheduler based on Bayesian Inference for sensing order problem so that computation complexity is reduced.
3. To develop centralized mechanism of transmission power assignment based on Convex Optimization for spectrum sharing and medium access problems so that interference is optimally minimized.
4. To develop distributed mechanism of transmission power assignment based on Deep Neural Networks for spectrum sharing and medium access problems so that centralized coordination is not required to minimize interference effectively.

By delivering these objectives, this thesis aim is achieved in addition to providing several theoretical insights that can be used in future works.

1.4 Thesis Motivation

Wireless environment is a very complex environment. The simplest interaction between wireless stations may cause big changes in the observed environment. Secondary users should be able to have a very good understanding of the surrounding environment to reach high level of efficiency. Forming necessary knowledge about environment requires very complicated techniques. This process of knowledge acquisition should be performed over operation time (On-Line) because of the dynamic nature of wireless environment. These challenging conditions motivated the author of this thesis to propose the use of Artificial Intelligence (AI) and Machine Learning (ML) techniques because of their ability to handle problems with high complexity and uncertainty (Bantouna et al., 2012; Clancy et al., 2007); which are the main characteristics of wireless environment.

1.5 Main Contributions

This research adopts multiple Artificial Intelligence (AI) techniques which are Fuzzy Inference System (FIS) (Nedjah and de Macedo Mourelle, 2005) with Genetic Algorithm (GA) (Holland, 1992), Bayesian Inference (BI) (Tipping, 2004) techniques and Deep Learning (DL) (Bengio, 2009) with Artificial Neural Networks (ANN) (Hwang and Yoon, 2008). They were used to develop sensing order schedulers which are capable of finding good sensing order strategy for each specific secondary user. In addition, these techniques were utilized to develop spectrum sharing and access control mechanisms that provided the best performance for all co-existing secondary users. This research contributed to the existing cognitive radio literature by delivering these main contributions:

1. Sensing order scheduler based on Fuzzy Inference System (FIS) technique is proposed. This scheduler utilizes FIS feature of defining the knowledge and control as IF-THEN rules. These rules can be easily interpreted by system designers. However, the total number of possible rules makes the regular engineering approach infeasible. Therefore, Genetic Algorithm (GA) is used to systematically optimize FIS rules.

2. The need to trade-off between accuracy and speed led to developing sensing order scheduler based on Bayesian Inference (BI) concept. This statistical machine learning concept is widely used due to its computation efficiency. This research contributes Convergence Indicator (CI) which is an effective technique to manage Bayesian learning in cognitive radio networks.

3. Comprehensive mathematical re-formulation of spectrum sharing and medium access control problem is provided. This re-formulation leads to the concept of Spectrum-Time duality which states that it is beneficial for secondary users to reduce their level of competition with other secondary users by giving spectrum in return for time and vice versa. The idea depends on the fact that secondary users will be idle after they transmit all of their data. Such secondary users do not need to occupy the channels since they do not have any data to transmit. For secondary users which still have data to send, their jobs get easier after the other SU's become idle. Based on this concept, centralized transmission power mechanism is introduced where the main objective is to clear secondary users queues as soon as possible so that the competition for other secondary users is reduced.

4. Distributed transmission power rule is developed so that secondary users can assign their transmission power according to closed dynamical system evolution. By using this rule, the trajectory evolution of many system parameters can be predicted since it follows strict dynamics. Examples of system parameters are queue backlogs of secondary users, interference noise caused by secondary users and the actual transmission power of all secondary users.

5. Advanced method is proposed; which employs Deep Neural Network (DNN) approach. DNN is a very promising machine learning technique. The proposed method utilizes trajectory evolution of interference noise levels to forecast future noise levels. As a result, performance of transmission power rule is greatly enhanced. By employing DNN in cognitive radio technology, real cognition capabilities can be realized. Secondary users are able to generate decisions without the intervention of system designers.

Note that the proposed solutions are designed for cognitive radio technology since it is the main technology of next generation wireless communications. Nevertheless, these solutions can be easily implemented in conventional wireless technologies.

1.6 Thesis Organization

This thesis is organized by starting with comprehensive literature review in Chapter 2. The goal of this review is to present the most recent and related background regarding techniques and tools of Cognitive Radio (CR) and Artificial Intelligence (AI). The most important aspects of these tools and techniques regarding CR will be highlighted to ease the development of proposed approaches in later chapters. The third chapter develops the proposed sensing order scheduler based on FIS. It delivers a simple approach to incorporate GA optimization in designing the proposed scheduler. In addition, the third chapter uses BI concept to develop computationally efficient sensing order scheduler. A simple convergence indicator of scheduler accuracy is proposed as well.

Spectrum sharing and medium access control will be handled next in Chapter 3. First, rigorous mathematical treatment will be performed to develop centralized mechanism for spectrum sharing and medium access control. This centralized mechanism can be used in the most restricted situations where secondary users are homogeneous and they are actively cooperating. However, when homogeneity is not assumed, distributed mechanism with passive cooperation is needed. Based on dynamical system theory and deep learning such distributed mechanism is proposed.

All of the proposed solutions in this thesis were intensively tested by using simulation approaches in fourth chapter. Several performance variables and metrics were used during these simulation experiments. This thesis is concluded with fifth chapter where a summary of the research is presented and future directions for the research are proposed.

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