MATHEMATICAL MODELLING OF DYNAMIC SPECTRUM MANAGEMENT IN COGNITIVE NETWORK

BY

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ABSTRACT

A survey made by a Spectrum Policy Task Force (SPTF) within Federal Communications Commission (FCC) indicates that the actual licensed spectrum is largely under-utilized. A remedy to spectrum underutilization is to allow secondary users to access underutilized licensed bands dynamically when licensed users are absent. Due to this spectrum usage is undergoing a paradigm shift from the traditional licensed allocation to the dynamic spectrum access (DSA). Cognitive radios are intelligent radio, which can implement DSA efficiently. A cognitive radio can detect vacant licensed spectrum, access it and vacate when the licensed user starts transmitting. The cognitive radios can detect the spectrum more efficiently if they cooperate with other cognitive radios in the network. This results in increased transmission opportunity and hence increases the throughput of the cognitive radio network. Therefore, in order to realize the full potential of cognitive radio, there is a need for well-designed distributed cooperative algorithms that can realise the numerous gains from the vacant licensed spectrum. This thesis uses matching theory to develop such cooperation mechanism. Matching theory is a mathematical framework used to describe the formation of mutually beneficial relationships over time. This mutually beneficial relationship encourages the cognitive radio to form groups known as coalitions. The goal of matching theory in this thesis is to form coalitions of cognitive radios so that the overall benefits termed as “utility” is improved compared to benefit that cognitive radio receives when acting alone. This improved utility due to coalition formation results in improved spectrum detection, which in turn increases the opportunities for transmission in the vacant licensed spectrum. The detected vacant spectrum is shared among the cognitive radios in the network for achieving a higher throughput. For the purpose of coalition formation using matching theory, two algorithms are proposed. The first algorithm for coalition formation uses well-known Gale-Shapely algorithm to achieve cooperation among the cognitive radios for spectrum detection and management. This algorithm results in the formation of stable coalitions of cognitive radio. In order to form coalitions, each cognitive radio prepares a preference list of other radio in the vicinity with which the cognitive radio wants to cooperate and hence form a coalition. Each cognitive radio makes an offer to cognitive radio in its preference list for cooperation. The cognitive radio can accept or reject the offer based on the preference list. The second algorithm is based one-sided matching theory which is a variant of the Gale-Shapely algorithm. The procedure is similar to the first algorithm, however, the difference is in how the coalition formation takes place among the cognitive radios. Finally, using simulations and mathematical results, various aspects of the proposed algorithms were investigate and analysed. The proposed algorithms resulted in improved spectrum detection as well as spectrum management hence enhancing the throughput of the cognitive radio network as well as increasing the spectrum efficiency. Compared to the non-cooperative scenario the modified Gale-Shapley algorithm resulted in the reduction of false alarm probability approximately by 51% and one-sided matching resulted in a 46% reduction in AWGN channel when number of cognitive radio user in the network is set to 30. While in the fading environment the reduction was approximately by 40% and 39% respectively for modified Gale-Shapley and one-sided matching algorithm.

خلاصة البحث

دراسة حديثة صادرة عن لجنة تحديد سياسة الطيف (SPTF) التابعة لمنظمة الاتصالات الاتحادية (FCC) اشارة إلى أن الطيف المرخص الفعلي هو إلى حد كبير غير مستغل بالصورة المطلوبة. ولذلك، ولاستغلال الطيف بالصورة المطلوبة يجب السماح لبعض المستخدمين الثانويين باستخدام الطيف المرخص غير المستغل من قبل المستخدم الرئيسي بصورة فعالة. ونتيجة لهذا الاستخدام الفعال فان هناك نقلة نوعية من الطريقة التقليدية لتحديد الطيف الى طريقة فعالة وحيوية تسمى (DSA). الطريقة الادراكية في توزيع الطيف (Cognitive radios) هي طريقة ذكية بحيث توظف (DSA) بصورة فعالة و بكفاءة عالية. بامكان الطريقة الادراكية تحديد الاجزاء غير المستخمة من الطيف واستغلالها بالشكل الفعال وتركها في حال تمت الحاجة لها من قبل المستخدم الرئيسي المرخص. وفي حال تم التعاون بين اكثر من طريقة ادراكية فسيتم استغلال الطيف بفعالية اكبر. وبالتالي هذا يؤدي إلى زيادة فرصة انتقال البيانات، وبدوره يزيد من سرعة نقل البيانات في الشبكات التي تعتمد الطريقة الادراكية. ولذلك، من أجل تحقيق افضل نتيجة ممكنة لاستخدام الطرق الادراكية، يجب تصميم الخوارزميات المسؤولة عن تحديد الاجزاء غير المستغلة في الطيف المرخص بصورة جيدة. هذه الأطروحة تستخدم نظرية المطابقة لتحقيق افضل تعاون ممكن بين الطرق الادراكية. نظرية المطابقة هي اطار رياضي تم استخدامها في هذا البحث لايجاد تحالفات بين الطرق الادراكية وبالتالي فان الفائدة الكلية (المنفعة) لهذا التحالف تكون اكثر من استخدام كل طريقة على حدة. مما يحسن عملية اكتشاف الطيف غير المستغل واستخدامه بالصورة المناسبة مما يمعكس على على سرعة نقل البيانات. تم اقتراح اثنتين من الخوارزميات لغرض تشكيل التحالف باستخدام نظرية المطابقة. الخوارزمية الأولى تسمى (Gale-Shapely) وتستخدم لايجاد ما يسمى بالتحالفات الثابته. حيث ان كل طريقة ادراكية تقوم بعمل قائمة تفضيلية للشبكات الادراكية المجاورة وبالتالي تقديم عرض لهذه الشبكات الادراكية المتوفرة في القائمة لعمل تحالفات. وللشبكات الاخرى الحق في قبول التحالف من عدمه. اما الخوارزمية الثانية فهي تستند على جانب واحد من نظرية المطابقة والتي تختلف عن (Gale-Shapely)**.** الاجراءات في هذه الخوارزمية مشابهة بشكل كبير للخوارزمية الاولى ولكن الاختلاف يكمن فقط في طريقة تشكيل التحالفات. وأخيرا، تم تحقيق وتحليل الخوارزميات المقترحة رياضيا وباستخدام برامج المحاكاة.اظهرت النتائج ان هناك تحسن ملحوظ في اكتشاف اجزاء الطيف غير المستغل وطريقة استخامه مما اسفر عن زيادة معدل نقل البيانات وزيادة كفاءة الشبكة. مقارنة بسيناريو عدم وجود تعاون بين الشبكات الادراكية فان النتائج اظهرت ان الخوارزمية الاولى حدت من عملية الانذار الكاذب لانتقال البيانات بنسبة 51 ٪ مقابل 46 ٪ للخوارزمية الثانية مقارنة باطرق التقليدية في حالة وجود 30 شبكة اداركية. بينما في وجود بعض العوامل المؤثرة فان النسبة انخفضت الى 40 ٪ و 39 ٪ للخورزمية الاولى والثانية على التوالي.

APPROVAL PAGE

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Mohammad Tahir

Signature …………………………………… Date ……………………..

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In the name of Allah, the Most Gracious and the Most Merciful

All praise and glory goes to Almighty Allah (Subhanahu Wa Ta'ala) who gave me the courage and patience to carry out this work. Peace and blessings of Allah be upon His last Prophet Muhammad (PBUH) and all his Sahaba (companions) who devoted their lives towards the prosperity and the spread of Islam.
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Family support plays a vital role in the success of an individual. I owe thanks to my mother, father and my lovely wife who have motivated, encouraged and provided moral support in my journey. I would like to thank my siblings, my aunt and my loving cousins, other family members from the core of my heart. Their prayers and encouragement always helped me take the right steps in life.

May Allah help us in following Islam, according to the Quran and Sunna! *(Aameen*)

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LIST OF SYMBOLS

$(N, \succcurlyeq_S)$	A hedonic game
(N, v)	Game with N players and utility function v
$T_1 \succcurlyeq_S T_2$	S prefer T_1 over T_2
$\succcurlyeq_S$	Preference relation operator
μ	Matching
$h_i(t)$	Channel gain of the sensing channel
m	Time-bandwidth product
$n_i(t)$	zero-mean additive white Gaussian noise
P_d	Probability of detection
$P_d^{'}$	Target probability of detection
Pe	Probability of error
P_f	Probability of false alarm
PL(M)	Preference list of man
PL(W)	Preference list of women
P_m	Probability of miss detection
P_{PU}	PU transmit power
Q_f	False alarm probability for a coalition
$s_i(t)$	Transmitted PU signal
T_f	Frame duration
α	path loss exponent
γ	Signal to noise ratio
λ_i	Energy detection threshold
σ^2	Noise power

τ_c	Decision combining duration
τ_s	Sensing duration
$v(S)$	Utility function

LIST OF ABBREVIATION

AWGN	Additive white Gaussian noise
BPSK	Binary phase shift keying
CCC	Common control channel
CDMA	Code division multiple access
CF	Coalition Formation
CPC	Cognitive pilot control channel
CR	Cognitive radio
CRN	Cognitive radio network
CSCG	Circular symmetric complex Gaussian noise
CSMA/CA	Carrier sense multiple access/collision avoidance
DARPA	Defence Advanced Research Projects Agency
DSA	Dynamic spectrum access
ESS	Evolutionarily stable strategy
FCC	Federal Communications Commission
FDMA	Frequency division multiple access
FPD	First preferences digraph
GPS	Global positioning system
IP	Internet protocol
ISM	Industrial, Scientific, Medical
MAC	Medium access control
MAN	Metropolitan Area Network
MGS	Modified Gale-Shapley
MIMO	Multiple input multiple output

NBS	Nash bargaining solution
NE	Nash equilibrium
NTU	Non-transferable utility
OFDMA	Orthogonal frequency division multiplexing
PL	Preference list
PU	Primary user
QoS	Quality of service
SDR	Software defined radio
SNR	Signal to noise ratio
SPTF	Spectrum Policy Task Force
SU	Secondary user
TCP	Transmission control protocol
TDMA	Time division multiple access
TU	Transferable utility
TVWS	TV white space
WRAN	Wireless Rural Area Network

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

At present most of the spectrum bands suitable for wireless communication have been already allocated to different wireless services, often requiring licenses for operation. A fundamental problem faced by future wireless systems is to find suitable spectrum to meet the growing demand for speed and accommodate future wireless services. The current license-free ISM bands (Industrial, Scientific, and Medical) are not enough for future wireless services as they are already congested hence making it difficult to accommodate new technologies. Due to this situation, there is a common belief that there is not enough usable frequency left, which is threatening the expansion of high-speed ubiquitous wireless networks. However, a recent survey made by the Spectrum Policy Task Force (SPTF) within FCC indicates that the actual licensed spectrum is largely under-utilized in vast temporal and geographic dimensions. For instance, a spectrum measurement performed in New York City has shown that the maximum total spectrum occupancy is only 13.1% in 30 MHz to 3 GHz range (Shared Spectrum Company, 2005). This similar trend follows in Malaysia too. A scan in the Malaysian capital of Kula Lumpur confirms this scenario as seen in Figure 1.1 (Omar, 2010).

This exciting discovery encourages new directions of research to solve the problem of spectrum scarcity and at the same time helps to get rid of spectrum under-utilization. A remedy to spectrum scarcity is to improve spectrum utilization by allowing unlicensed users to access under-utilized licensed bands dynamically when licensed users are absent. This idea of spectrum utilization is called Dynamic spectrum access (DSA).

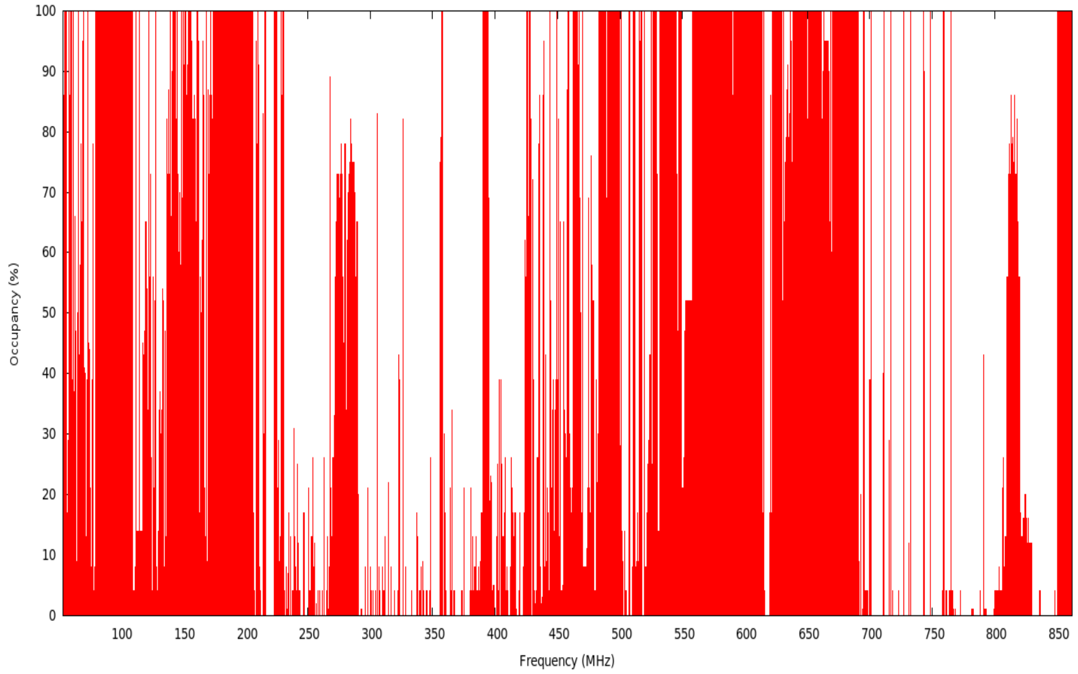

Figure 1.1 Spectrum occupancy plot for KL between 54-862 MHz (Omar, 2010).

One of the solutions, that promise efficient and flexible DSA, is cognitive radio (CR). CR is a novel technology, which improves the spectrum utilization by allowing unlicensed users, also termed as secondary users (SUs), to borrow or share the unused radio spectrum from licensed users, also termed as primary users (PUs). As an intelligent wireless communication system, CR is aware of the radio frequency environment. It selects the communication parameters (such as carrier frequency, bandwidth, and transmission power) to optimize the spectrum usage and adapts its transmission and reception accordingly.

A collection of CRs which communicate in a networked architecture (.e.g. centralized, distributed) is called a cognitive radio network (CRN). CRN is a wider concept than CR since the main concern of CR is the awareness, understanding, and adaptation of radio resources, such as spectrum, time, space and power only. Power control, spectrum sharing, routing, cooperative spectrum sensing and spectrum sharing etc. are actually network level problems, and without the necessary support from the network level, the flexibility brought by CR is limited. Moreover, this way of dynamic spectrum access paradigm creates a wireless ecosystem in which CRs work in a highly coupled way. It requires new network design principles and philosophy breaking away from traditional methods of wireless networking (centralized access controller) to realize the power of this new wireless ecosystem. With the amount of research effort being put in CRN by researchers around the world, this thesis embarks on the research of utilizing the licensed spectrum opportunistically to improve the spectrum utilization and at the same time improving the efficiency of in order to realize the full potential of CRN. Novel ways are explored to increase the spectrum efficiency and improve the throughput of CRN using licensed spectrum without interfering with the PUs or the licensed users.

1.2 PROBLEM STATEMENT AND SIGNIFICANCE

CR has been researched extensively to enhance the efficiency of spectrum usage in the next generation wireless and mobile computing systems. The techniques for channel measurement, learning, and optimization, that are crucial in designing DSA schemes for CR under different communication requirements, are widely investigated. From the network level point of view, the literature is not very extensive and still requires a significant amount of research to realize the advantages brought by the CR on a network scale. Usually, the research on CR is divided into four major areas which are:

1. Spectrum sensing
2. Spectrum decision

3. Spectrum Sharing

4. Spectrum mobility

All four areas mentioned above are crucial for the CR to operate efficiently. However, they are studied and addressed independently. Out of these four areas, this thesis will focus on the spectrum sensing and management of the CRN. CRs are desirable as a large volume of traffic is expected to be transferred wirelessly in the near future. Since CRs are able to transmit on the underutilized licensed spectrum, they can significantly improve the network capacity. However, this process introduces additional complexities such as bandwidth allocation among multiple CR users and cooperation between CR. Spectrum sensing and management provides the capability to share the spectrum resources opportunistically with multiple CRs to avoid causing interference to the PUs network.

In addition, a licensed channel is said to be available to a CR only if communications on this channel will not disrupt communications among PUs. Therefore, channel availability depends on the activities of PUs and thus may change over time. In order to utilize the spectrum resources efficiently and overcome the drawback caused by the limited knowledge of the availability of the channel, all of the spectrum management functions are based on cooperative operations where CRs determine their actions based on the observed information exchanged with their neighbours. This leads to another issue of cooperation that is how the nodes in CRN should cooperate in order to achieve the desired goal. Despite having quite a number of advantages, cooperation, however, is hindered by the cost. For example, the power required for cooperation, selfish behaviour and bandwidth required etc. In a network with cognitive functionality, users tend to be selfish, i.e. they may pursue their own goal to improve their performance without trying to cooperate or even cheat during the cooperation process. Therefore, deriving a practical cooperation algorithm where the decision to cooperate does not degrade the performance of any of the cooperating users is a challenging task.

Furthermore, in order to achieve spectrum efficiency and increased throughput for CRN without causing any interference to the primary network, a well-defined cooperation technique among CRs is needed. This cooperation technique will help in efficiently detecting the vacant spectrum band and, hence, sharing the detected spectrum. This, in turn, will lead to improved throughput and enhanced spectrum efficiency in the wireless network.

Therefore, designing a distributed, fair and cooperative strategy is highly challenging and desirable in practice. This thesis attempts to address the above issues and answer some of the open questions pertaining to the problem of throughput and spectrum efficiency in CRN.

1.3 RESEARCH OBJECTIVES

The main objective of this study is to utilize cooperation strategies using well-known mathematical tools in order to achieve spectrum efficiency and increased throughput for CRNs without introducing interference to the PUs. The specific objectives can be summarized as follows:

1. To develop novel distributed, cooperative and decision-making algorithms for spectrum sensing and management in CRNs for increasing spectrum efficiency.
2. To analyse the proposed distributed strategies for cooperation and spectrum management under the context of the matching theory.

3. To evaluate and validate the performance of various quality of service (QoS) metrics (e.g. capacity, throughput, false alarm) of the CRN using simulation and compare it with the non-cooperative scenario.

1.4 RESEARCH METHODOLOGY

In this thesis, matching theory is used to develop cooperation strategies among the CRs so that spectrum bands can be detected efficiently and in the process the throughput can be increased. In order to design cooperative algorithms for CRN, the cooperative game theory that deals with the analysis of interaction between groups of cooperating rational players in order to improve their overall outcome, is a widely used mathematical tool. In particular, coalition game theory where rational player organizes themselves into coalitions in order to improve their performance has been utilized by many researchers to study CRN. Despite the popularity of game theory, it has several problems when applied to CRN. First, classical game-theoretic algorithms require some form of knowledge on the action of other players, which limit their distributed implementation. Second, most of the solution in game theory, for example, the Nash equilibrium, investigates one-sided stability notions in which equilibrium divergences are evaluated at the level of a single player rather than the entire set of players. Third, for equilibrium in game theoretical methods certain criteria must be met by the objective function. For example, convexity criteria for practical wireless metrics may not always be satisfied. Last but not the least, for cooperative game theory there are no formal rules or analytical concepts that can apply to coalition formation and hence the solutions are application specific.

In order to overcome the limitation imposed by game theory, Matching theory is being investigated recently for resource allocation in wireless networks. Matching