SPECTRUM SURVEYING FOR POLICY BASED COGNITIVE RADIO

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ABSTRACT

Rapid growth in wireless communication technologies and services creates high demands for radio spectrum. Current spectrum management and regulations are unable to cater these demands despite claims that radio spectrum is underutilised. Cognitive Radio (CR) aims to resolve these conflicts by enabling opportunistic spectrum access to licensed spectrum. Understanding the spectrum occupancy patterns of licensed spectrum users is important for large scale deployment of CR. This thesis aims to evaluate the 24-hour spectrum occupancy in the 30-3000 MHz frequency band of a suburban outdoor radio environment in Johor Bahru, Malaysia and its applications in the policy development for Policy Based Cognitive Radio (PBCR) concept. A spectrum survey was carried out whereby spectrum measurement was performed, and spectrum data was classified and analysed using energy detection and duty cycle based method. Findings revealed that the spectrum occupancy was 11.29% and several potential spectrum bands for future deployment of CR were identified. Distributions of the duty cycle variable were modelled using continuous probability distributions and their entropy was investigated for different occupancy levels. Results indicated that the beta and Kumaraswamy distributions were an accurate fit and investigations on the entropy distributions proposed characterisations for high, moderate and low spectrum occupancy level. The information gained was applied to demonstrate the development and testing of PBCR policies using Cognitive Radio Language. The demonstration proved the practicability of using the information from spectrum survey in the policy development of PBCR.

ABSTRAK

Perkembangan yang pesat dalam teknologi dan servis komunikasi tanpa wayar mewujudkan permintaan yang tinggi terhadap spektrum radio. Pengurusan dan peraturan spektrum yang sedia ada tidak dapat memenuhi permintaan ini walaupun terdapat pihak yang mendakwa bahawa spektrum radio masih tidak digunakan sepenuhnya. Radio Kognitif (CR) bertujuan untuk menyelesaikan konflik ini dengan membolehkan penggunaan spektrum berlesen secara oportunis. Memahami corak penggunaan spektrum oleh pengguna spektrum berlesen adalah penting bagi penggunaan CR pada skala yang besar. Tesis ini bertujuan untuk menilai penggunaan spektrum 24 jam pada jalur frekuensi 30-3000 MHz bagi persekitaran radio luar di kawasan pinggir bandar di Johor Bahru, Malaysia dan aplikasinya dalam pembangunan polisi untuk kegunaan Radio Kognitif Berasaskan Polisi (PBCR). Kajian spektrum telah dijalankan dimana pengukuran spektrum telah dilakukan dan data spektrum telah diklasifikasikan dan dianalisis menggunakan kaedah berasaskan pengesanan tenaga dan kitar tugas. Keputusan telah menunjukkan bahawa penggunaan spektrum adalah sebanyak 11.39% dan beberapa jalur spektrum yang berpotensi untuk penggunaan CR telah dikenalpasti. Taburan kitar tugas yang berubah-ubah telah dimodelkan menggunakan taburan kebarangkalian selanjar dan entropinya dikaji bagi tahap penggunaan spektrum yang berbeza. Hasil kajian menunjukkan bahawa taburan beta dan Kumaraswamy adalah paling sesuai dan kajian terhadap taburan entropi pula mencadangkan pencirian bagi tahap penggunaan spektrum yang tinggi, sederhana dan rendah. Maklumat yang diperolehi telah digunakan untuk mendemonstrasikan pembangunan dan pengujian polisi bagi PBCR menggunakan "Cognitive Radio Language". Demonstrasi ini telah membuktikan bahawa maklumat yang diperolehi melalui kajian spektrum dapat memainkan peranan dalam pembangunan polisi untuk kegunaan PBCR.

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2G	-	Second Generation
3G	-	Third Generation
4G	-	Fourth Generation
ARSR	-	Air Route Surveillance Radar
ATRS	-	Analog Trunk Radio System
ATSC	-	Advanced Television System Committee
AV	-	Audio Visual
BW	-	Bandwidth
BWA	-	Broadband Wireless Access
CDF	-	Cumulative Distribution Function
CDMA	-	Code Division Multiple Access
CoRaL	-	Cognitive Radio language
CPE	-	Customer Premise Equipments
CR	-	Cognitive Radio
CRA	-	Cognitive Radio Architecture
CRS	-	Cognitive Radio System
CSI	-	Channel-State Information
CVD	-	Channel Vacancy Distribution
DANL	-	Display Average Noise Level
DARPA	-	Defense Advanced Research project Agency
DFS	-	Dynamic Frequency Selection
DFS	-	Dynamic Frequency Selection
DSA	-	Dynamic Spectrum Access
DSP	-	Digital Signal Processing
DTRS	-	Digital Trunk Radio System

DTT	-	Digital Terrestrial Television
HDTV	-	High Definition Television
EDGE	-	Enhanced Data Rates for Global Evolution
EDTV	-	Multi-channel Enhanced Digital Television
EIRP	-	Effective Isotropic Radiation Power
ETSI	-	European Telecommunications Standards Institute
FCC	-	Federal Communications Commission
FM	-	Frequency Modulated
FWA	-	Fixed Wireless Access
GOM	-	Government Of Malaysia
GPIB	-	General Purpose Interface Bus
GPS	-	Global Positioning System
GSM	-	Global System for Mobile Communication
GUI	-	Graphical User Interface
HSDPA	-	High-Speed Downlink Packet Access
HSPA	-	High Speed Packet Access
IDA	-	Infocomm Development Authority
ILS	-	Instrument Landing System
IRs	-	Interface Requirements
ISM	-	Industrial, Scientific and Medical
ITU	-	International Telecommunication Union
ITU-R	-	International Telecommunication Union-Radiocommunication
LE	-	Licensed Exempt
LTE	-	Long Term Evolution
MCMC	-	Malaysian Communications and Multimedia Commission
MIMO	-	Multiple Input Multiple Output
MINDEF	-	Ministry of Defence
NTIA	-	National Telecommunication and Information Administration
NTSC	-	National Television System Committee
OFDMA	-	Orthogonal Frequency Division Multiple Access
OSA	-	Opportunistic Spectrum Access
PBCR	-	Policy Based Cognitive Radio
PSD	-	Power Spectral Density
QoS	-	Quality of Service

RCT	-	Return Channel Terrestrial
RF	-	Radio Frequency
S-DMS	-	Satellite Digital Multimedia Service
SDR	-	Software-Defined Radio
SSF	-	Spectrum Surveying Framework
TDD	-	Time Division Duplex
TDMA	-	Time Division Multiple Access
T-DMS	-	Terrestial Digital Multimedia Service
TPC	-	Transmit Power Control
TV	-	Television
TVBD	-	TV Band Devices
UHF	-	Ultra High Frequency
UMTS	-	Universal Mobile Telecommunication Standard
USB	-	Universal Serial Bus
UTM	-	Universiti Teknologi Malaysia
UWB	-	Ultra Wideband
VHF	-	Very High Frequency
WiMAX	-	Worldwide Interoperability for Microwave Access
WLANs	-	Wireless Local Area Networks
WRAN	-	Wireless Regional Area Network
WRCs	-	World Radio Communication Conferences
XG	-	Next Generation

CHAPTER 1

INTRODUCTION

The chapter starts by giving a brief background followed by the problem statement which highlights the motivation for this study. Next, the objectives are presented along with the scopes that have been defined. The chapter concludes with the thesis structures and summaries.

1.1 Background

The radio spectrum is a scarce, natural and finite resource. New developments of wireless technologies and innovative services have increased demands for radio spectrum. Regulators and current users of the radio spectrum are being pressured to provide more and more services. Among these services are enhanced wireless broadband, enhanced mobile phone services, mobile entertainment services, mobile health services, and wireless sensor network. With the current trend in the wireless industries, it is no wonder that the radio spectrum is vision to be "*overcrowded*".

The wireless industries are now progressing at an exponential pace. Figure 1.1 illustrates the evolution of wireless technologies over the past two decades. Mobility is the main focus in the continuing needs to improve and develop new wireless technologies. Mobility enables people to be mobile in their everyday communication. Through mobility, people are able to connect on the go, whenever and wherever they are. Mobility has changed the way people communicate, social interaction and work. According to a report released by FCC in January 2011 [1], nearly 12,000 wireless devices was authorised in 2010 compared to only 3,000 wireless devices authorised in 1999 for the US market. The increase of four times the amount in a decade indicates the high impact mobility has towards our life.

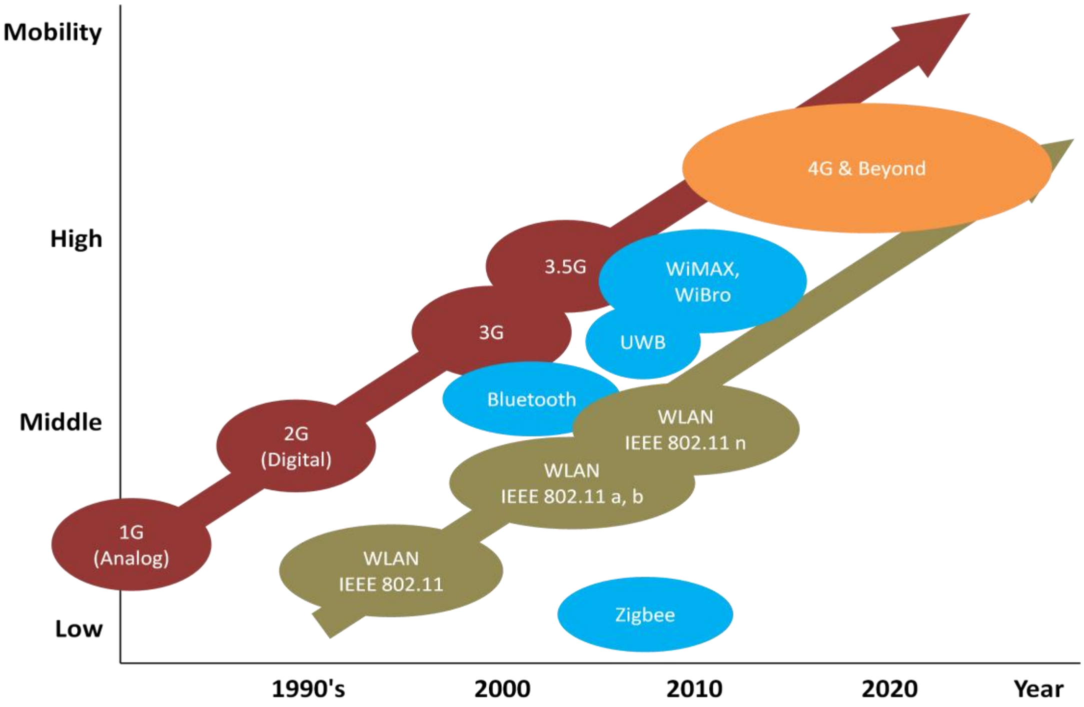

Figure 1.1 Evolution of wireless technologies.

Different wireless technologies conform to their own standards and radio platforms. For example, most of mobile phones of the 2nd generation (2G) use the Global System for Mobile Communications (GSM) standard while International Mobile Telecommunications - 2000 (IMT-2000) is the standards for mobile phones of the 3rd generation (3G). Similarly, wireless local area network uses the IEEE

802.11 standard which has many variations such as IEEE 802.11a, IEEE 802.11b, IEEE 802.11g and IEEE 802.11n. As different standards have their own unique radio platforms, it can be concluded that current radio systems operate in a very specific manner, i.e. specific frequency bands, specific radio access technologies, specific bandwidth, etc.

Although much progress has been made in the wireless technologies itself, little have been done to improve the policies used by the regulators. Current spectrum management compromised of a static, fixed and strict spectrum policies where the radio spectrum are divided into chunks of frequency bands which are already allocated and assigned to various services and radio standards in the particular countries, on a long term basis and under exclusive licenses usage, following the international agreement coordinated by International Telecommunication Union (ITU). Static spectrum access policies typically exercised by the regulators are very efficient in managing interference among the spectrum users. Furthermore, with the operating radio frequencies known and in a fixed range, design of hardware is easier to make.

Deploying new wireless technologies into the radio spectrum brings difficulties to the regulators and is a complex decision to make. Many factors need to be taken into account such as availability of spectrum, technology design, bandwidth efficiency, spectrum cost, end-user demand, and many other technical and market conditions that need to be examined. Additionally, regulators are trouble on the lack of spectrum bands with commercially attractive radio propagation characteristics. Report of preliminary field measurements reveals that spectrum usage for majority of the allocated spectrum is greatly underutilised with values ranging from 15% to 85% of utilisation, temporally and geographically [2-3]. Nevertheless, regulators resort to spectrum re-farming to resolve the issue of spectrum scarcity. However, such solution is only temporary as the problem root from the static and inflexible spectrum management policies. The policies that was once consider appropriate is now outdated and has become irrelevant.

Since 1960s, the techniques used in spectrum management has been criticised as inefficient and constraining the economic development of the spectrum usage [4-5]. Therefore, new spectrum management paradigms offering flexibility and dynamics are required to provide more efficient utilisation of the radio spectrum. Flexible spectrum access policies with the objectives to overcome the drawbacks and shortcomings of the current inefficient static spectrum access policies are sought after. Termed as Dynamic Spectrum Access (DSA) coined by the research communities, it refers to the innovative solutions recommending a procedure or scheme to share spectrum among the spectrum users in order to increase the overall spectrum utilisation. DSA is one of the promising solutions to resolve the struggling issues of the growth in spectrum demand and spectrum underutilisation.

Key enabler in realising DSA concept is the Cognitive Radio (CR) paradigm. CR could be described as a radio that is capable to sense the local radio environment, learn about the radio resources, user and application requirements and accordingly change the behaviour to adapt to the requirements. Working principle of CR is to opportunistically use the vacant channel in a frequency band in an unlicensed manner as a secondary user without causing harmful interference to the primary users (licensed spectrum holders). Important characteristics of CR are the cognitive abilities and reconfigurability. Cognitive abilities enable CR to become aware of its surrounding by sensing the spectrum occupancy and identifying the empty channels. Based on the properties of the empty channels, CR is able to reconfigure its transmission parameters e.g. the operating frequency, modulation scheme, transmit power, communication protocols, etc. Reconfigurability of CR could be achieved through software-defined radio (SDR) or adaptive radio technology. CR is therefore an extension of SDR with cognition. While CR is the key enabler in realising DSA, the former represents a wider communications concept of improving wireless communication system via cognition and reconfiguration.

1.2 Problem Statement

In these couple of years, the research in CR concept has been gaining the attention of the research communities worldwide. With DSA as the vision to resolve the issues of growth in spectrum demand and spectrum underutilisation, progressive achievements of research in CR would be a stepping stone. As explained in Section 1.1, the most important underlying principle of CR is enabling secondary usage of the spectrum in an unlicensed opportunistic non-interfering manner of the licensed spectrum bands which are temporarily unoccupied by its primary users. CR continuously sense and detect the spectrum for any *spectrum holes* in the primary user bands, opportunistically transmit on them and immediately released the channel once primary user returns. While doing these, CR must guarantee at all times to not cause any harmful interference to the primary users.

Although the concept of CR is straightforward, actual implementation and realisation of CR presently appears to be quite difficult in practice. It is envisioned that a “full CR” would eventually be realised in the year 2030 [6]. However, certain elements of CR have been proven successful. Progress in the field of digital signal processing theory and techniques, reconfigurable antenna and RF front end, MIMO, OFDM, and artificial intelligence are among the contributors towards realising the CR concept. Recent prototyping of spectrum sensing devices [7] to sense the TV white space have been demonstrated in the field trials of the IEEE 802.22 Wireless Regional Area Network (WRAN), the first standard to adopt CR in their radio system operations. The field trials have been quite a success, but further improvements are required. This demonstrated that CR is no longer a theoretical concept but a practical promising solution.

However, many research questions still remain open especially on the effect of CR towards the spectrum management and regulations. Regulators and primary users are sceptical in the capabilities of CR to avoid causing harmful interference. How to sense and identify spectrum holes, reliability of a CR nodes and network, coexistence of CR with the heterogeneous primary user systems are several examples of simple questions that troubles the sceptics. Primary users fear for CR violating their exclusive spectrum rights which have been obtained through expensive and scrutinise procedures albeit the cry for more spectrum from several primary users i.e. wireless operators. Regulators are more concern in CR behaviour in the spectrum. Which frequency band would CR choose to transmit, what are the power limits for CR devices, which schemes is effectives in avoiding interference, how would CR devices would be certified are among the questions that regulators sought for answers.

Due to the opportunistic nature of CR principle, their behaviours are heavily dependable on the spectrum occupancy patterns of the primary users. Hence, observation and understanding of the patterns usage is an important and a crucial first step. With this knowledge, realistic and accurate modelling of the patterns would be essentially useful in the domain of CR research. Spectrum usage models could be applied in various areas of analytical studies in CR network, CR network simulation tools and more efficient techniques in CR. More importantly, thorough analysis of the spectrum occupancy patterns provides essential information towards the realistic understanding of dynamic spectrum usage. At the same time, the specific spectrum regulations of geographical regions could be investigated. For large scale deployment, studies on spectrum occupancy at multiple geographical regions are needed, taken into account the possibility of CR to operate under many different spectrum regulations and scenarios.

In this context, this thesis seeks to address the importance of spectrum occupancy in the deployment and implementation of CR from the Malaysia spectrum regulation perspective. Method to investigate spectrum occupancy is through spectrum surveying. A tool in exploring the spectrum, spectrum survey provides information of the spectrum usage in environments with various spectrum regulations, user profiles, geographical characteristics and population densities.

1.3 Objectives

A 24 hour spectrum survey for frequencies of 30–3000 MHz in an outdoor radio environment of a suburban area in Johor Bahru: Universiti Teknologi Malaysia (UTM) campus and Taman Universiti, has been carried out. The objectives are as follows:

1. To evaluate the spectrum occupancy and utilisation of the measured spectrum.
2. To identify the potential spectrum bands for future deployment of CR.
3. To investigate how spectrum surveying could be applied in the regulatory measures towards the implementation and deployment of CR.

1.4 Scope of Study

The scopes of the study are as follows:

1. Survey in a suburban area in Johor Bahru, Malaysia was carried out. The locations are the Universiti Teknologi Malaysia Johor Bahru campus and Taman Universiti.
2. Outdoor radio environment was chosen because of the interest in investigating the licensed spectrum bands. Since CR basic principle is to operate in the licensed bands in an opportunistic unlicensed manner, therefore unlicensed bands were intentionally discarded
3. Frequencies that were selected for the survey range from 30 MHz to 3000 MHz which covers the VHF and the UHF bands. VHF and UHF bands have always been the sweet spot in deployments of various commercial wireless communication systems due to their radio propagation characteristics.
4. Spectrum usage in a 24-hour period was analysed. Measurement was conducted in duration of approximately a week period for the observed frequencies. The 24 hour data was obtained by averaging the week data.

5. Standard off the shelves equipments and software were used in the measurement setup. MATLAB software was used for data analysis.
6. Duty cycle based method was explored to characterise the spectrum occupancy and usage pattern. Through this method also, the spectrum utilisation was obtained.
7. Primary dimension in a spectrum survey are frequency, time, space and signal format. Data analysis was focused on the frequency and time dimension. Since the measurement data only include power of the received signal, the signal format dimension is not relevant. Space dimension was not discussed in this study.
8. Continuous probability distributions were used to model the duty cycle variable with emphasis on the beta distribution and Kumaraswamy distribution. Characteristics of the distribution's entropy on different occupancy levels were investigated and discussed.
9. Technical regulations proposed by the Federal Communication Commission in the US and Ofcom in UK were discussed. These two are amongst the early regulators in adapting CR towards better spectrum management.
10. Concept of Policy based Cognitive Radio (PBCR) was focused as the most practical regulatory measure. In order to demonstrate PBCR, Cognitive Radio Language (CoRaL) policy system was used for demonstration. CoRaL uses the information that was obtained through the spectrum survey in the demonstration.

1.5 Organisation of Thesis

This thesis comprises of six chapters. The first chapter provides an introduction of the study. The chapter start with a brief background that leads to the motivation of the study discussed in the problem statement, objectives and scopes.

Chapter 2 provides the context for the study by examining the relevant literature. The chapter offer background on the relationship between spectrum and CR. It also reviews and discusses related work on spectrum surveying. Chapter 2 explores several regulatory measures for CR which includes the technical regulations proposed by regulators and the concept of Policy based Cognitive Radio (PBCR).

Chapter 3 addresses the methodologies for the spectrum measurement setup and the data processing techniques for the spectrum occupancy analysis. The chapter explores the duty cycle based method for the analysis of the spectrum occupancy.

Chapter 4 presents the results of the research. The chapter proceeds to discuss the spectrum occupancy for each licensed spectrum bands. It then identifies the potential bands for deployment of CR and summarises the spectrum occupancy and utilisation in the suburban area in Johor Bahru. The chapter then discussed on the duty cycle distributions and their entropy characteristics.

Chapter 5 demonstrates CoRaL as the underlying technology in enabling PBCR. Demonstration of CoRaL uses the information gathered through the spectrum survey in a case study approach. Chapter 6 concludes the thesis. It summarizes and further elaborates on the findings in the study. In addition, the chapter identifies possible research opportunities.

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