國 立 交 通 大 學

電信工程學系

碩 士 論 文

感知無線網路之動態頻譜接取與閒置資源偵測

Dynamic Spectrum Access and White Space Detection for Cognitive Radio Networks

研究生：劉建興

指導教授：張仲儒 博士

中 華 民 國 九十六 年 六 月

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感知無線網路之動態頻譜接取與空閒資源偵測

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摘 要

隨著既有與新興無線通訊服務的增加，對於頻寬的需求量也日漸提高，然而頻寬資源卻是有限的，對此問題大家已經開始尋求更有效的利用頻寬之方法。而感知無線電(Cognitive Radio)被視為一個可以有效的使用頻寬的重要技術。

在本篇論文中，我們提出了一個感知無線電式的動態頻譜接取(Cognitive Radio-Based Dynamic Spectrum Access)演算法來提供感知無線電系統之下鏈路資料傳送。此演算法控制了包含空閒頻譜資源偵測、頻譜切換與下鏈路無線通訊資源分配。其主要目的是在固定頻段中提升整體的傳輸量。在提出的演算法中，我們針對兩段頻譜來做空閒頻譜偵測，包含了以 WLAN 為現行運行系統的免執照頻譜與需要執照的 WCDMA 頻譜，根據這兩個系統的特性，我們設計了各自的空閒頻譜偵測演算法。此外，我們還控制感知無線電系統在此兩個頻段上做切換的控制機制。最後我們提供了一個簡單的下鏈路無線通訊資源分配方法來最有效的提升感知無線電系統的傳輸量。從模擬的結果可以顯示出來我們所提出的方法，可以減少閒置的頻譜資源，有效的提升整體傳輸量，得到最佳的頻譜使用效率。

Dynamic Spectrum Access and White Space Detection for Cognitive Radio Networks

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Abstract

With the demand for additional bandwidth increasing due to existing and new services, both spectrum policy and communication technologists are seeking solutions for this apparent spectrum scarcity. The use of “cognitive radio” (CR) technology is viewed as the key technology to fully utilize the bandwidth. In this thesis, a CR-based dynamic spectrum access (DSA) algorithm is proposed for CR systems downlink transmission. The white space detection in WLAN spectrum and WCDMA spectrum, frequency bands switch between two spectrums and downlink radio resource allocation are controlled by CR-based DSA algorithm. The goals of CR-based DSA algorithm are throughput maximization in a fixed bandwidth. The proposed CR-based DSA algorithm dynamically decides CR systems to be active for periods of time and be quiet for another periods of time in WLAN spectrum and gives the holding time in WCDMA spectrum. In addition, it controlled the timing when CR systems shift their operational spectrum to another. Finally, a simple downlink radio resource allocation is presented to maximize the throughput of CR systems. From the simulation results, we can conclude that the CR-based DSA algorithm improve the overall throughput, reduce the idle time in WLAN spectrum and fully utilize the power resource in WCDMA spectrum.

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此篇碩士論文能夠完成，真的要感謝許多人的幫忙，首先要感謝指導老師張仲儒教授，在碩士生涯的兩年的論文方向引導與待人處世上的教誨。感謝芳慶學長在論文的思考過程給了我很多新的思維，並學習到了如何去探討現象的產生與原因，以及總是犧牲下班後的時間來指導我們。感謝志明、耀興、詠翰、建華、文祥、立峰、俊帆、琴雅、煖玉學長姐在我遇到問題的時候總是給予我適時的幫助，不管是在課業上或是生活上，受到學長姊們的幫助真的太多了。感謝世宏、建安、正昕、佳璇、佳泓在這兩年大家一起度過了許多歡笑與淚水，沒有你們，做研究的日子肯定是無聊的。感謝實驗室的學弟妹，巧瑩、邱胤、維謙、英奇、宗利、浩翔、尚樺替實驗室注入了一股新的活力，也祝你們最後一年做研究順利。

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建興　謹誌

民國九十六年七月

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Wireless communications offer a great number of benefits. With advances in wireless technologies, more industries are relying on modern wireless communications to provide services and assist their operations. Regardless of types of wireless service and technologies, a critical component common to all wireless communication deployment is the access to radio spectrum.

In most regulatory bodies of countries, all of them use a static command and control model for the management of radio spectrum. In this model the available model radio spectrum is divided into fixed and non-overlapping blocks, separated by guard band, and assigned to different services and wireless technologies. However, measurement studies have shown that the licensed spectrum is relatively unused across time and frequency [1]. They found that a large portion of the spectrum assigned and allocated was unused much of the time in many areas. The limited available spectrum and the inefficiency in the spectrum usage necessitate a new communication paradigm to exploit the existing wireless spectrum opportunistically. In addition, with the demand for additional bandwidth increasing due to existing and new services, both spectrum policy and communication technologists are seeking solutions for this apparent spectrum scarcity. This new networking paradigm is referred to as dynamic spectrum access (DSA) and cognitive radio (CR) networks.

The term CR network is used through the paper.

In order to provide the necessary bandwidth, a critical rethinking of the spectrum regulatory requirements is essential. The Federal Communications Commission (FCC) of America has already commenced work on the concept of unlicensed users "borrowing" spectrum from spectrum licensees [2]. This approach to spectral usage is known as DSA. In an effort to improve radio spectrum management and promote a more efficient use of it, DSA is viewed as a novel approach for improve the utilization of the radio spectrum. However, this is a tough problem that the unlicensed users borrow spectrum from spectrum licensees while respecting incumbent license right.

To enable DSA networks, the use of cognitive radio technology is the key technology. The term, cognitive radio, can formally be defined as follows [3,4]: *A "Cognitive Radio" is a radio that can change its transmitter parameters based on interaction with the environment which it operates.* Two main characteristics of the cognitive radio can be found from the definition [3]: cognitive capability and reconfigurability. Cognitive capability refers to the ability of the radio technology to sense the information from its radio environment. Through this capability, the portions of the spectrum that are unused at a specific time or location can be identified. Consequently, the best spectrum and appropriate operating parameters can be selected. Reconfigurability refers to the ability of the radio can be dynamically programmed to transmit and receive on a variety of frequencies according to the radio environment supported by its hardware design. Furthermore, cognitive radios are capable of performing a multitude of functions to support operations within DSA network, such as wide-band spectrum sensing, real-time spectrum allocation and acquisition.

The ultimate objective of the CR is to obtain the best available spectrum through cognitive capability and reconfigurability. Since most of the spectrum is already assigned to some communication networks, the challenge is to share the licensed spectrum with secondary users (CR users) without interfering licensed users. The CR enables the usage of temporally unused spectrum, which is referred to as *white space* (spectrum hole) [3]. If the frequency band is further used by licensed user, the CR system switches to another white space. In Fig. 1.1, it shows the concept of white space. The gray space stands for the spectrum in use and the white space stands for the unused spectrum.

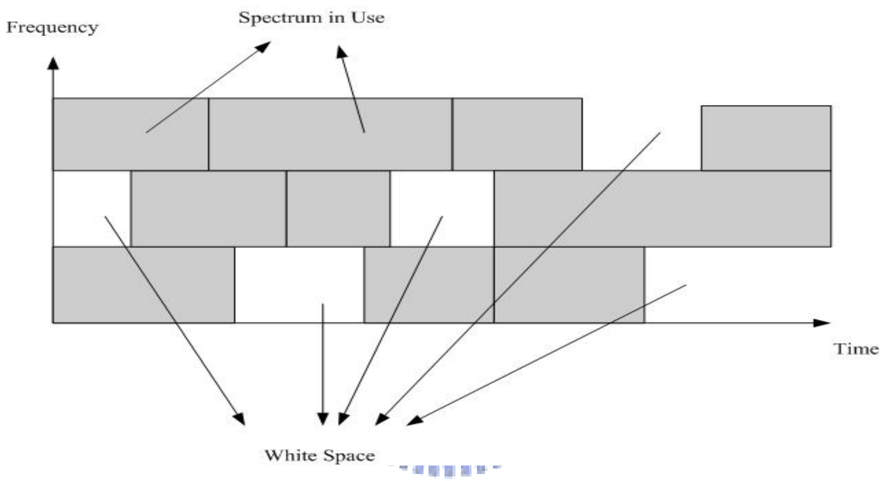

Fig. 1.1: White Space concept

One of the market-oriented approaches to manage spectrum is the creation of secondary spectrum market. Usually licensed incumbents may not be able to put their spectrum to the highest price and best use. The licensed incumbent who owns excess spectrum in the short run are not allowed to lease to others who might have the short-term need of spectrum. The licensee must hold their spectrum through their full license terms. Therefore, the desirability to promote the development of a secondary market for spectrum sharing is emerging. Also, CR-based DSA is viewed as a solution to the spectrum sharing.

It has already had many researches in the topic: the secondary use of the spectrum.

Weiss [5] showed a survey of the issues about the secondary use of the spectrum. Note that no strict definitions of secondary use and secondary spectrum market exist; various people have different points of views on the possible secondary markets, such as secondary use systems structures, properties and interaction mechanism among secondary users. However, there is a common basic idea that these secondary markets should create the possibility that licensed spectrum could be temporarily or permanently reassigned to other users using mechanisms or other kinds of protection schemes that are technically and economically efficient. In [6,7], issues that needed to be taken into considerations for the spectrum sharing idea to become reality are outlined. Generally speaking, the term secondary use of radio spectrum is defined as a temporal use (by secondary user) of existing licensed spectrum currently occupied by incumbent (primary user). This could include various scenarios of secondary use. Table 1.1 lists the possible dimensions of the spectrum space which was proposed in [7].

Table 1.1: Possible Dimensions of the Spectrum Space

General Class	Parameter	Units	Notes
Power	Power	W(or V/m)	Often viewed as the independent variable of the spectrum space
Frequency	Frequency	Hz	
Time	Time	sec	
Space	Location	Latitude, longitude, elevation	3 dimensions
	Signal direction (transmission direction, angle of arrival)	Azimuth, elevation	2 dimension
Signal	Polarization	Vertical/horizontal	
	Coding/modulation	(variable)	

Most papers put emphasis on the time domain and frequency domain sharing scheme, usually defined as time division multiple access (TDMA) and frequency division multiple access (FDMA) scheme. Only few papers outline the problems about the secondary use of the code division multiple access (CDMA). The basic idea of CDMA system is to allow signal of multiple users to occupy the same spectrum space in both frequency and time dimensions. The secondary access in the CDMA system is a very complicated issue and is independent on spread spectrum techniques. Although sharing spectrum through orthogonal code is merely impractical due to very complex signal processing frameworks that are not likely to be accomplished in the secondary system without the same standard and very close coordination, we still could theoretically use the frequency spectrum of the CDMA system as long as the capacity is not reached. In such a case, the signal of the secondary access appears as a wideband noise to the primary system [6].

In this thesis, we propose a cognitive radio-based dynamic spectrum access algorithm for CR systems to dynamically select the spectrum between two spectrums. One is the unlicensed frequency bands, the other is the licensed frequency bands. We define the CR system as a system that can dynamically select the best channel to access. Generally speaking, CR systems could be any systems, even a new defined system. However, we choose an existing system to be the CR system in this thesis. In order to analyze the performance of dynamic spectrum access in cognitive network, CR systems in this thesis are considered as 802.16-OFDMA systems. In the unlicensed bands, 2.4 GHz is the most popular unlicensed band which is allocated for the Industrial, Scientific, and Medical (ISM) bands. Only WLAN systems are considered in 2.4 GHz frequency band (ISM frequency bands). WLAN frequency bands are chosen as the main frequency bands in this work for CR systems to access.. In the licensed bands, the 2.0 GHz is the licensed band which is allocated for the third generation (3G) use. 3G (WCDMA) frequency bands are chosen as a backup frequency bands in this work for CR systems to access, if WLAN frequency bands are occupied by WLAN systems. This thesis proposes a CR-based DSA algorithm that could dynamically access the frequency spectrum between the two frequency bands. When CR systems are assigned one frequency band, WLAN frequency band or WCDMA frequency band, CR system uses OFDM transmission technology to send data and runs 802.16-OFDMA system protocols in upper layers. In unlicensed bands (WLAN frequency bands), the challenge is how to coexisting with the WLAN systems subject to minimize the degradation of existing WLAN systems. In unlicensed bands, there is no clear definition about primary user and secondary user. Therefore, CR systems try to coexist with the existing WLAN systems in WLAN frequency bands. In licensed bands, the WCDMA system is the primary user and the CR system is the secondary user. Therefore, in this band, our challenge is to protect the WCDMA user's right under bit error rate constraints which is tolerable for some kind of application or service and we can open some spectrum opportunities for the CR systems temporarily to use the frequency spectrum. This thesis discusses the system's model, proposed algorithm, the performance of total throughput, average packet delay and spectrum utilization.

The remaining part of the thesis is as follows. Section 2 describes the system environment and the network topology, including primary systems and CR systems. Then, section 3 describes the CR-based dynamic spectrum access algorithm . In section 4, simulation results are presented and discussed. Finally, concluding remarks and future works are given in section 5.

Chapter 2

System Environment

The components of the CR network architecture, as shown in Fig. 2.1, can be classified in two groups as the *primary network* and the *CR network*. The basic elements of the primary network and the CR network are defined in [4].

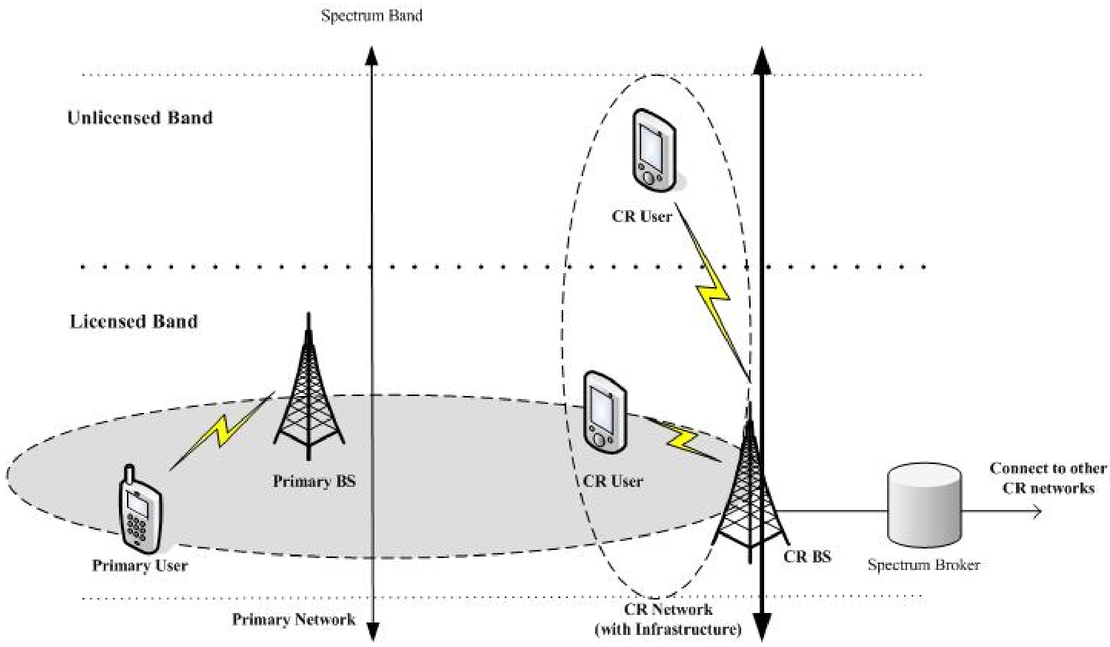

Fig. 2.1: CR network architecture

- Primary network: An existing network infrastructure is generally referred to as the primary network, which has an exclusive right to a certain spectrum band. The components of the primary network are as primary user and primary base station.
- CR network: CR network (or DSA network, secondary network) does not have

license to operate in a desired band. Hence, the spectrum access is allowed only in an opportunistic manner. The CR network can be deployed both as an infrastructure network and an ad hoc network. However, only infrastructure network deployment of CR network is considered in this paper. The ad hoc network deployment of CR network is not in our consideration. Therefore, the components of an CR network are as CR user, CR base station and spectrum broker.

Fig. 2.1 shows a CR network architecture, which consists of two types of networks: a primary network and an infrastructure based CR network. The CR networks are operated under the mixed spectrum environment that consists of both licensed band and unlicensed band. In this paper, two primary networks are taken in consideration: IEEE 802.11 wireless LAN (WLAN) network and WCDMA cellular network. The WLAN network is operated in unlicensed band, but the WCDMA cellular network is operated in licensed band. The CR networks in this paper are operated under the mixed spectrum environment of the two types networks: the unlicensed WLAN frequency band and licensed WCDMA frequency band Therefore, the topology of CR networks with two primary networks, WLAN and WCDMA networks, are shown in Fig. 2.2.

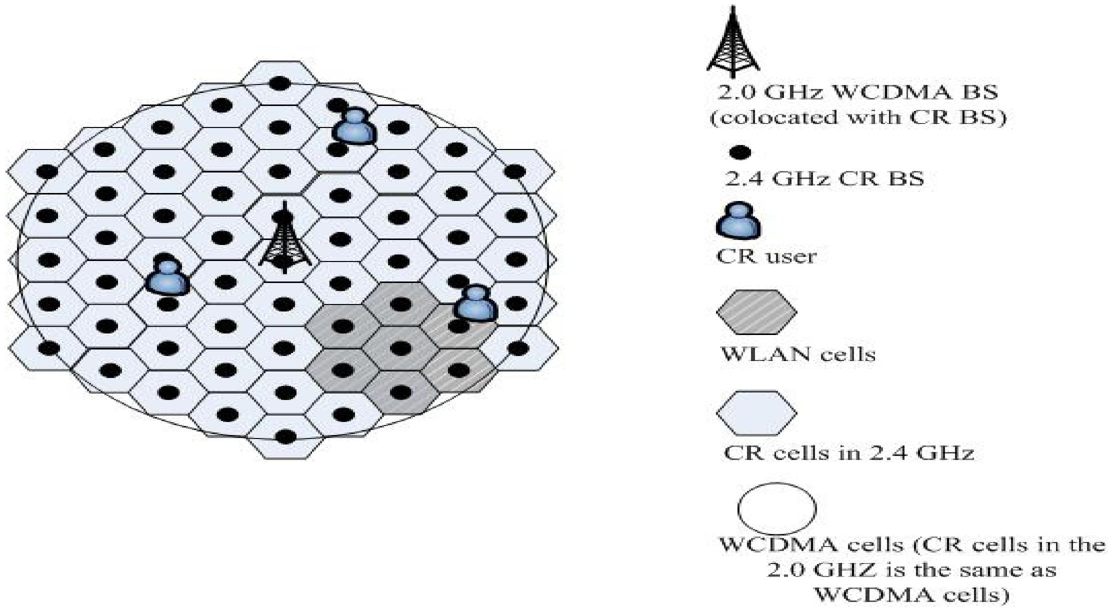

Fig. 2.2: The topology of CR networks with WLAN and WCDMA networks

As shown in Fig. 2.2, the primary networks are WLAN network and WCDMA network. These two communication networks are infrastructure-based networks and the CR network in this paper is with infrastructure, too. Therefore, we make an assumption that the CR BSs are collocated with WCDMA and WLAN BSs (primary BS). Obviously, the WLAN networks support small area coverage and WCDMA networks provide larger service coverage. In the topology, the WLAN BSs are only planned in hotspot zone in a WCDMA cell and the CR BSs are collocated with WLAN BSs only in the hotspot zone.

In general, the inference from other cells should be taken into account. However, with the cell planning, the interference from other cells could be reduced. We assume the reuse factor is equal to 4 in WCDMA cells, each WCDMA cell has 5 MHz bandwidth (in order to meet the CR system, WiMAX system) and each WCDMA cell use different central frequency. Fig. 2.3 shows the topology of the WCDMA cell planning. Because of the cell planning, other cells interference are not considered. Only one WCDMA cell is in the consideration. Therefore, Fig. 2.2 only shows one WCDMA cell. Also, we assume the reuse factor is equal to 3 in WLAN cells, each WLAN cell has 20 MHz bandwidth and use different central frequency.

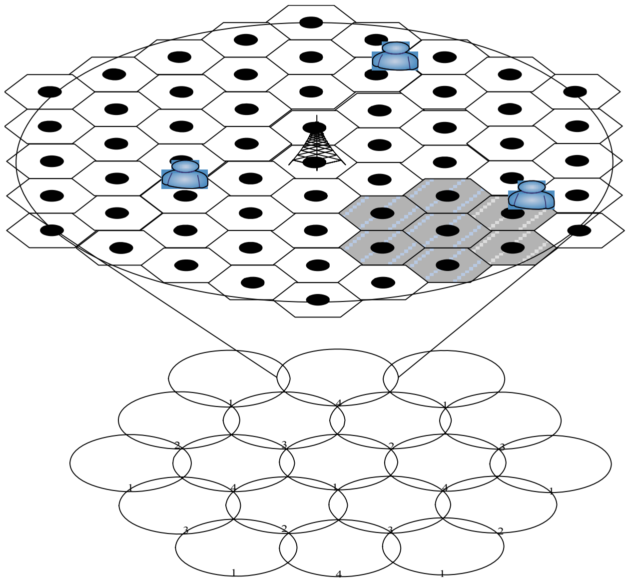

Fig. 2.3: The cell planning of WCDMA cells (reuse factor=4)

2.1 CR network System

In [3], OFDM was proposed as a better modulation strategy for cognitive radio by virtue of its flexibility and computational efficiency. For its operation, OFDM uses a set of carrier frequencies centered on a corresponding set of narrow channel bandwidths. Most important, the availability of rate feedback through a feedback channel permits the use of bit-loading, whereby the number of bits/symbol for each channel is optimized for the SNR characterizing that channel. Therefore, many existing CR network architectures are OFDM-based [4]. Consequently, we assume the CR network systems are 802.16 WiMAX-OFDMA systems. In this paper, we assume the resource of frequency spectrum of the 802.16 system is not enough to support data transmission. Hence, we try to find a new dimension of radio spectrum space for 802.16WiMAX-OFDMA systems to use it.

WiMAX-OFDMA can support data rate in the range of 32-130 Mbps depending on the bandwidth of operation as well as the modulation and the coding scheme. Different modulation schemes such as QPSK, 16-QAM, and 64-QAM can be used, depending on the channel quality (i.e., signal-to-noise ratio (SNR) at the receiver). We assume the bandwidth of WiMAX systems are 20 MHz when operating in WLAN frequency band and 5MHz when operating in WCDMA frequency band. For downlink transmission, time-division multiplexing (TDM) is used as the protocol in WiMAX-OFDMA system.

We make the following assumptions in this thesis paper:

- WLAN, WCDMA and CR systems use omni-directional antennas.
- The WCDMA BS can interchange some information about power budget with WiMAX BS in the 2.0 GHz.
- The BSs of the CR users have perfect channel state information (CSI). We do not consider the uplink transmission problem of the CR users in the paper. Only downlink transmission is considered.

2.2 WCDMA Cellular System

WCDMA cellular system is operating around 2.0 GHz. In the topology , there is 5 MHz spectrum for each WCDMA cell to use. In the downlink transmission, the WCDMA cell capacity depends on the downlink transmit power, which is limited by the power of the NodeB's (base station) power amplifier. Each WCDMA user will use a share of the Node B's transmit power and the more users in the cell the higher the power required for each individual user. Therefore, for the interference-limited WCDMA networks, the BS needs to control the number of the interference users in the cell. In the downlink transmission, the interference can be controlled because the number of users and the transmission rate are fixed, and the channel condition is estimated. In [9], many WCDMA downlink power allocation algorithms are studied. In this thesis, we consider the available resource in WCDMA frequency bands is the total power of the NodeB's power amplifier. Generally speaking, the admission control of the WCDMA system is to check if the power budget of the NodeB's power amplifier is enough for data transmission or not. However, in order to simplify the variation of the power of the NodeB's power amplifier, equal power allocation is used for each user. Each WCDMA user is allocated with equal power to perform the downlink data transmission.

2.3 WLAN System

WLAN system is operating around the 2.4 GHz (ISM band). In this band, every device could access this spectrum under the FCC transmitter power constraints. The total spectrum which can be used is about 72 MHz to offer 11 WLAN channels. Practically, it provides 3 non-overlapping channels for the purpose to avoid interference. Each of the three non-overlapping channels is 22 MHz. We use three non-overlap frequency bands (channel 1、6、11 is used) as the center frequency of CR systems. The WLAN access point (AP) acts as the BS in WCDMA networks. The MN's information are collected and recorded by the WLAN AP. Behind the AP, a wired core network is used to connect all APs to provide authentication, authorization, accounting and transmission. Two choices to access channel in WLAN networks are distributed coordinator function (DCF) and point coordinator function (PCF). DCF is a slotted binary exponential backoff scheme based on the carrier sense multiple access with collision avoidance (CSMA/CA) protocol. PCF is an optional mode that is centralized polling protocol controlled by the WLAN AP.

Also, the current 802.11 specifies that a High-Rate DSSS ("802.11b") system must use one of the 3 CCA (Clear Channel Assessment) modes. In the first mode (CCA Mode 1), the channel is declared busy when “any signal” is detected above the energy detection (ED) threshold and declared not busy when energy drops below the ED threshold. In the second mode (CCA Mode 4), if a properly formed High Rate DSSS signal is detected, the device declares the channel busy and starts a 3.65 ms timer. When the timer expires, the channel is declared not busy, but only if no High Rate DSSS is detected. The timer duration is based on the transmit time of the longest possible PHY SDU in a 20 MHz channel. The third mode (CCA Mode 5), like CCA mode 4, only declares the channel busy if a properly formed High Rate DSSS signal is detected, but declares the channel is not busy when energy drops below the ED threshold. In this paper, we consider DCF medium access control (MAC) which is based on the CSMA/CA protocol and CCA Mode 1 for the in WLAN system.

Chapter 3

Cognitive Radio-Based Dynamic Spectrum Access Algorithm

The CR-based DSA algorithm shown in Fig. 3.1 contains three parts, CR-based white space detection, frequency bands switch, and downlink radio resource allocation. White space detection scheme is the most important part of CR-based DSA algorithm. This scheme provides CR systems white space to allocate radio resource for downlink transmission. In addition, frequency bands switch scheme is used for CR users to dynamically switch frequency bands. After that, a simply power and subchannels allocation algorithm is used for downlink radio resource allocation. The simply power and subchannels allocation algorithm try to use the white space more efficiently to maximize the throughput in the white space duration.

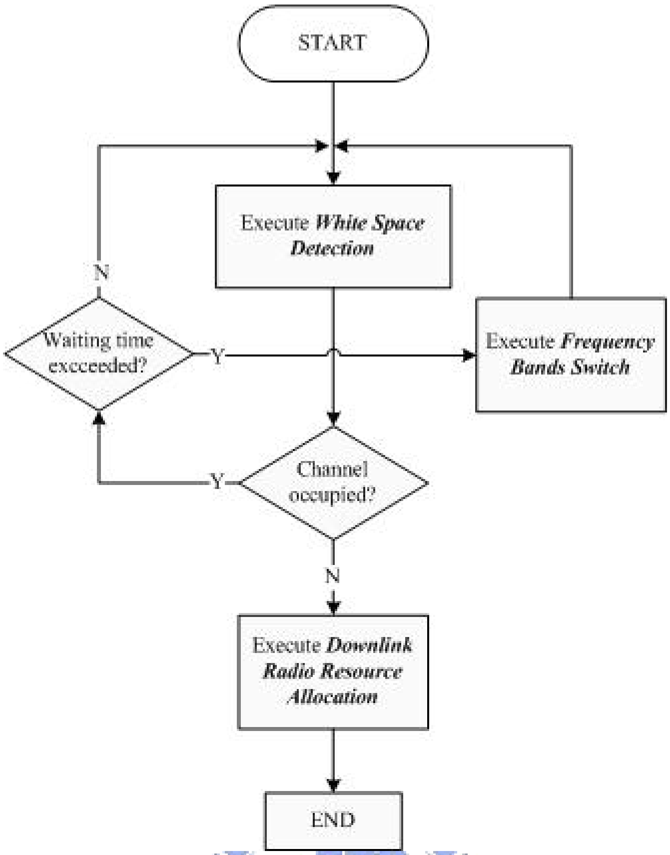

Fig. 3.1: the CR-based dynamic spectrum access algorithm

3.1 White Space Detection

White space detection is composed of "white space detection in WLAN frequency band" and "white space detection in WCDMA frequency band". "White space" here is the unused spectrum which is across the time in WLAN spectrum and the power budget in WCDMA spectrum.

In WLAN Frequency Band

As we know that WLAN system is a contention-based system and the CR system is selected as 802.16 systems, we adopt listen-before-talk (LBT) protocols and extended quiet period (EQP) to detect white space in WLAN frequency band.

In [8], the EQP is a period of an integer number of frames during which both uplink and downlink transmission is suspended. The primary purpose of the EQP is to give WLAN users reasonable opportunity to operate when an alternative channel is not available. For 802.11 coexistence, the quiet period duration should be chosen to allow transmission of an entire maximum length 802.11 PHY PDU (PPDU) using the 802.11 5.5 Mbit/s PHY mode. The duration, in frames, of the EQP is signaled in the DL-MAP. The EQP is shown in Fig. 3.2. It shows the EQP concept that the CR system transmit n+1 frames and become quiet for k frames.

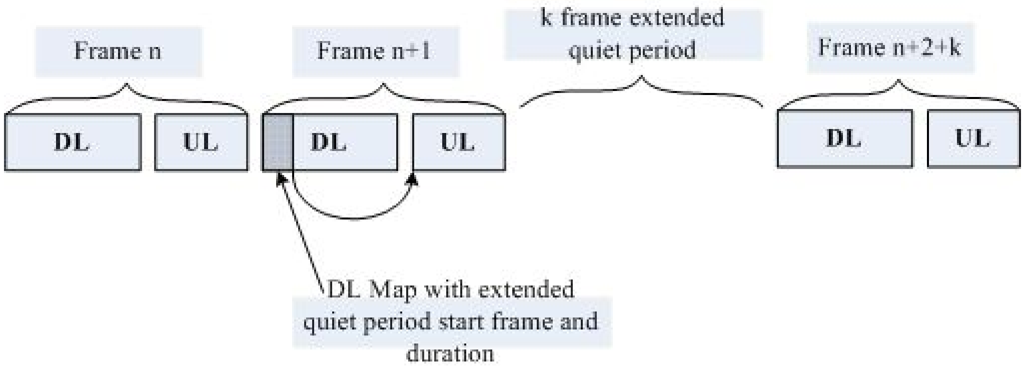

Fig. 3.2: The EQP protocol

When attempting to coexist with certain non-802.16 users of non-exclusively assigned or licensed bands. EQPs may not be sufficient. In these cases, a listen-before-talk protocol must be used to protect WLAN users' right. We consider the DL and UL subframes to be logically viewed as a single "packet" of constant duration equal to the frame duration. The BS shall allocate the UL subframe such that a time period is reserved between the end of UL allocations and the start of the frame preamble for the next DL subframe as shown in Fig. 3.3. It shows the LBT concept that the CR system should listen to the channel before transmission.

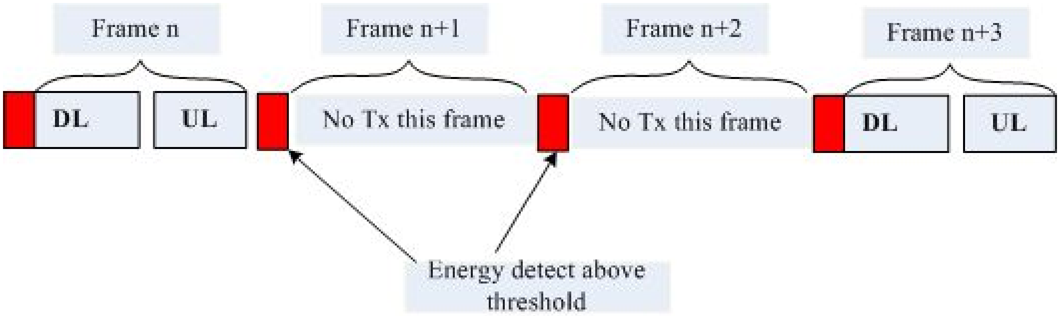

Fig. 3.3: The LBT protocol

We combine EQP and LBT together to detect white space in WLAN frequency band shown in Fig. 3.4. The flow chart of white space detection in WALN frequency band is shown in Fig. 3.5. The CR BS shall listen to the channel all the time and decide to occupy the channel or not before each DL transmission. Also, EQP is the solution to avoid CR systems occupying the channel for a long time. The white space detection procedure is shown in Fig. 3.4. We consider that the channel load of WLAN is an important parameter. In the white space detection procedure, the channel load of WLAN ρ_{WLAN} calculated by CR BS can be precisely expressed by,

$$\rho_{WLAN} = \frac{\text{the time occupied by WLAN system in quiet period and in extended quiet period}}{\text{quiet period} + \text{extended quiet period}}$$

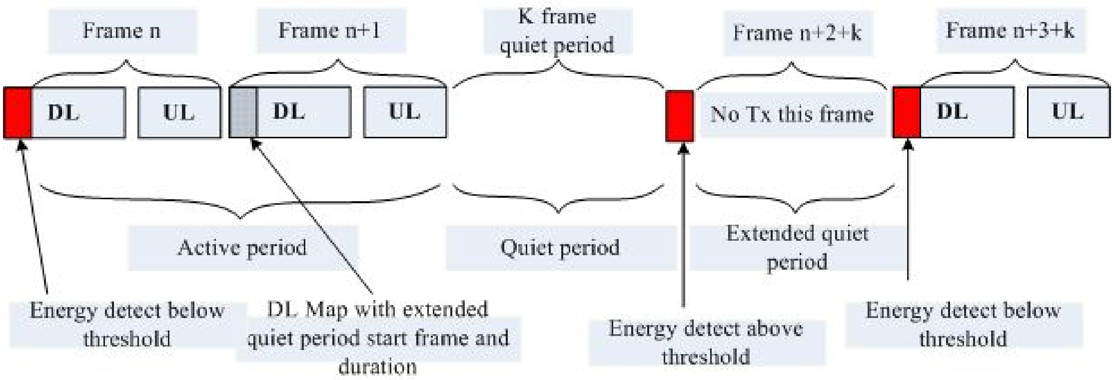

Fig. 3.4: EQP + LBT

According to ρ_{WLAN}, we define a duty cycle parameter μ for CR BS DL transmission in WLAN frequency band. The μ is expressed by,

$$\mu = \frac{\text{active periods (frames)}}{\text{quiet periods (frames)} + \text{active periods (frames)}}$$

There may be frequency bands where there is a possibility of WLAN users, but the probability is low. In these cases, it is important to not waste bandwidth in these bands and to use them more efficiently. Hence, the CR BS shall operate a duty cycle more adaptively depending on the current channel load of WLAN. We divide the duty cycle uniformly into three, μ1, μ2 and μ3 (μ1>μ2>μ3), shown in Table 2.

Table 3.1: Duty Cycle Value

$0<\rho_{WLAN}<1/3$	$\mu=\mu_1$
$1/3<\rho_{WLAN}<2/3$	$\mu=\mu_2$
$2/3<\rho_{WLAN}<1$	$\mu=\mu_3$

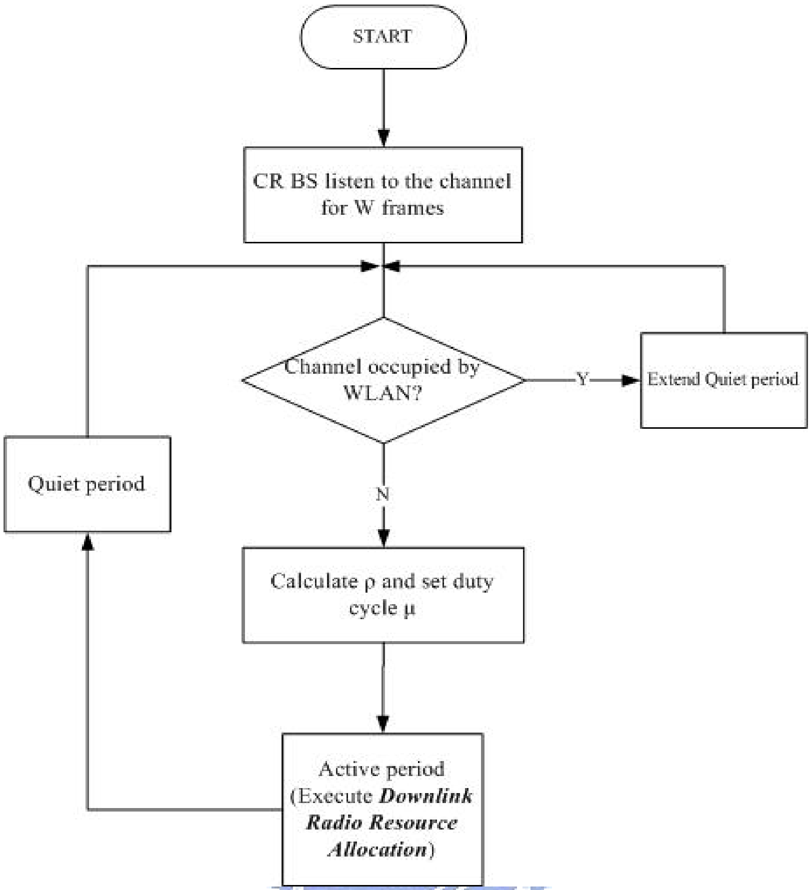

Fig. 3.5: The flow chart of white space detection in WALN frequency band

In summary, the procedure of white space detection is implemented iteratively as the following 5 steps.

Step 1:

The BS of CR system listens to the channel for W frames in order to calculate ρ_{WLAN}

Step 2:

The CR BS uses a listen-before-talk protocol to decide to transmit or not

Step 3:

If "No", it means that the channel is free. The CR BS calculates ρ_{WLAN} and sets duty cycle μ according to ρ_{WLAN}

Step 4:

The CR BS can perform 802.16 DL resource allocation algorithm in active period. Then go to quiet period. Finally, go to step 2.

Step 5:

If "Yes", it means that the channel is busy. Therefore, CR BS extends quiet period, then go to step 2.

In WCDMA Frequency Band

We consider the available resource in WCDMA frequency band is the total transmission power. Therefore, the residual power budget α in WCDMA can be expressed as follows,

$$\alpha = p_{\max} - \sum_i p_i$$

where *Pi* is the transmitted power allocation from WCDMA BS to WCDMA user *i* and *Pmax* is the maximal total power of the NodeB's. In this paper, we choose the equal power control allocation to simplify the WCDMA users' behavior (i.e. *Pi* is equal to p_1).We assume n_w WCDMA users in the cell at each detecting time.

$$\alpha = p_{\max} - n_w \times p_1$$

At each scheduling time, the CR BS shall check the residual power budget α in WCDMA is enough for CR users DL transmission or not. Therefore, a power budget threshold P_{th} is needed for CB BS to detect white space.

According to the power and subchannels allocation scheme for WiMAX system transmission, the value of the power budget threshold P_{th} will be different. In this paper, the equal power allocation scheme on some subchannels in WCDMA frequency band is used. We divided the maximal total power of the NodeB's P_{max}

into N subchannels. The power allocation unit on each subchannel is $\frac{p_{\max}}{N}$.

Therefore, the P_{th} is set to be $\frac{p_{\max}}{N}$

The flow chart of white space detection in WALN frequency band is shown in Fig. 3.6. In summary, the procedure of white space detection is implemented iteratively as the following 4 steps.

Step 1:

Initial α=0

Step 2:

CR BS update the residual power budget α in WCDMA

Step 3:

If $\alpha > P_{th}$, CR BS can perform 802.16 DL resource allocation algorithm subject to the residual power budget α, then go to step 2

Step 4:

If $\alpha < P_{th}$, CR BS keeps quiet for an OFDMA frame, then go to step 2

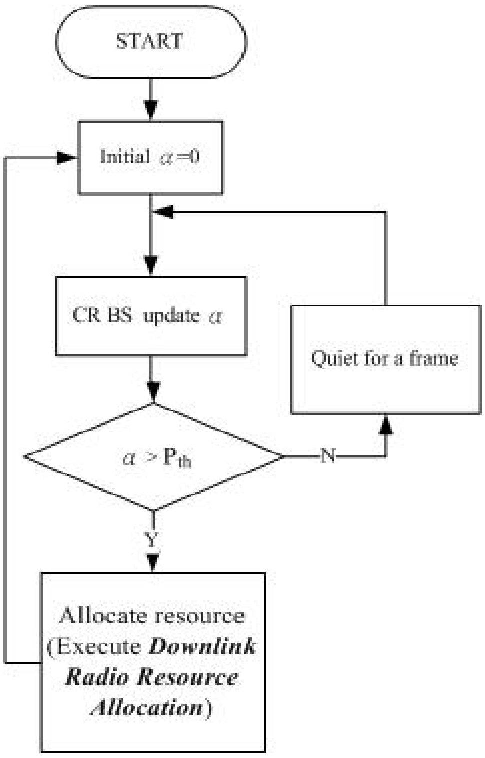

Fig. 3.6: The flow chart of white space detection in WCDMA frequency band

3.2 Frequency Bands Switch

The selection between the two frequency bands, WLAN and WCDMA frequency bands, are determined by CR users. CR users have to dicede which frequency bands to operate and when to switch to another frequency band. The maximal tolerance time for CR systems are denoted by T_{WLAN} in WLAN frequency band and T_{WCDMA} in WCDMA frequency band. If there is no opportunity for CR systems to transmit data from current frequency band within the maximal tolerance time in each frequency band, the CR users will switch to another frequency band to detect the white space. Also, the CR BS will switch to another frequency band to perform downlink transmission and the data in the queue will be transfered to another BS by internetworking. In our proposed dynamic spectrum access algorithm, we assume CR systems operate in WLAN frequency bands most of the time and

WCDMA frequency bands are regard as a backup frequency band. Therefore, the CR users will listen to WLAN frequency bands and detect white spaces in this frequency bands at first. If there is no opportunity for CR systems to transmit data in WLAN frequency bands, the CR users will switch to WCDMA frequency bands and CR BS will also switch to that frequency bands. The illustration of frequency bands switch is shown in Fig. 3.7.

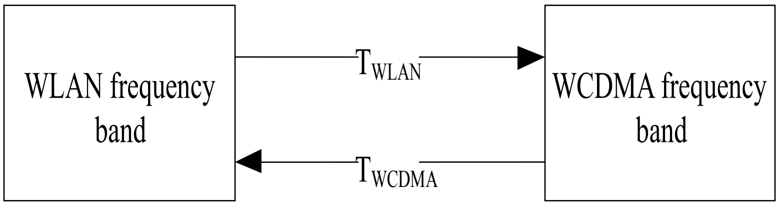

Fig. 3.7: The illustration of frequency band switch

3.3 Downlink Radio Resource Allocation

After white space detection is done, radio resource allocation algorithm is used to allocation resource for downlink transmission. In this paper, the goal is the throughput maximization. Therefore, linkgain-based (LB) resource allocation algorithm is selected for downlink WiMAX systems.

In LB algorithm, the resource is allocated to users according to the users' CSI. The LB algorithm is an simple algorithm to select the user with better channel for throughput maximization [11]. For each subchannels, the user with best channel quality is selected and the highest possible modulation order without violating the total power constraint is set for the user. The algorithm sequentially allocates subchannels to users until the remaining power connot support the lowest possible modulation order for the selected user. The same procedure is repeated for each symbol in a OFDMA frame.

In this paper, the radio resource allocation algorithm is modified with LB algorithm and equal power allocation is applied. In WLAN frequency bands, the LB algorithm with equal allocation on all subchannels is used to allocate resource. Therefore, the allocated power on all subchannels is the same. For each subchannel, the user with best channel quality is selected and the highest possible modulation order without violating the allocated power is set for the user. In WCDMA frequency bands, the LB algorithm with equal allocation on some subchannels is used to allocate resource. Power allocation in WCDMA frequency band is quiet different from that in WLAN frequency band. In WLAN frequency band, total transmission power is uniform distributed on all subchannels. However, in WCDMA frequency band, the total power is limited by the power budget. Hence, only some subchannels with better channel quality to some users could be allocated power for CR system to transmit data. These subchannels with poor channel quality would not be allocated power.

Note that in above statements, only the users with nonempty buffer are considered. The algorithm would not select the user that does not has data in its buffer even if the channel quality of the user is good.

Chapter 4

Simulations

Table 4.1 lists system parameters of a considered WLAN environment and values of PHY-related parameters, which are referred to specifications of IEEE 802.11. In the simulations, we use the basic access mechanism CSMA/CA.

Table 4.1: Parameter settings for a WLAN environment

Slot time,	20 μs
DIFS	20 μs
SIFS	10 μs
Propagation Delay	1 μs
Bit rate	11 Mbps
PHY overhead	192 μs
MAC header	28 byte
ACK length	14 byte
Data packet Payload	1500 byte
Initial Contention Window	32
Maximum Contention Window	1024

Table 4.2 lists system parameters of a considered WCDMA environment. The total downlink transmission power at WCDMA B.S. is assumed 30 w. In order to simplify the power variations of the WCDMA B.S, each arrival user is allocated with 0.3 w equally in one WCDMA frame to perform downlink transmission.

Table 4.2: Parameter settings for a WCDMA environment

Total transmission power at WCDMA B.S.	30 W
Allocated power per WCDMA user	0.3 W

The system-level CR downlink environments are set to be compatible with IEEE 802.16 standard [12]. Table 4.3 lists system parameters of a considered CR system. The CR system is based on 20 MHz bandwidth in WLAN spectrum and 5 MHz in WCDMA spectrum. The frame duration is 5 ms for CR system in both spectrums. The number of subcarriers in WLAN spectrum is equal to the FFT size, 2048, but only 1536 subcarriers are used for data transmission, while the others are used for pilot channel or guard channel. However, the number of subcarriers in WCDMA spectrum is equal to the FFT size, 512, but only 384 subcarriers are used for data transmission, while the others are used for pilot channel or guard channel. Modulation order is set to be QPSK for CR systems in WLAN spectrum and WCDMA spectrum to avoid the near-far problem for CR users.

Table 4.3: Parameter settings for a CR system

	In WLAN spectrum	In WCDMA spectrum
System bandwidth	20 MHz	5 MHz
FFT size	2048	512
CR frame duration	5 ms	5 ms

CR symbol duration	102.86 us	102.86 us
Number of data subcarriers	1536	384
Number of subchannels	32	8
Number of data subcarriers per subchannel	48	48
Number of CR symbol for downlink transmission per CR frame	25	25
Modulation order	QPSK	QPSK
CR Maximum Waiting Time	640 ms	40 ms

4.1 Scenario

Fig. 4.1 shows the simulation scenario. We only simulate one WLAN cell collated with one CR cell in the WLAN frequency bands (the gray zone) and one WCDMA cell collated with one CR cell in the WCDMA frequency bands (the white zone). The CR users only appear in the gray zone and there are two spectrums (the WLAN spectrum and the WCDMA spectrum) CR users can use. We calculate performance of CR users in the gray zone as the CR system performance in WLAN spectrum and in the white zone as the CR systems performance in WCDMA spectrum.

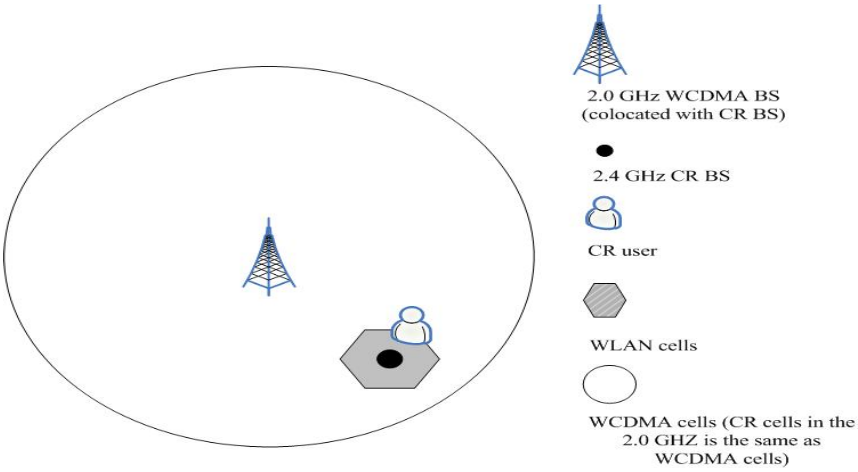

Fig. 4.1: Scenario

4.2 Source Traffic Model

Each WLAN user traffic model is modeled as HTTP traffic. Fig. 4.2 shows the packet trace of typical HTTP traffic, where the traffic of HTTP user is modeled as a sequence of page downloads. Each page is composed of a main object and several embedded objects, each object is divided into several packets. The interval between download pages, which represents reading time in web browsing, is distributed in an exponential distribution. The parameters for HTTP traffic model are defined in Table 4.4 [12]. Note that the packets of HTTP traffic used a maximum transmission unit of 1500 bytes.

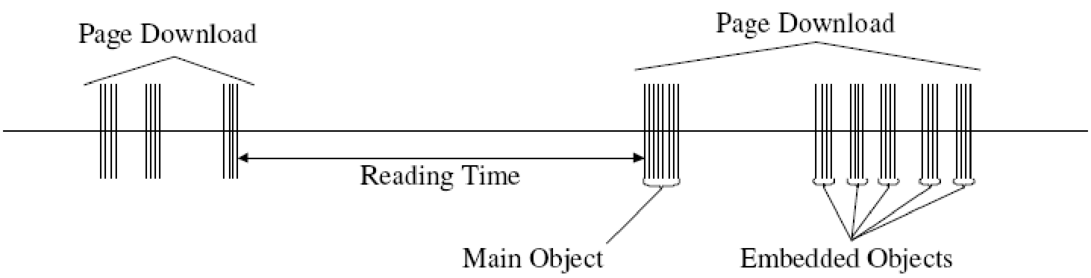

Fig. 4.2: Packet Trace in Typical HTTP traffic

The WCDMA user traffic model is modeled as follows: in order to simplify the user arrival in WCDMA network in a cell, we randomly select a value from {+1, 0, -1} as the number of user arrival in each WCDMA frame. Each WCDMA system user allocates 0.3w equally.

As to CR user traffic model, in order to identify the performance more easily, the CR users are assumed that they always have data to be transmitted and the CR base station provides one individual queue for each CR user. Arriving packets from each CR user are stored in its own queue in a first-in first-out manner.

Table 4.4: HTTP Traffic Model Parameters

Component	**Distribution**	**Parameters**
Main object size	Truncated Lognormal	Min. = 100 bytes, Max. = 2 Mbytes Mean = 10710 bytes Std. dev. = 25032 bytes
Embedded object size	Truncated Lognormal	Min. = 50 bytes, Max. = 2 Mbytes Mean = 7758 Std. dev. = 126168 bytes
Number of embedded objects per page	Truncated Pareto	Mean = 5.64, Max. = 53
Inter-arrival time between each page	Exponential	Mean = 3 sec
Packet size	Deterministic	Chop from objects with size 1500 bytes
Packet inter-arrival time	Exponential	Mean = 0.013 sec

4.3 Performance Evaluation

In this simulation, the number of WLAN users is increased from 8 to 69 and the number of WCDMA users is increased from 20 to 100. we define the offered WALN traffic load as the ratio of the total average arrival rate of all WLAN users over the system maximum transmission rate which is 11 Mbps in 802.11b. Note that the average arrival rate of WLAN user is equal to 145 kbps. Thus, the offered WLAN traffic load varies from 0.1 to 0.9 as the number of WLAN users varies from 8 to 69.

In the performance evaluation, we compare the systems consisting of WLAN and WCDMA to the systems consisting of WLAN, WCDMA and CR. The duty cycle values are chosen as follow:

$$\text{Duty cycle values: } \begin{cases} 70\%\ , & 0 \le \rho_{\text{WLAN}} < 33\% \\ 50\%\ , & 33\% \le \rho_{\text{WLAN}} < 66\% \\ 10\%\ , & 66\% \le \rho_{\text{WLAN}} \le 100\% \end{cases}$$

The basic unit frame (BUF) of each duty cycle values is 100 frames. Another BUF of duty cycle values is 50 frames. The resulting duty cycle values are shown in Table 4.5. We also compare the performance between two different BUFs.

Table 4.5: duty cycle values

BUF = 100 frames	Duty cycle values: $\begin{cases} 70\% \times 100 = 70 \text{ frames}, & 0 \le \rho_{\text{WLAN}} < 33\% \\ 50\% \times 100 = 50 \text{ frames}, & 33\% < \rho_{\text{WLAN}} < 66\% \\ 10\% \times 100 = 10 \text{ frames}, & 66\% < \rho_{\text{WLAN}} < 100\% \end{cases}$
BUF = 50 frames	Duty cycle values: $\begin{cases} 70\% \times 50 = 35 \text{ frames}, & 0 \le \rho_{\text{WLAN}} < 33\% \\ 50\% \times 50 = 25 \text{ frames}, & 33\% < \rho_{\text{WLAN}} < 66\% \\ 10\% \times 50 = 5 \text{ frames}, & 66\% < \rho_{\text{WLAN}} < 100\% \end{cases}$

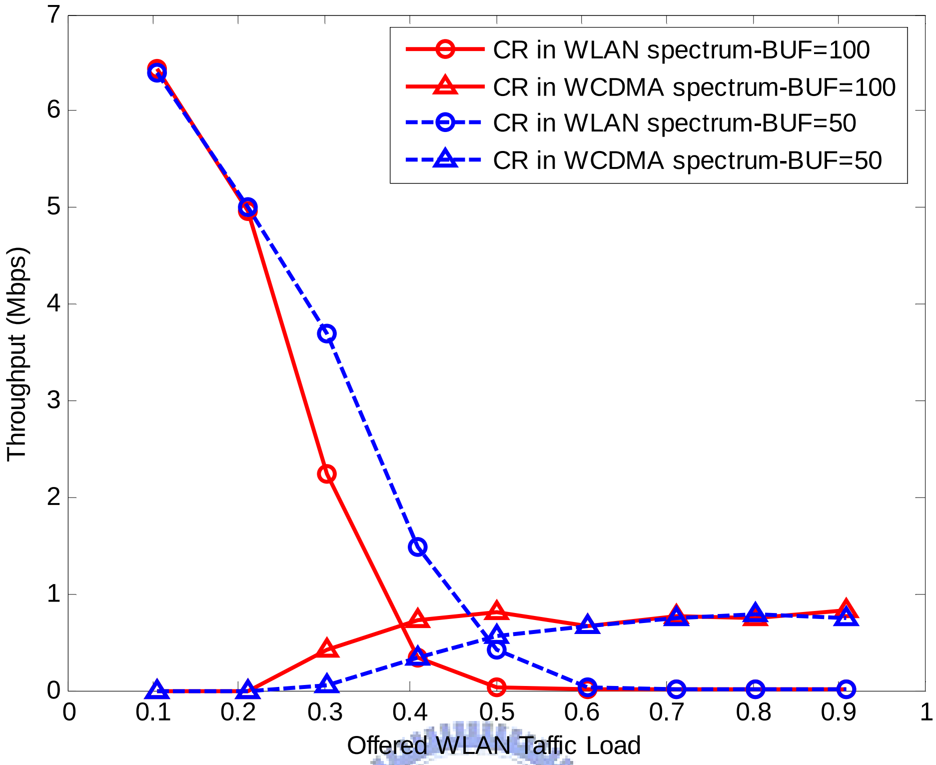

Fig. 4.3: The individual CR throughput

Fig. 4.3 illustrates the individual CR throughput in WLAN spectrum and WCDMA spectrum. It can be found that CR systems obtain large throughput in WLAN spectrum when the offered WLAN traffic load is light. With increasing offered WLAN traffic load, CR systems operating in WLAN spectrum achieves a smaller throughput and almost zero at high offered WLAN traffic load. The reason is that CR systems using CR-based DSA algorithm in WLAN spectrum will adaptively choose proper duty cycle values according to the estimated channel load. On the other hand, CR systems operating in WCDMA spectrum obtain no throughput at light offered WLAN traffic load. When offered WLAN traffic load increase, the throughput of CR systems in WCDMA spectrum increases slowly and finally becomes a constant value. The reason is that CR-based DSA algorithm using frequency bands switch shifts the operational spectrum from WLAN spectrum to

WCDMA spectrum with a higher probability when the offered WLAN traffic load is larger. However, the resource in WCDMA spectrum is limited by the primary users, WCDMA users. Only the residual power of WCDMA B.S can be shared to CR systems. Therefore, the maximal throughput of CR systems in WCDMA spectrum keeps a constant value. In addition, the performance of CR with 50 BUF is better than that with 100 BUF at middle offered WLAN traffic load shown in Fig. 4.3. The reason is that when the BUF becomes larger, the active periods and quiet periods of CR systems become larger. The larger active periods cause long packet delay and serious collision problems to WLAN systems. During the quiet periods, the larger active periods cause higher estimated WLAN traffic load than the smaller active periods. Therefore, CR systems have larger opportunity to access channels with larger duty cycle value when BUF becomes smaller. Hence, at middle offered WLAN traffic load, CR systems with smaller BUF perform better performance in throughput.

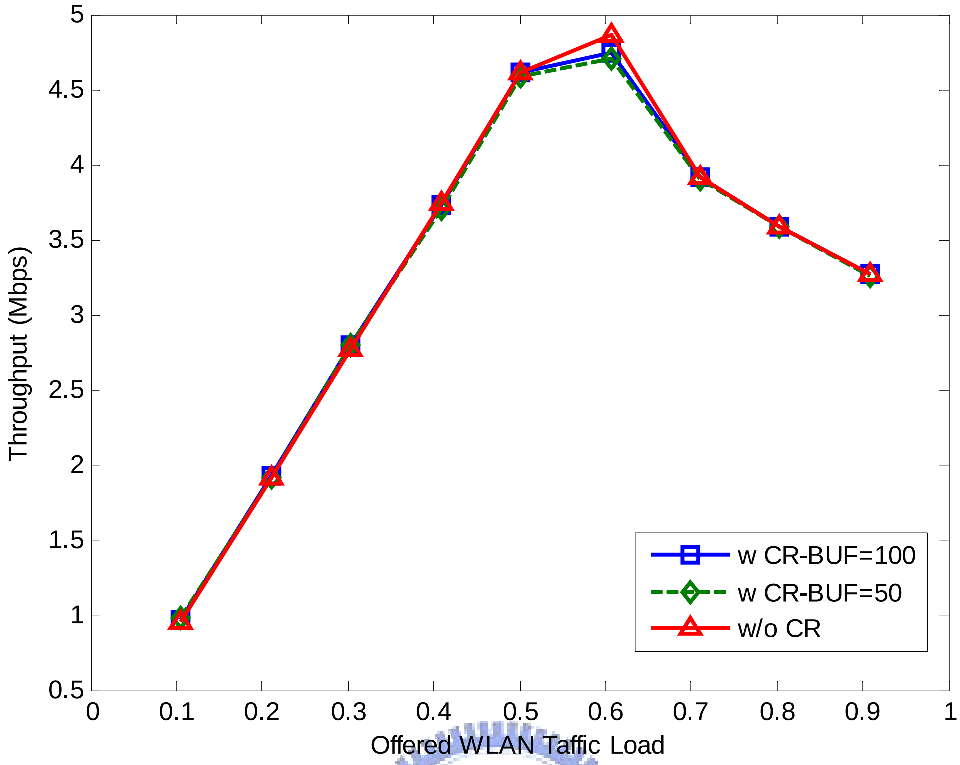

Fig. 4.4: The Throughput of WLAN Systems

Fig. 4.4 shows the throughput of WLAN systems. The resulting throughput of a WLAN system without CR is shown in Fig. 4.4. In WLAN systems, the probability of successful transmission increases when offered WLAN traffic load increases at light and middle traffic load. Hence, the throughput of WLAN systems increase with offered WLAN traffic load. This phenomenon is expected since current channel resource is larger than current users' needs. However, at heavy traffic load, the probability of successful transmission decreases and collision increases when offered WLAN traffic load increases. Therefore, the resulting throughput of WLAN systems decrease with offered WLAN traffic load. The reason is that the offered WLAN traffic load increases with the number of WLAN users. More uses in a WLAN system, more contention it causes. With increasing contention, the probability of successful transmission decreases and the probability of collision increases. On the hand, the resulting throughput of a WLAN system with CR is also shown in Fig. 4.4. It is obviously that resulting throughput of a WLAN system with CR is as much the same as that without CR. The reason is that CR systems with CR-based DSA algorithm do not suppress the resource allocation of WLAN systems. CR-based DSA algorithm in WLAN spectrum adopts a duty cycle value to decide the active periods and quiet periods of CR systems. The quiet periods protect WLAN users' rights to transmit data.

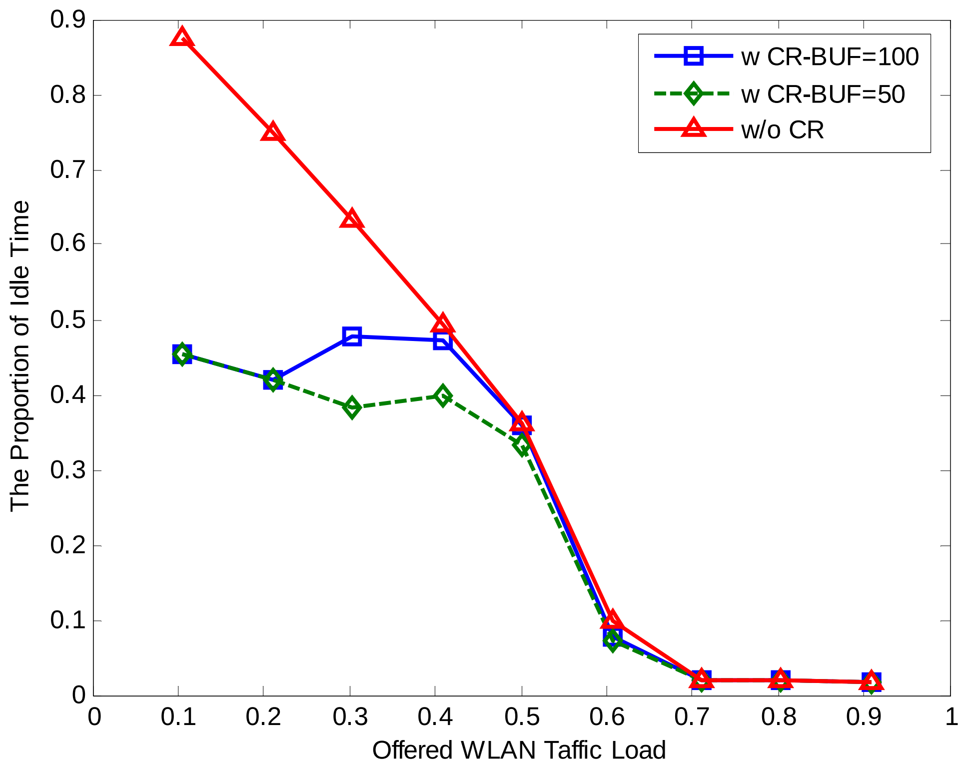

Fig. 4.5: The Proportion of idle time in WLAN spectrum

Fig. 4.5 shows the proportion of idle time in WLAN spectrum. The proportion of idle time in WLAN spectrum is the total idle time in WLAN spectrum over the total simulation time. It is clearly that CR with CR-based DSA algorithm improves the idle time in WLAN spectrum at low and middle offered WLAN traffic load. The phenomenon is expected since CR-based algorithm adopts a larger duty cycle value to extend active periods and shorten quiet periods at low and middle offered WLAN traffic load. As to the residual idle time at low and middle traffic load, CR-based DSA algorithm enforces CR systems to keep quiet for such periods of frames. The reason is that the estimated WLAN traffic load is heavy at high traffic load. Therefore, CR systems try to release more channel resource to WLAN systems, resulting in the residual idle time large at low and middle offered WLAN traffic load. In addition, the performance of CR systems with shorter BUF is better than that with longer BUF at middle offered WLAN traffic load shown in Fig. 4.5. The reason is that when the BUF becomes larger, the active periods and quiet periods of CR systems become larger. CR systems with larger BUF will occupy the channel for a long time. The larger active periods cause long packet delay and serious collision problems to WLAN systems. During the quiet periods, the larger active periods cause higher estimated WLAN traffic load than the smaller active periods. Therefore, CR systems have larger opportunity to access channel with larger duty cycle value when BUF becomes smaller. Hence, at middle offered WLAN traffic load, CR systems with smaller BUF perform better performance in idle time reduction.

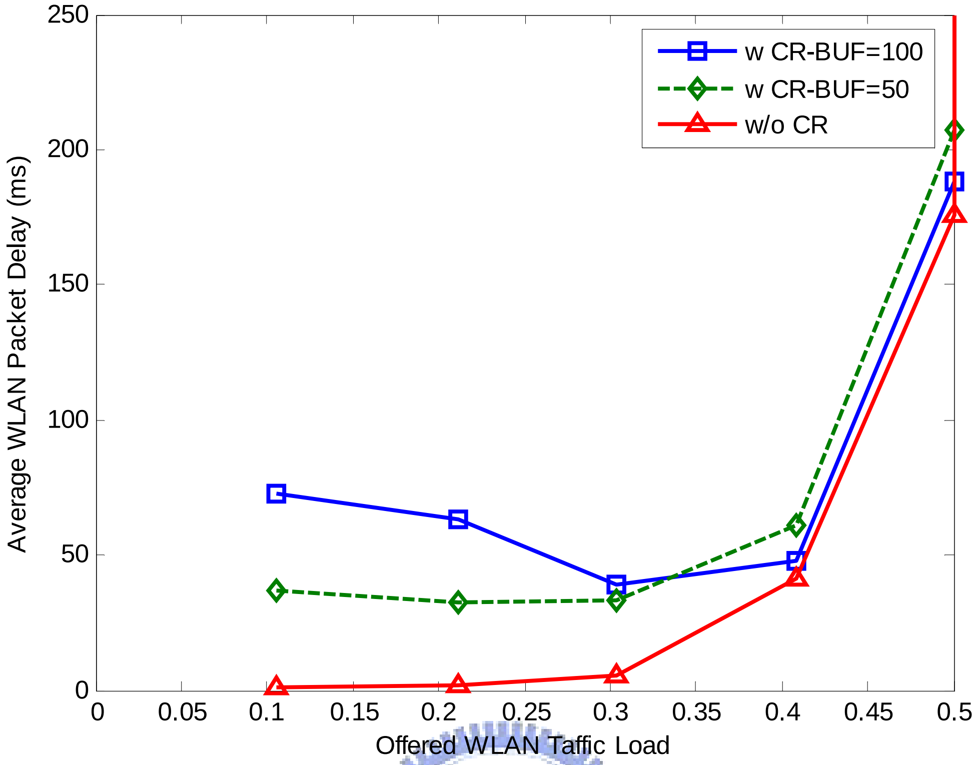

Fig. 4.6: Average packet delay of WLAN systems

Fig. 4.6 shows the average packet delay of the WLAN system. When the WLAN system operates with the CR system, the average packet delay of the WLAN system decreases when the offered WLAN traffic load is smaller than 0.3. The reason is that the CR system measures the current WLAN traffic load is small. Therefore, the CR system with CR-based DSA algorithm chooses the larger duty cycle value to extend the active periods. When the offered WLAN traffic load increases, the CR system measures the current WLAN traffic load is large. Then, the CR system chooses the smaller duty cycle value to shorten the active periods and extends the quiet period. When the offered WLAN traffic load is greater than 0.5, the WLAN spectrum is always very busy. Therefore, the CR system only occupies the WLAN spectrum for a very short time. On the other hand, the performance is better at low and middle offered WLAN traffic load when BUF is shortened shown in Fig. 4.6. The reason is that the quiet periods and active periods of CR systems become smaller. Therefore, CR systems will not occupy the channel for a long time and release more opportunity to WLAN users to transmit data. As a result, CR systems with smaller basic unit frame perform better in term of the impacts of average WLAN packet delay than that with large basic unit frame.

Chapter 5

Conclusion

The limited available spectrum and the inefficiency in the spectrum usage necessitate a new communication paradigm to exploit the existing wireless spectrum opportunistically. In addition, with the demand for additional bandwidth increasing due to existing and new services, both spectrum policy and communication technologists are seeking solutions for this apparent spectrum scarcity. In this thesis, a CR-based dynamic spectrum access algorithm is proposed for CR systems downlink transmission. The white space detection in WLAN spectrum and WCDMA spectrum, frequency bands switch between two spectrums and downlink radio resource allocation are controlled by CR-based DSA algorithm. The goals of CR-based DSA algorithm are throughput maximization in a fixed bandwidth. The proposed CR-based DSA algorithm dynamically decides CR systems to be active for such periods and be quiet for another periods of time in WLAN spectrum and gives the holding time in WCDMA spectrum. In addition, it gives the timing when CR systems shift their operational spectrum to another. Finally, a simple downlink radio resource allocation is presented to maximize the throughput of CR systems.

In the simulation results and discussion, the CR-based DSA algorithm is presented for CR systems to operate in WLAN and WCDMA spectrum. From the results, we can conclude that the CR-based DSA algorithm improve the overall throughput, reduce the idle time in WLAN spectrum and fully utilize the power resource in WCDMA spectrum.

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