SIDELOBE SUPPRESSION AND AGILE TRANSMISSION TECHNIQUES
FOR MULTICARRIER-BASED COGNITIVE RADIO SYSTEMS

by

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Abstract

With the advent of new high data rate wireless applications, as well as growth of existing wireless services, demand for additional bandwidth is rapidly increasing. Existing spectrum allocation policies of the *Federal Communications Commission* (FCC) prohibits unlicensed access to licensed spectrum, constraining them instead to several heavily populated, interference-prone frequency bands, which causes spectrum scarcity. However, it has been shown by several spectrum measurement campaigns that the current licensed spectrum usage across time and frequency is inefficient. Therefore, a concept of unlicensed users temporarily "borrowing" spectrum from incumbent license holders to improve the spectrum utilization, called "spectrum pooling", which is based on *dynamic spectrum access* (DSA), is proposed. Cognitive radio is a communication paradigm that employs software-defined radio technology in order to perform DSA and offers versatile, powerful and portable wireless transceivers.

Orthogonal frequency division multiplexing (OFDM) is a promising candidate for cognitive radio transmission. OFDM supports high data rates that are robust to channel impairments. In addition, some subcarriers can be deactivated which constitutes a *non-contiguous OFDM* (NC-OFDM) transmission. However, one of the biggest problems for OFDM transmission is high *out-of-band* (OOB) radiation, which is caused by sinc-type function representing the symbols during one time constant. Thus, high sidelobe may occur that will interfere with neighboring transmissions. This thesis presents two novel techniques for NC-OFDM sidelobe suppression. Another concern about cognitive radio systems is that the influence of frequency-selective fading channel. Consequently, this thesis also presents a combined approach employing power loading, bit allocation and sidelobe suppression for OFDM-based cognitive radio systems optimization.

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1   Research Motivation

The demand for wireless spectrum is increasing drastically. A large part of the spectrum has been segmented and rented to licensed users by national spectrum regulators such as *Federal Communications Commission* (FCC) based on traditional spectrum allocation policies. Wireless spectrum assigned to licensed users via these policies can only be used by these users since they maintain exclusive rights across the specified range of frequencies within a geographical area. In other words, only licensed users can use this spectrum allocation, while other unlicensed users are not permitted to access this spectrum block and transmit their signal in this frequency range. Unlicensed devices have access to only heavily populated and highly interference-prone frequency bands.

However, spectrum measurement studies have shown that a large part of the licensed spectrum are actually unoccupied both in frequency and time [4]. Figure 1.1 shows a wireless spectrum measurement across the 924 MHz to 948 MHz frequency band collected at the Wireless Innovation Laboratory of Worcester Polytechnic Institute in Worcester, MA on July 11, 2007. Notice now, less than half of the spectrum is used, making the rest of the unoccupied spectrum inefficiently utilized. New policy needs to be developed to improve this situation.

To make better use of radio spectrum resources, FCC is currently working on
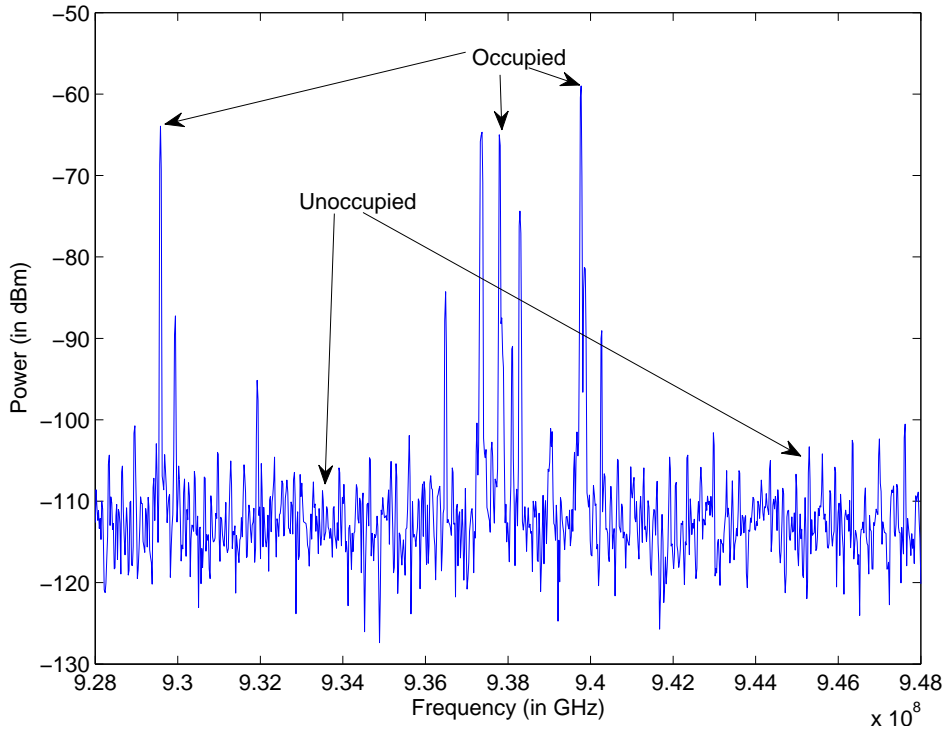
Figure 1.1: Spectrum occupancy measurements from 924 MHz to 948 MHz (7/11/2008, Worcester, MA, USA).

the concept of unlicensed users "borrowing" spectrum from incumbent license holders. This concept is call *dynamic spectrum access* (DSA), wherein the secondary user decides on whether or not a particular frequency band is current being used and transmits the signal in that unused licensed bad, while ensuring that the system performance of the primary as well as the secondary is not impacted [37]. "Spectrum pooling" is a strategy in DSA to promotes the secondary usage of licensed spectrum [16]. Unlicensed users [1] can temporarily rent the spectral resources during the idle periods of licensed user. The legacy licensed systems do not need to be modified and the installed hardware can be operated like there was no other system present in the same frequency range [16]. Figure 1.2 shows how "spectrum pooling" works. In Figure 1.2(a), the spectrum is only occupied by primary users and some part of the

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[1]In this thesis, the terms *legacy users*, *primary users* and *first users* are used to refer to the *licensed owners* of the RF spectrum. The terms *rental users* and *secondary users* are used to refer to the *unlicensed users* that utilize the idle licensed portions of the spectrum.
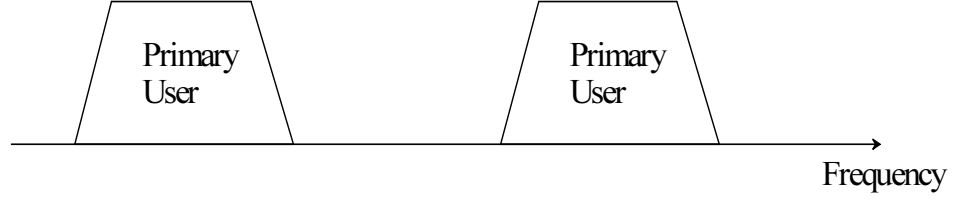
(a) Spectrum occupied by primary users.
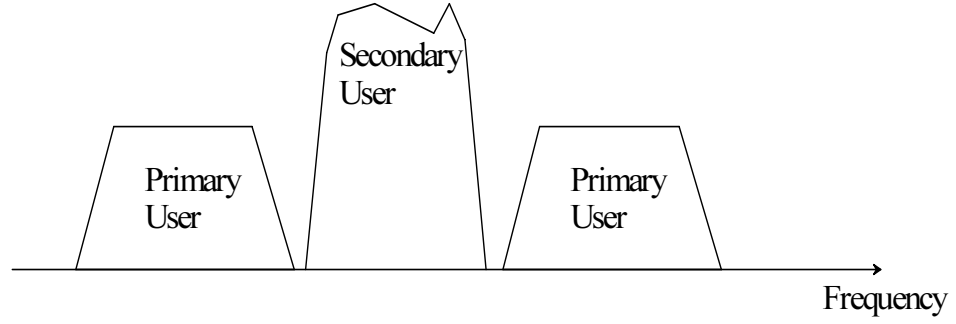
(b) Spectrum shared between primary users and secondary users.
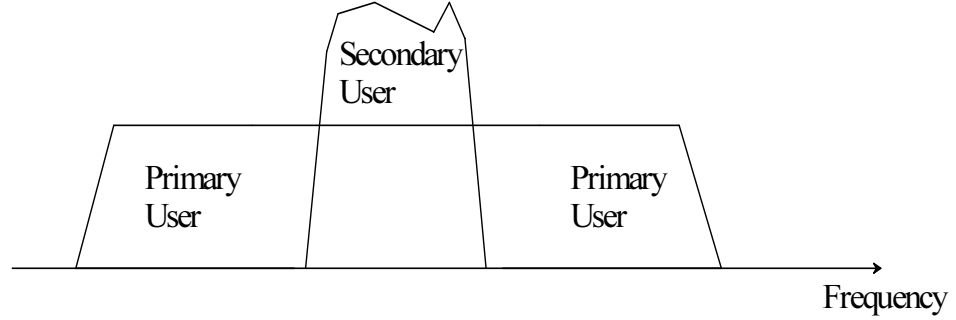
(c) Secondary users interfere with primary users' transmissions.

Figure 1.2: Illustration of "spectrum pooling".

spectrum is wasted. In Figure 1.2(b), secondary users can temporarily transmit their signals where in the frequency domain primary users are idle. In Figure 1.2(c), interference occurs when the primary users want to use the part of the spectrum which is used by the secondary users before and at this time, secondary users need to stop

their transmissions. This is an overlay system in which secondary users only operate in unused spectral regions and avoids interference to primary users, while in an underlay system secondary users spectrally coincident with primary assigned users and inducing minimum tolerable interference [38]. This policy can significantly improve the utilization of the spectral resources. Efficient pooling of the radio spectrum can be achieved by using a *cognitive radio* (CR), which is an autonomous unit in a communications environment that can determines the appropriate transceiver parameters based on its interaction with the environment, to enable secondary utilization of the spectrum [8].

Physical layer design is a very important part of the communication system and has a profound impact on the feasibility of the communication processes at the higher layers. *Orthogonal frequency division multiplexing* (OFDM)-based transmission is a promising candidate for a flexible spectrum pooling system [25]. OFDM has received great interest in the last several decades for its ability to transmit at high data rates by utilizing a number of orthogonally-spaced frequency bands that are modulated by many slower data streams [31]. The division of the available spectrum into several orthogonal subcarriers makes the transmission robust to frequency-selective fading due to multipath propagation. These features have led to the adoption of OFDM as a standard for *digital audio broadcasting* (DAB) and broadband indoor wireless system [32]. Another important property of OFDM is its flexibility. With OFDM, it is possible to realize transmission systems which do not require a continuous transmission band. Given the "spectrum pooling" policy, secondary users employing OFDM to transmit the signal can deactivate subcarriers that are located in the frequency bands occupied by the primary licensed users. This is referred to as *non-contiguous OFDM* (NC-OFDM). So we can solve an important problem that makes the coexistence of legacy and rental systems a practical solution to the existing under-utilization of the radio spectrum.

1.2   Research Objectives

The main objective of this research is to develop a number of performance enhancing techniques that are applicable to an OFDM-based cognitive radio system, including:

- **OFDM sidelobe suppression via genetic algorithm optimization.** OFDM OOB radiation may be a big interference with neighboring transmissions. There exists a technique called cancellation carriers which can be used for OFDM sidelobe suppression. However, we do not know how good this technique works and how much improvement we can make for this cancellation carriers technique. It is important to find an optimal solution.

- **OFDM sidelobe suppression with combined modulated filter banks and cancellation carriers.** Most OFDM sidelobe suppression techniques can only provide a reduction of about 15 dB, which is not enough. We must suppress the sidelobes at least 60 dB to achieve a tolerable interference with neighboring transmissions.

- **Unified optimization for OFDM-based cognitive radio systems in frequency-selective fading channel.** Frequency-selective channel will influence the performance of the system, including reducing signal to noise ratio, increasing bit error rate and reducing data throughput. In addition, as we talked before, out-of-band radiation is always a big problem which may interfere with the neighboring transmissions. Therefore, we need to use different techniques to realize a unified optimization.

1.3   Current State-of-the-art

Dynamic spectrum access (DSA) was first demonstrated in 2006 by the *Defense Advanced Research Projects Agency* (DARPA) and *Shared Spectrum Company* (SSC) of Vienna, VA, which enables users of virtually any modern radio device to utilize

dynamic spectrum access techniques and thereby dramatically improve spectrum efficiency, communications reliability, and deployment time. The idea of spectrum pooling and cognitive radio were first introduced in [18] by Dr. Joseph Mitola III. This paper outlines the basic factors that need to be considered in determining the pooling strategy and in designing the radio etiquette. Further insight into the notion of spectrum pooling is provided by another paper by Dr. Timo A. Weiss and Dr. Friedrich K. Jondral in [16].

OFDM-based transceiver systems have been proposed to be the viable solution for building a spectrum pooling system [16]. The advantage of using OFDM in a spectrum pooling based cognitive radio including the flexibility in filling up the spectral gaps left behind by the licensed users in their idle periods, turning off the subcarriers in the frequency bands used by the licensed users [28], the inherent frequency subbanding [33], high data rate and being robust to channel impairments. However, an important challenge in the physical layer design of an OFDM-based cognitive radio is the interference caused by high sidelobe. Only a few research groups have conducted research on OFDM sidlobe suppression, such as DoCoMo Communications Laboratories, Munish Germany and *German Aerospace Center* (DLR), Institute of Communications and Navigation, Wessling, Germany. Some of the proposed techniques are: sidelobe suppresion by windowing [22], wherein the time domain signal is multiplied with a windowing function with less steep edges; by guard bands [24], wherein additional subcarriers are deactivated in the vicinity of the licensed user or other unlicensed users; by inserting cancellation carriers [6, 7], wherein a few subcarriers which do not carry any data information are inserted on both sides of the OFDM spectrum to cancel out the sidelobe; by using constellation expansion [8], which is based on the fact that different sequences have different sidelobe power levels; and by subcarrier weighing [21], wherein the subcarriers are multiplied with weighting factors which are chosen such that the sidelobes are suppressed.

Another challenge is that a frequency selective fading channel may impact the performance of the OFDM-based cognitive radio system. By adapting the operating parameters of the subcarriers to each subchannel, such as the choice of modulation scheme and/or power level, the system can be optimized by maximizing system

throughput given an error constraint and minimizing the aggregate error given a throughput limit. This is referred to *power loading* and *bit allocation* [20]. With respect to bit loading, one of the classic works on bit loading strategies for multicarrier systems was presented by Kalet[35]. Using a multitone *quadrature amplitude modulation* (QAM) framework, the overall bit rate of the system was maximized when operating in an additive white Gaussian noise (AWGN) channel, first with a two-level transfer function and then extended to a multiple level transfer function. In addition, one of the most prolific research teams in this area is that of Professor John Cioffis group of Stanford University [39]. Cioffis algorithm and all its variants focus on an approximation of the channel capacity to define a non-integer number of bits per subcarrier. With respect to power loading, Fasano, Zucchi, Baccarelli, and Biagi proposed a number of power loading algorithms that attempt to avoid violations of the power constraints imposed by regulatory agencies [40]. In particular, they impose a subcarrier power constraint on each subcarrier such that when power is allocated, it cannot exceed this constraint. Yoshiki, Sampei, and Morinaga proposed a multi-level transmit power control for OFDM adaptive modulation systems to achieve high bit rate transmission without increasing the overall transmit power level [36].

1.4   Thesis Contributions

This thesis presents the following two novel algorithms for sidelobe suppression and a combined approach for power loading, bit loading and sidelobe suppresion for OFDM-based cognitive radios in a DSA environment:

- A *genetic algorithm* (GA) framework for *cancellation carrier* (CC) technique. There can be different GA frameworks, including GA frameworks based on the two existing CC algorithms and the GA framework with general fitness function. Using the results from the other two CC algorithms as initial population seeds for GA framework can greatly improve the performance of sidelobe suppression. Simulation results show that a 11.7447 dB reduction of OFDM sidelobe power can be achieved when two cancellation carriers are used on either side of the

BPSK-OFDM spectrum in a 64 subcarrier system based on genetic algorithm. This GA framework performs better than other published CC algorithms and can conveniently combine different requirement together, such as data throughput, to realize a unified optimization.

- A combined approach employing both modulated filter banks and cancellation carriers. Raised-cosine filters are chosen for modulated filter banks due to their efficiency and straight-forward implementation. Cancellation carriers are inserted on both sides of the OFDM spectrum to provide further sidelobe reduction. Simulation results show that we can achieve a significant reduction of out-of-band radiation after using this combined approach and the OFDM signal after using this approach is good enough for digital signal transmission since the sidelobe can be suppressed to be as low as -60 dBm. In addition, a fast and simple algorithm is developed based on simulation results to determine the number of OFDM subcarriers that can be transmitted in a given spectrum space in cognitive radio systems.

- A combined optimization employing power loading, bit allocation and sidelobe suppression. Given the frequency-selective fading channel, different power levels are assigned to different OFDM subcarries. However, due to the fact that the power difference between different subcarriers cannot be too big, or those subcarriers with low power may be clipped and large *peak to average power ratio* (PAPR) requires large dynamic ranges of the *digital-to-analog* (D/A) converters and *power amplifiers* (PA), we have to set threshold for power allocation. Then bit allocation is employed and different subcarriers are assigned with different number of bits in order to achieve a maximum data throughput. However, a threshold for BER is needed for each subcarrier and some subcarriers that have poor BER performance have to decrease the number of bits assigned to them. Finally, modulated filter banks are used to suppress the high sidelobe of OFDM signal.

1.5   Thesis Organization

This thesis is organized as follows: Chapter 2 briefly introduces the OFDM-based cognitive radio system, high out-of-band radiation problem and an overview of several existing techniques which can be used to suppress OFDM out-of-band radiation. In Chapter 3, the proposed genetic algorithm framework for cancellation carriers technique for OFDM sidelobe suppression is explained in detail and the simulation results obtained are presented. A comparison between this genetic algorithm framework and the other two existing cancellation carriers algorithms is also provided. In Chapter 4, the proposed approach combining modulated filter banks and cancellation carriers is illustrated. Simulation results are also presented and a comparison between different techniques is provided to prove the efficiency of the proposed approach. Furthermore, based on the simulation results, a simple and fast algorithm is developed to determine the number of OFDM subcarriers that can be transmitted in a given spectrum space. Chapter 5 presents the proposed combined optimization approach employing power loading, bit allocation and sidelobe suppresion. Power loading and bit loading are introduced and simulation results are provided in Chapter 5. Finally, in Chapter 6, several conclusions are drawn and directions for future research are presented.

Chapter 2

Out-of-band Radiation Problem in OFDM-based Cognitive Radio Systems

This chapter provides an introduction to OFDM-based *cognitive radio* (CR) communications. OFDM modulation is well-suited for CR communications due to its ability for achieving high data rate and low *intersymbol interference* (ISI). However, OFDM uses sinc-type pulses to represent symbols transmitted over all the subcarriers per time constant. Consequently, large sidelobes may occur that could potentially interfere with the signal transmissions of the neighboring legacy systems or with the transmissions of other rental users. Several existing techniques which can be used to suppress high sidelobe are also introduced in this chapter.

2.1 Spectrum Pooling-based Cognitive Radio System

As wireless applications become increasingly sophisticated and widely used, the demand for more spectral resources is growing substantially [16]. Recent spectrum measurement studies have shown that utilization of radio spectrum is quite low [4].

This is largely due to the traditional approach of exclusive allocation of portions of spectrum to specific wireless systems and services. Given that such spectrum is licensed over large regions and time spans, it is inaccessible to unlicensed wireless systems even if the licensed systems are under-utilizing the spectrum. Based on observation by the *Federal Communications Commission* (FCC) and their spectral efficiency working group regarding traditional spectrum allocation policies, allotting fixed portions of spectrum to licensed users causes a potential waste of spectral resources since the licensed spectrum is heavily underutilized over time and frequency [9]. In the process of finding a solution for supplying the limited spectral resources to the almost unlimited demand for more spectrum, one has to conceive new concepts for a more efficient way of using spectral resources. Old policies of spectrum licensing need to be rethought. A whole new policy called *dynamic spectrum access* (DSA) is then proposed.

In DSA networks, the secondary user decides on whether or not a particular frequency band is currently being used and transmits the signal in that unused licensed band, while ensuring that the system performance of the primary as well as the secondary is not impacted. The notion of "spectrum pooling", which was first mentioned in [18], is based on DSA. It basically represents the idea of merging spectral ranges from different spectrum owners into a common pool. From this common spectrum pool hosted by the licensed system, users may temporarily rent spectral resources during idle periods of licensed users. The licensed system does not need to be changed and the installed hardware can be operated as though there are no other systems present in the same frequency range [16]. Although the leasing of licensed spectral resources to rental users may provide additional revenue to the licensed users, the implementation of the proposed approach brings forth many technological, juridical, economic and political questions concerning the regulatory aspects of spectrum pooling.

Flexible pooling of the spectral resources is made possible by the *cognitive radio* (CR), an extension of *software-defined radio* (SDR), where the radio platform not only rapidly reconfigures its operating parameters and functions but also senses its environment, tracks changes, and reacts upon its findings. A CR is an autonomous unit in a

communications environment that can determines the appropriate transceiver parameters based on its interaction with the environment, to enable secondary utilization of the spectrum [8]. In order to use the spectral resource most efficiently, the CR has to be aware of its location, be interference sensitive, comply with some communications etiquette, be fair against other users and keep its owner informed. In order to handle these tasks, a CR carries location sensors in order to determine its own location. It has to monitor its spectral environment, e.g. by employing a broadband *fast Fourier transform* (FFT). To track its location or the spectral environment's development, it has to use appropriate learning and reasoning algorithms. Most important, CRs should respect the rights of other spectrum users, especially incumbent license holders, *i.e.* it has to compromise its own demands with the demands of other users. In this way we can solve an important problem that makes the coexistence of legacy and rental systems a practical solution to the existing under-utilization of the radio spectrum.

2.1.1 General Schematic of an NC-OFDM Based Cognitive Radio System

OFDM has received significant attention over the past several decades due to its ability to robustly transmit at high data rates. By utilizing a number of orthogonally-spaced frequency bands that are each modulated by numerous slower data streams, the division of available spectrum into several orthogonal subcarriers makes the transmission system resilient to frequency-selective fading due to multipath propagation [2]. In addition, the spectrum flexibility of an OFDM signal can realize transmission schemes that do not require a contiguous spectral band. A potential rental system needs to be highly flexible with respect to the spectral shape of the transmitted signal. This property is absolutely necessary in order to efficiently fill the spectral gaps the licensed users leave during their own idle periods. Wireless transceivers employing OFDM transmission can deactivate subcarriers that are located in the vicinity of frequency bands occupied by other wireless transmissions, which can greatly improve spectrum usage efficiency. This type of wireless transmission is referred to as

(a) A general OFDM-based transmitter

(b) A general OFDM-based receiver
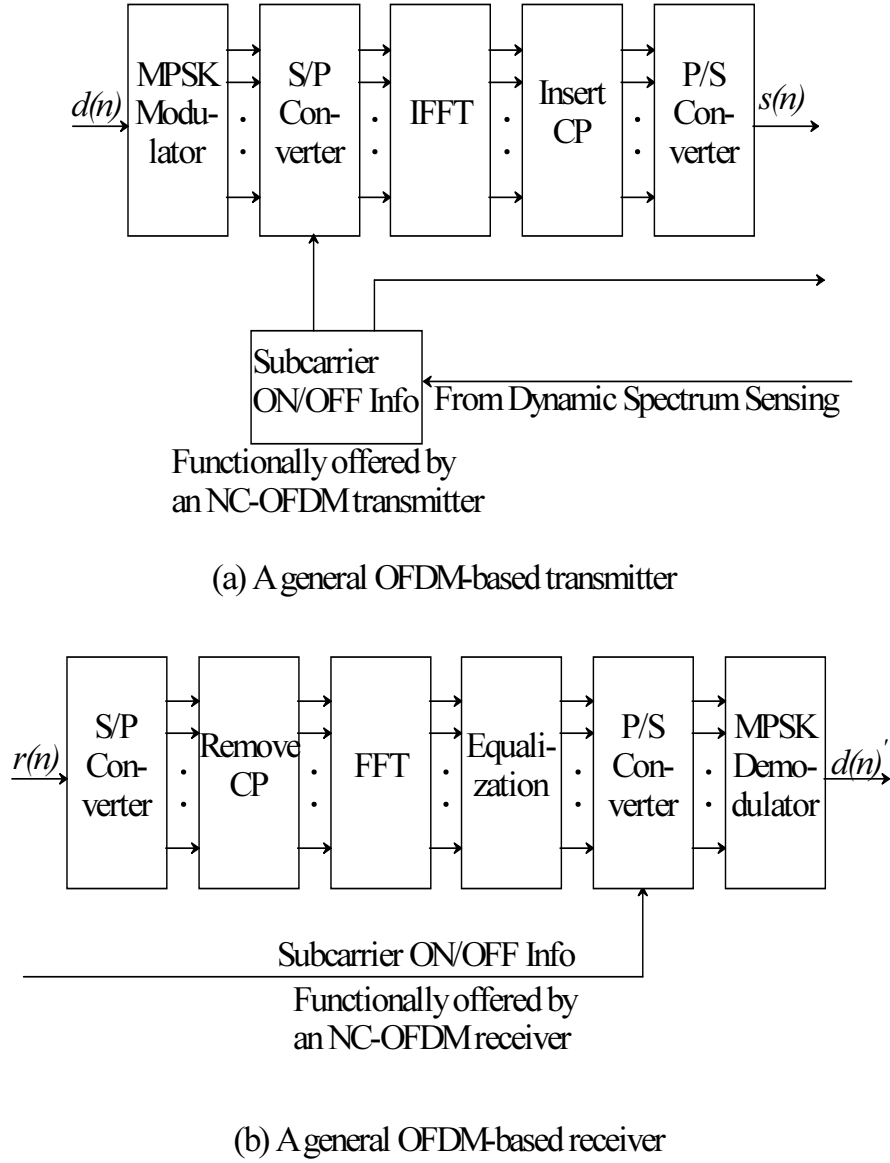
Figure 2.1: A general schematic of an OFDM-based cognitive radio transceiver.

non-contiguous OFDM (NC-OFDM), which is perfectly suitable for cognitive radio [25].

Figure 2.1 shows a general schematic of an OFDM-based cognitive radio transceiver.

A high speed data stream, *d(n)*, is modulated using *M-ary phase shift keying* (MPSK). The modulated data stream is split into *N* slower data streams using a *serial-to-parallel* (S/P) converter. In the presence of primary user transmissions, which are detected using *dynamic spectrum access* (DSA) and channel estimation techniques, the secondary OFDM user turns off the subcarriers in their vicinity resulting in a non-contiguous transmission. The *inverse fast Fourier transform* (IFFT) is then applied to these modulated signals. A *cyclic prefix* (CP) whose length is greater than the delay spread of the channel is inserted to mitigate the effects of the *intersymbol interference* (ISI). Following the *parallel-to-serial* (P/S) conversion, the baseband OFDM signal is passed through the transmitter's RF chain, to amplify the signal and upconvert it to the desired frequency.

At the receiver, the reverse operations are performed, namely, mixing the bandpass signal to downconvert it to a baseband signal, then applying S/P conversion, discarding the CP and applying *fast fourier transform* (FFT) to transform the time domain signal to frequency domain. After performing channel equalization and P/S conversion, the symbol stream is demodulated to recover the original high-speed input signal.

2.2 High Out-of-band Radiation Problems

Even though OFDM-based cognitive radios have proven to be ideal in efficiently filling up the spectral white spaces left unused by the licensed systems, there is an important challenge that needs to be solved for the coexistence of the legacy and rental systems in the RF spectrum. OFDM uses sinc-type pulses in representing symbols transmitted over all the subcarriers per time constant. Large sidelobes resulting from this sinc-type pulses are a source of interference to the legacy systems or other rental systems that might be present in the vicinity of the spectrum used by the unlicensed system. Conversely, in the presence of a non-orthogonal rental system, the system performance of the secondary system might suffer from this interference [8]. With respect to the interference, the primary issue that needs to be addressed when designing an OFDM-based overlay system is minimizing (or eliminating if possible) its

impact on the legacy systems. Assuming the unlicensed transmit signal, $s(t)$, on each subcarrier of the OFDM-transceiver system is a rectangular *non-return-to-zero* (NRZ) signal, the *power spectral density* (PSD) of $s(t)$ is represented in the form:

$$\phi_{ss}(f) = A^2 T \left(\frac{\sin(\pi f t)}{\pi f t} \right)^2 \tag{2.1}$$

where A donates the signal amplitude and T is the symbol duration which consists of the sum of symbol duration, T_S, and guard interval, T_G. Now assuming that the legacy system is located in the vicinity of the rental system, the mean relative interference, $P_{\text{int}}(n)$, to a legacy system subband is defined as:

$$P_{\text{int}} = \frac{1}{P_{Total}} \int_n^{n+1} \phi_{ss}(f) df \tag{2.2}$$

where P_{Total} is the total transmit power emitted on one subcarrier, and n represents the distance between the considered subcarrier and the legacy system in multiplies of Δf.

As an illustration, Figure 2.2 shows the power spectral density of an OFDM modulated carrier. In Figure 2.2, the subcarrier spacing and the interference power due to the first sidelobe in the first adjacent band are shown. It is observed that as the distance between the locations of the subcarrier of the rental system and the considered subband increases, the interference caused by it reduces monotonically, which is a characteristic of the *sinc* pulse. However, it should also be noted that in a practical scenario consisting of N subcarriers, the actual value of the interference caused in a particular legacy system subband is a function of the random symbols carried by the *sinc* pulses and N.

The idea of interference calculation for the case of one subcarrier can be extended to a system with N subcarriers. Let $s_n(x)$, for $n = 1, 2, 3, \ldots, N$, be the subcarrier of index n represented in the frequency domain. Then, we define:

$$s_n(x) = a_n \frac{\sin(\pi(x - x_n))}{\pi(x - x_n)}, n = 1, 2, 3, \ldots, N. \tag{2.3}$$

In Eq. (2.3), $a = [a_1, a_2, \ldots, a_N]$ in a data symbol array, x is the normalized frequency given by:

$$x = (f - f_0)T \tag{2.4}$$
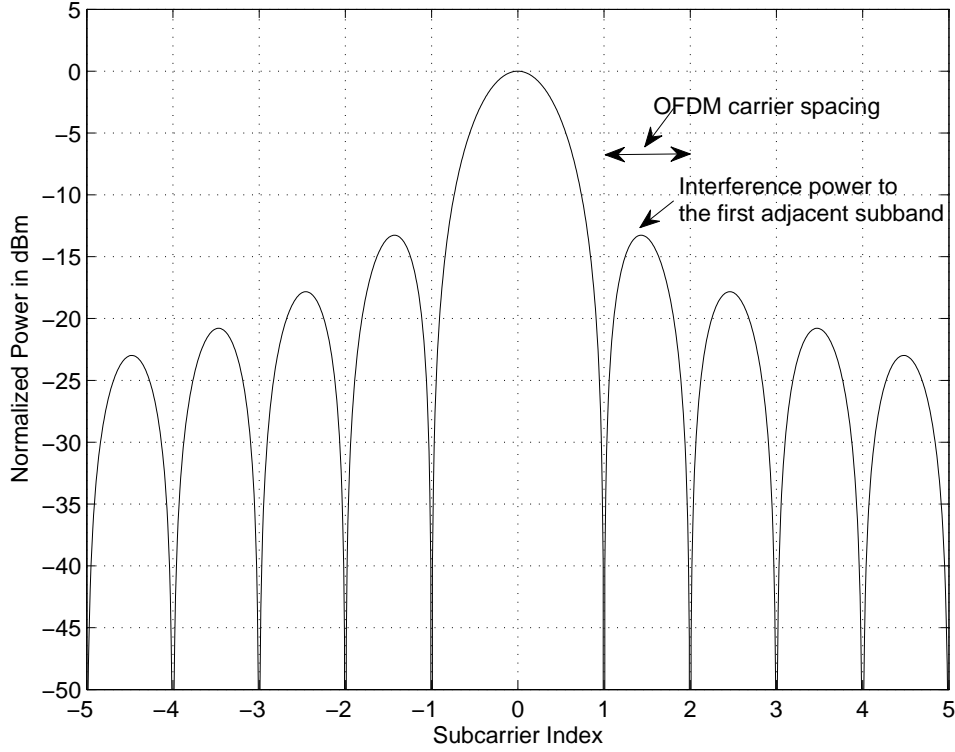
Figure 2.2: An illustration of the interference due to one OFDM-modulated carrier.

where f defines the frequency, and f_0 is the center frequency. Consequently, the OFDM symbol in the frequency domain over the N subcarriers is:

$$S(x) = \sum_{n=1}^{N} s_n(x). \tag{2.5}$$

Moreover, the PSD of $S(x)$ is given by:

$$\phi_{ss}(f) = |S(x)|^2 = \left| \sum_{n=1}^{N} a_n \frac{\sin(\pi(x - x_n))}{\pi(x - x_n)} \right|^2. \tag{2.6}$$

Figure 2.3 shows the normalized *binary phase shift keying* (BPSK)-modulated OFDM power spectrum with 15 subcarriers. The simulation results is based on 1000 random combinations of subcarrier amplitudes and the average results are shown. The portion outside the OFDM *data carriers* (DCs) is the sidelobe part and we can find that the first sidelobe is as high as -15 *dBm*. This is only the average case and
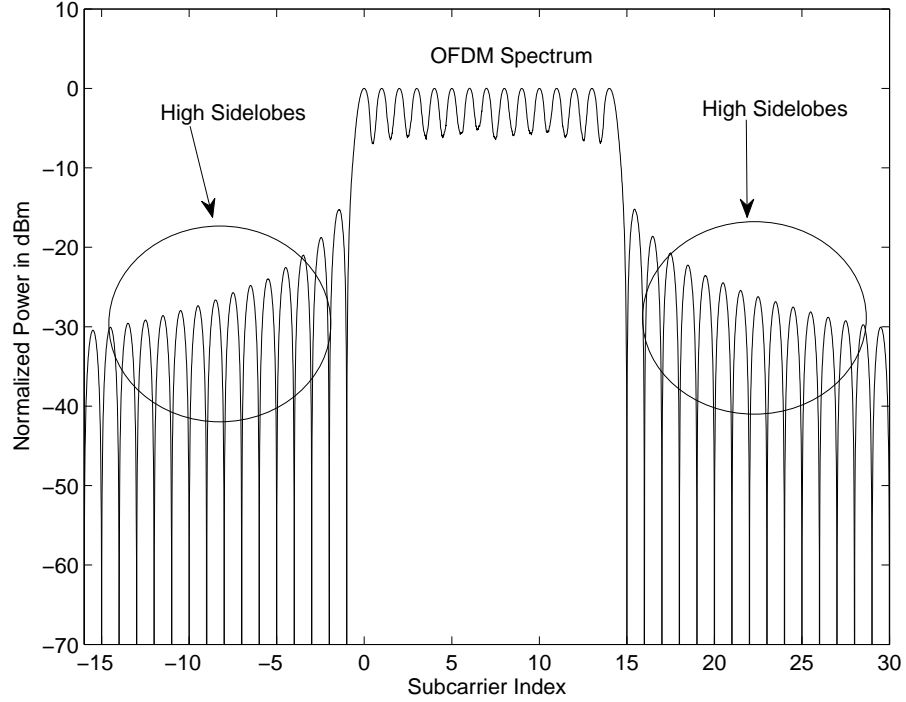
Figure 2.3: An illustration of the high interference in a OFDM-based system using BPSK modulation with 15 subcarriers.

for some cases, such as alternating '1' and '-1', the first sidelobe power can be as high as -3 dBm given 15 subcarriers. Moreover, the sidelobe decreases very slowly with increasing distance from the OFDM main spectrum in the frequency domain. As shown in Figure 2.3, the sidelobe 15 is about -30 dBm. This means even if we use 15 guard bands, which are not used for data transmission, the sidelobe power is unacceptably high and will cause significant interference with other neighboring transmissions.

2.2.1 Existing Techniques for OFDM Sidelobe Suppression

2.2.2 Guard Bands

Reference [24] proposed a simple technique for OFDM sidelobe suppression that employs *guard bands* (GBs). The idea is to deactivate additional subcarriers in the
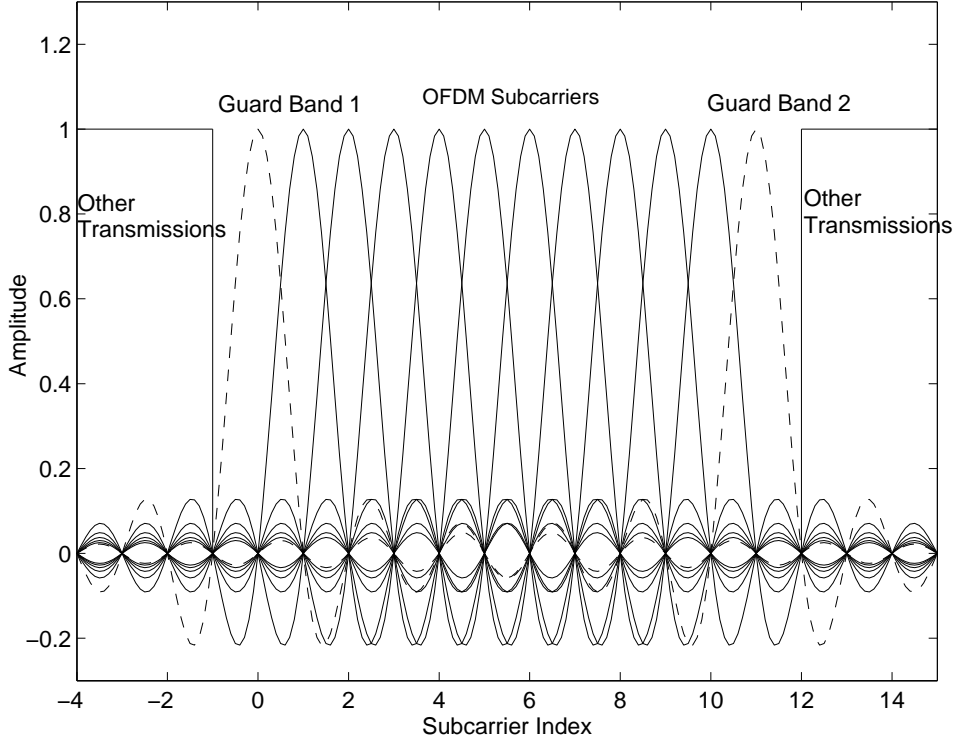
Figure 2.4: An illustration of the guard band technique for OFDM sidelobe suppression.

vicinity of the licensed user or other unlicensed users, as shown in Figure 2.4. In Figure 2.4, one guard band is used on each side of the OFDM signal in order to reduce the OOB radiation. However, these guard bands just act as buffer regions between the transmissions and are actually wasted spectrum. The space used by the GCs could be used to transmit additional OFDM subcarriers, thus increasing data throughput, but at the expense of more interference. The effect of GBs on the OOB radiation of an OFDM signal differs for different nonlinear devices. The GBs are not capable of reducing the OOB radiation caused by excessive clipping of the OFDM signal [24]. Simulation results show that using a certain amount of GBs can achieve a sidelobe reduction of 15 dB. However, the reduction effect using guard bands is not significant enough and the drawback of this method is the less effective use of the available bandwidth.

OFDM symbol *n-1*   OFDM symbol *n*   OFDM symbol *n+1*

$$T=T_U+T_{prefix}+T_{postfix}\text{-}\beta T$$

$\leftarrow \beta T \rightarrow$

t

$\leftarrow T_{prefix} \rightarrow$ $\leftarrow T_U \rightarrow$ $\leftarrow T_{postfix} \rightarrow$
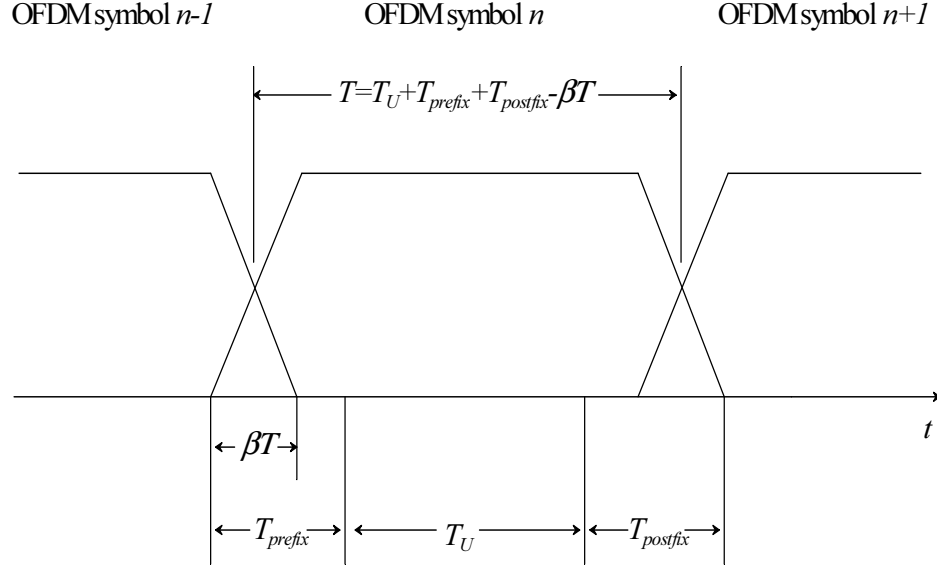
Figure 2.5: Structure of the temporal OFDM signal using a raised cosine window.

2.2.3   Windowing

Another well known technique is called transmit windowing, proposed in [22]. The sharp transitions between consecutive OFDM symbols cause significant OOB radiation. To smooth these transitions, the time domain signal can be multiplied with a windowing function. In contrast to the conventional rectangular window, the edges of the windowing function are less steep. As a result, the spectrum of each OFDM subcarriers has lower sidelobes than the sinc-pulse obtained with conventional rectangular windowing [19]. A raised cosine window is a commonly used window type with straight-forward implementation. Figure 2.5 shows the OFDM signal in time-domain with a raised cosine window in trapezoid shapes applied to it for the purpose of smoothing the transition. We can see that the postfix needs to be longer than βT to maintain the orthogonality within the OFDM signal. That is, the application of windowing to reduce the OOB radiation of the OFDM signal has the adverse effect of expanding the temporal symbol duration by $(1 + \beta)$, resulting in a lowered system throughput for the unlicensed user.

Analysis has shown that the benefit of this windowing approach with respect to
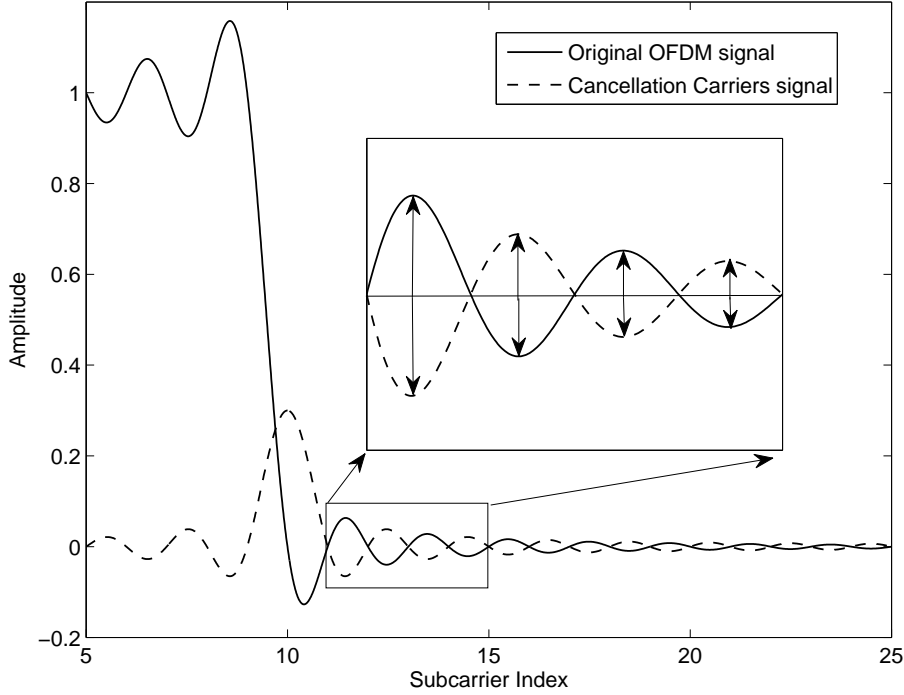
Figure 2.6: An illustration of the cancellation carriers technique.

interference reduction is fairly low [23]. Nevertheless, windowing can be conveniently combined with any other sidelobe suppression technique as an additional means to suppress the high OOB radiation [19].

2.2.4 Cancellation Carriers

The *cancellation carrier* (CC) technique is a promising technique for OFDM sidelobe suppression. This technique operates by inserting carriers on the left and right hand side of the OFDM spectrum with optimized weights. These carriers do not carry data information, but are rather calculated to cancel out the OOB interference. Figure 2.6 illustrates how the CC technique operates. In this case, one CC is inserted on the right side of the OFDM spectrum, with the solid line representing the BPSK-modulated OFDM signal and dashed line representing the CC. The amplitude of the CC is calculated to cancel out the sidelobe of the original OFDM signal. In total,

there are two types of CC algorithms found in the literature. Reference [7] proposed a method for calculating the amplitudes of CCs by solving linear least squares problems. We call this an optimization-based algorithm in this thesis. A low complexity algebraic algorithm to calculate amplitudes of CCs and avoid complex computation was also proposed in [6], which is called a heuristic algorithm in this thesis. Simulation results show that both CC algorithms can provide a 15 dB reduction for OFDM sidelobe power given 64 subcarriers. Nevertheless, there is a small loss in bit error rate performance due to the fact that a certain amount of the transmission power has to be spent on the CCs and is not available for data transmission [6].

2.2.5   Constellation Expansion

Another technique was proposed in [8] based on the fact that different sequences have different sidelobe power levels. This technique employs a *constellation expansion* (CE) based iterative approach to achieve a large decrease in the sidelobe power levels. In this CE technique, the symbols of a modulation scheme that modulates k bits/symbol and consisting of 2^k constellation points are mapped to a modulation scheme that modulates *(k+1)* bits/symbol and consisting of 2^{k+1} constellation points. Figure 2.7 shows the two ways of mapping from a 2-point signal constellation to a 4-point signal constellation. When point 'a' is mapped to either 'a1' or 'a2' at the transmitter, there will be more choices for different sequences. An algorithm can choose the sequence which has the lowest sidelobe level. At the receiver, 'a1' or 'a2' will be automatically mapped into 'a', and then no side information is needed. The logic behind this association of points from a lower constellation to a higher constellation is to take advantage of the randomness involved in selecting one of the two points and hence the combination of different in-phase and quadrature-phase components from all the subcarriers would result in a sequence with the lowest sidelobes. An important advantage of this technique is that there is no side information to be transmitted. However, the trade-off involved is a slight increase in the *bit error rate* (BER) which results only because symbols from higher constellation are used to reduce the sidelobe power levels.

(a) Mapping I.

(b) Mapping II.
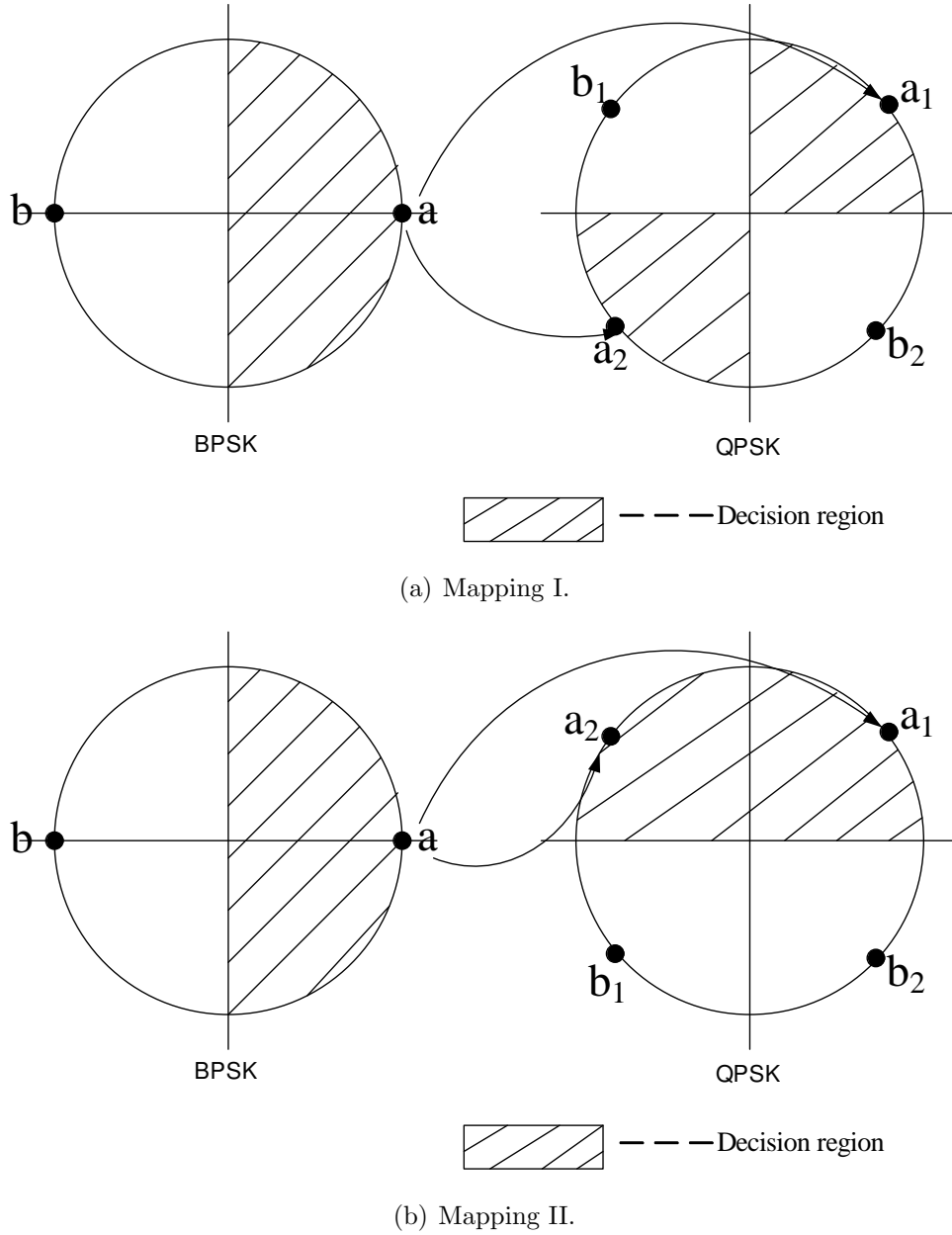
Figure 2.7: An illustration of the constellation expansion technique.

2.2.6 Subcarrier Weighting

Another technique was proposed in [21] called *subcarrier weighting* (SW) based on the multiplication of the used subcarriers with subcarrier weights which are chosen such that sidelobes are suppressed. Figure 2.8 shows how it works. There are totally
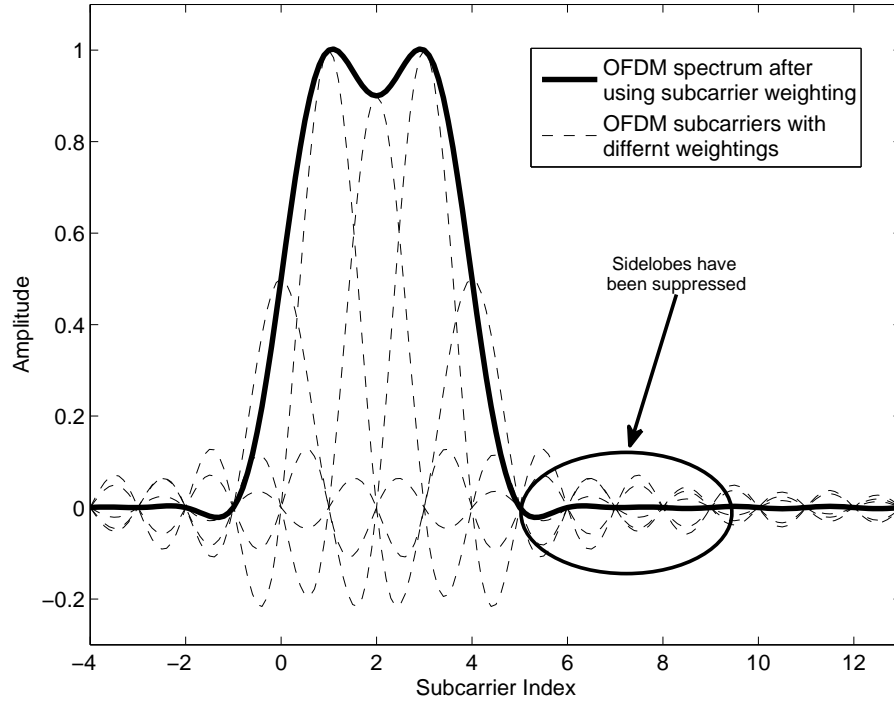
Figure 2.8: An illustration of the subcarrier weighting technique.

five subcarriers in Figure 2.8 and the amplitudes of individual subcarrier are adapted so as to mainly cancel each other in the optimization range thus lowering the sidelobe level. To achieve this, subcarriers are multiplied with weighting factors which are chosen such that the sidelobes are suppressed. This SW method does not need to transmit any side information and is capable of reducing the OOB radiation of OFDM signals by more than 10 dB. However, this SW method suffers from a slight loss in BER as with SW different subcarriers receive different amounts of transmit power.

2.2.7   Combining Existing Sidelobe Suppression Techniques

To achieve an even better sidelobe suppression, several of the above techniques can be combined. With respect to computational complexity and degradation in *bit error rate* (BER) performance, the combination of windowing with one of the other techniques seems to be preferable, since it can be easily combined with any

Table 2.1: Comparison for different techniques for OFDM sidelobe suppression.

	Reduction Value(dB)	Computation complexity
Guard bands	The 15th sidelobe is at -30 dBm	Low
Windowing	15 dB, roll off factor $\beta = 0.1$	Low
Constellation expansion	13.2 dB, 2-constellation to 4-constellation	High
Subcarrier weighting	7dB, $g_{max}/g_{min} = 2$	Medium
Cancellation carriers	14.5 dB, 2CCs at each side	Medium

of the techniques listed above. In addition, windowing operations do not depend on the transmitted data sequence, while CC, CE and SW perform data dependent procedures [19]. Furthermore, cancellation carriers and constellation expansion can be combined together to achieve better performance, as shown in Reference [29].

Table 2.1 shows the comparison of sidelobe suppression effects and computation complexity of different existing algorithms. There are totally 12 BPSK subcarriers in this case and the reduction values at the 12th sidelobe compared to the original OFDM sidelobes are shown. We can see that all the above techniques provide a certain amount of sidelobe reduction. However, none of them is efficient enough. In a cognitive radio system, when digital signal is transmitted, the sidelobe of OFDM signal should be suppressed to at most -60 dBm when the main band is at 0 dBm, which means low enough interference with other transmissions [34]. For some of the above techniques, only a reduction of about 15 dB can be achieved and the sidelobes are still as high as -45 dBm. If we want to suppress the sidelobes to -60 dBm using these techniques, a large part of the spectrum needs to be wasted to let the sidelobes go down to -60 dBm. In the following two chapters, we propose two novel techniques that can improve the performance of OFDM sidlobe suppression to levels that are acceptable for adjacent transmissions.

2.3 Chapter Summary

The sidelobes resulting from the use of OFDM for representing the symbols of the low data rate streams are a source of interference to neighboring transmissions in cog-

nitive radio systems. There are already several techniques exits to suppress this high out-of-band radiation. However, none of them is efficient enough and new techniques need to be developed to provide further reduction of OFDM OOB radiation.

Chapter 3

Cancellation Carriers Technique Using Genetic Algorithm

In this chapter, we investigate the sidelobe power reduction of non-contiguous *orthogonal frequency division multiplexing* (OFDM) signals using a *genetic algorithm* (GA) approach for *cancellation carriers* (CC) technique. Cancellation carrier technique is a promising technique that has been proved to be effective for OFDM sidelobe suppression. However, the two existing CC algorithms can not tell us exactly how well this technique can perform and whether there is space for improvement. In this chapter, different GA frameworks are developed and compared. Both GA with random initial population and GA with optimized population seeds are presented. In addition, the GA framework for CC technique is compared with other two pure CC algorithms and simulation results show that it works the best among the three with a cost of higher computation complexity.

3.1 Genetic Algorithm

Genetic algorithms are feature selection algorithms based on the mechanics of natural selection and natural genetics [5]. A GA is a random search technique that searches for the best feature from a search space provided to it. This search is done based on a *objective function*, otherwise called a *fitness function*, which is used

for finding the best fit within the search space. This function is evaluated at each individual search point in the population over several generations until a configuration is found that meets the desired objective. The search space is nothing more than a population of configurations. These configurations are the binary coded features called *chromosomes* or *strings*.

3.1.1 Why Genetic Algorithm?

An effective GA representation and meaningful fitness evaluation are the keys to success in GA applications. GA is known for its simplicity as an efficient search algorithm, such as its power to rapidly discover the best solutions for difficult multi-dimensional problems. The advantage of the GA approach is the ease with which it can handle arbitrary kinds of constraints and objectives. These situations can be handled as weighted components of the fitness function [5]. In our case, the variation of the number of CCs, the amplitudes and phases of CCs makes the whole problem complicated. Consequently, GA is a perfect tool that can help us conveniently find the best solution.

3.1.2 How Does Genetic Algorithm Work?

Genetic algorithms are implemented as a computer simulation in which a population of chromosomes of candidate solutions to an optimization problem evolves toward better solutions. Traditionally, solutions are represented in binary as strings of 0s and 1s, but other encodings are also possible. The three basic operators used in GAs are reproduction, crossover, and mutation. Reproduction is a process in which configurations are copied directly to the next generation according to their fitness function values. The configurations with a higher value of fitness function have a higher probability of contributing one or more offsprings to the next generation. Crossover is a recombination operator that combines subparts of two parent chromosomes to produce offspring that contain some parts of both parents' genetic material. Mutation is an operator that introduces variations into the chromosome. The evolution usually starts from a population of randomly generated individuals and

Start

Generate Initial
Population

Evaluate Fitness
Function

Are Optimization
Criteria Met?

No

Reproduction

Generate
New
Population

Crossover

Mutation

Yes

Best Individuals

Result
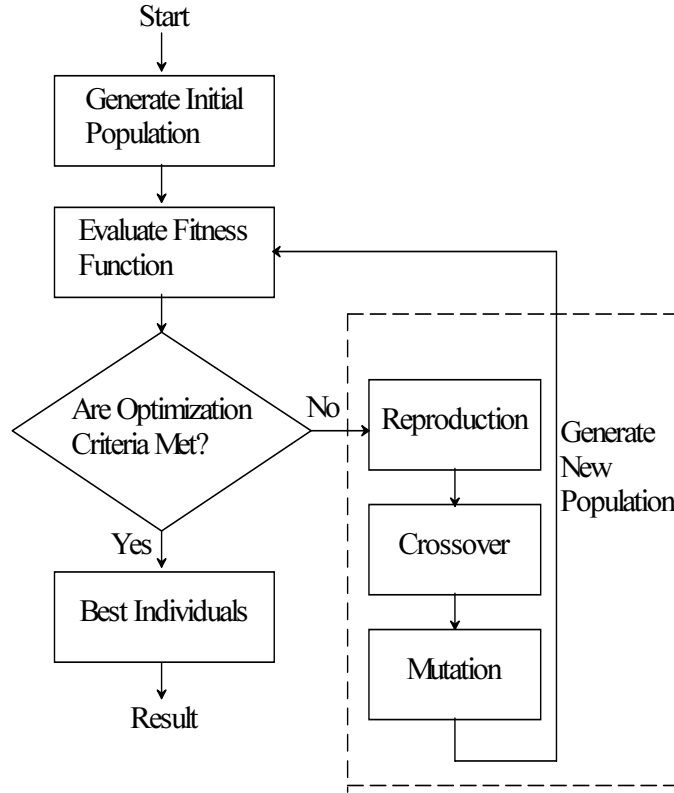
Figure 3.1: Genetic algorithm flow diagram.

happens in generations. In each generation, the fitness of every individual in the population is evaluated, multiple individuals are stochastically selected from the current population based on their fitness score, and modified using crossover and mutation to form a new population. The new population is then used in the next iteration of the algorithm. Commonly, the algorithm terminates when either a maximum number of generations has been produced, or a satisfactory fitness level has been reached for the population. If the algorithm has terminated due to a maximum number of generations, a satisfactory solution may or may not have been reached [5].

Figure 3.1 shows the GA procedure. Initially, a random population is generated and the fitness function values are evaluated over each configuration. Any configuration that meets the optimization objective is considered as a best configuration. The configurations that do not meet the optimization objective undergo reproduction,

crossover and mutation which in turn leads to a new population of configurations. This new population will now undergo the same process as stated earlier until the best configurations are found.

3.2   Proposed Genetic Algorithm Frameworks for Cancellation Carriers Technique

For the cancellation carrier technique for OFDM sidelobe suppression, we can write different fitness functions based on the heuristic CC algorithm and the optimization-based CC algorithm. We can also write a fitness function that directly calculates the highest sidelobe level in a fixed OOB optimization region.

3.2.1   Proposed Genetic Algorithm Framework for the Heuristic CC Algorithm

Based on the fact that the total OOB radiation power at any location in the OOB region consists of a sum of the power contained in each sinc-pulse at that location, the approach proposed in [6] concludes that the amplitudes of the CCs are calculated according to the highest sidelobe level close to the position where the CCs are to inserted.

We can write a GA fitness function based on this heuristic CC algorithm, with the result of the fitness function being the difference between the original sidelobe power value needed to be reduced at a certain position and the sidelobe power values at the same position caused by CCs. We call this *Fitness Function 1* in this thesis. The GA can determine the best fit of amplitudes of CCs and the number of CCs inserted. Suppose there are N_{DC} *data carriers* (DC) in the OFDM signal and N_{CC} cancellation carriers are inserted. We know that due to the existence of the primary users, the total number of carriers (N_{TOTAL}), including digital carriers and cancellation carriers, is limited. Therefore, N_{TOTAL} is decided by the spectrum usage of the primary user,

which is off-limits by secondary users. Then we have:

$$N_{TOTAL} = N_{DC} + N_{CC}. \tag{3.1}$$

The situations on the left and right side of the OFDM spectrum are assumed in this paper to be the same in the frequency domain, so we only need to consider one side. However, in general conditions on either side of the OFDM spectrum may not be identical. Here we consider the right side. First we define one point, x_{ampmax}, which is in the second sidelobe right to the original OFDM spectrum and it has the highest OOB power value in this sidelobe space. Suppose B_i is the sidelobe power level of the ith data carrier in OFDM signals at point $x = x_{ampmax}$, where the value of the sum of all B_i (i.e., $\sum B_i$) is calculated to produce the largest sidelobe levels that need to be suppressed. Suppose A_j is the amplitude of mainlobe of the jth CC, where $-1 \le A_j \le 1$, then the value of the CC sidelobes at point $x = x_{ampmax}$ is $f(A_j)$. Here, $f(A_j)$ is a function of A_j and we need to divide it into two situations, which are the left side CCs and the right side CCs. Consequently, the total sidelobe power level inserted by the CCs at the point $x = x_{ampmax}$ is $\sum f(A_j)$. Our goal is to make the value of sidelobe power at the point $x = x_{ampmax}$ as small as possible, which means that the value $| \sum B_i - \sum f(A_j) |$ approaches zero. As a result, the fitness function for the right part of the spectrum can be defined as:

$$y_{right} = \left| \sum_{i=0}^{N_{DC}-1} B_i - \left(\sum_{j1=0}^{N_{CC(l)}-1} f(A_{j1}) + \sum_{j2=0}^{N_{CC(r)}-1} f(A_{j2}) \right) \right|, \tag{3.2}$$

where $N_{CC(l)}$ represents the number of CCs on the left side of spectrum and $N_{CC(r)}$ represents the right side. In addition, $f(A_{j1})$ and $f(A_{j2})$ respectively represents the sidelobes caused by the CC on the left side of the OFDM spectrum at the point $x = x_{ampmax}$ and those caused by CCs on the right side.

We can get the fitness function y_{left} for the left part of the spectrum in the same way. Consequently, the total fitness function can be defined as:

$$y = y_{right} + y_{left}. \tag{3.3}$$

3.2.2   Proposed Genetic Algorithm Framework for the Optimization-Based CC Algorithm

In the CC technique proposed in [7], CCs are calculated by using the average value of all sample points in the optimization range. The sample points are the values in the middle of each sidelobe in order to reduce the computational complexity of the optimization and to reduce memory usage[7].

We can write the fitness function based on this optimization-based CC algorithm. The result of the fitness function is the average OOB power value of all sample points. We call it *Fitness Function 2* in this thesis. These OOB power values of sample points are calculated after the CCs are inserted. Similar to Fitness Function 1, we have $N_{TOTAL} = N_{DC} + N_{CC}$. Setting the middle of each sidelobe in the optimization range as sample points and defining m sample points, the OOB power value of each sample point is the sum of the sidelobes caused by all carriers, including data carriers and cancellation carriers. Suppose $B(i,j)$ is the sidelobe power level caused by the jth digital carrier in OFDM signals at the ith sample point. Furthermore, if A_k is the amplitude of mainlobe of kth CCs, where $-1 \leq A_k \leq 1$, then the value of sidelobe power value of CCs at ith sample point is $f(i, A_k)$. Here we also need to divide into two situations, which are the left side CCs and the right side CCs and the total sidelobe power level inserted by CCs at ith sample point is $\sum f(i, A_k)$. Thus, for the ith sample point, the total OOB power value is $\sum B(i,j) + \sum f(i, A_k)$. Consider the left and right part of CCs, we can get the fitness function for the ith sample point:

$$y_i = \sum_{j=0}^{N_{DC}-1} B(i,j) + \sum_{k1=0}^{N_{CC(l)}-1} f(i, A_{k1}) + \sum_{k2=0}^{N_{CC(r)}-1} f(i, A_{k2}), \tag{3.4}$$

where $f(i, A_{k1})$ and $f(i, A_{k2})$ respectively represents the sidelobes caused by the CCs on the left hand side of the OFDM spectrum at ith sample point and those caused by CCs on the right hand side.

Consequently, for m sample points, the final fitness function is:

$$y = \frac{1}{m} \sum_{i=0}^{m-1} y_i. \tag{3.5}$$

3.2.3   Proposed Genetic Algorithm Framework Employing General Fitness Function

A third approach to write a fitness function is to calculate the highest OOB power value directly in the optimization range and using the GA to reduce this value. We call this *Fitness Function 3* in this thesis. Although this approach is straight-forward with respect to suppressing the highest sidelobe power level, one of the main issues is that when the GA finds one point with the highest OOB power value in the whole optimization range, it will only try to reduce the the power value of this single point. Consequently, this will cause the OOB power values in the other positions to go up and the initial point will no longer be the point that has the highest OOB power value. Therefore, it is difficult to say whether this approach is the best way for GA to suppress OFDM sidelobe or not.

The fitness function is relatively simple compared to the other two approaches, although it requires additional computation complexity and memory. First, we need to calculate all the points in the optimization range and find the one which has the highest OOB power value. Sampling space should be small enough to make sure that we can get those peak points in their own sidelobes. Suppose the optimization range is M with $\frac{M}{2}$ at both sides of the spectrum, and the sampling space is m such that we need to calculate the OOB power value of $\frac{M}{m}$ points. We can calculate the OOB power level in the same way as in Eq. (3.4) and we can get sidelobe power value at the ith point as y_i. As a result, the final fitness function can be defined as:

$$y = \max(y_i), i = 1, 2, ..., \frac{M}{m}. \tag{3.6}$$

3.3   OFDM Transceiver Employing CCs with GA Framework for Sidelobe Suppression

A general schematic of the OFDM transceiver employing the proposed sidelobe suppression technique is shown in Figure 3.2. A high speed data stream, *d(n)* is modulated using *M-ary phase shift keying* (MPSK). The modulated data stream is

split into N slower data streams using a *serial-to-parallel* (S/P) converter. In the presence of primary user transmissions, which are detected using DSA and channel estimation techniques, the secondary OFDM user turns off the subcarriers in their vicinity resulting in a non-contiguous transmission. Of the remaining active subcarriers, a small fraction is used for cancelling out the OOB interference arising from the OFDM symbols used in the secondary signal transmission. GA framework is employed to determine the parameters of these cancellation carriers. The *inverse fast Fourier transform* (IFFT) is then applied to these modulated signals. A *cyclic prefix* (CP) whose length is greater than the delay spread of the channel is inserted to mitigate the effects of the *intersymbol interference* (ISI). Following the *parallel-to-serial* (P/S) conversion, the baseband OFDM signal is passed through the transmitters *radio frequency* (RF) chain, to amplify the signal and upconvert it to the desired frequency.

At the receiver, the reverse operations are performed, namely, mixing the bandpass signal to downconvert it to a baseband signal, then applying S/P conversion, discarding the cyclic prefix and applying *fast Fourier transform* (FFT) to transform the time domain signal to frequency domain. As the symbols over the cancellation carriers do not carry any information, they are discarded. After performing channel equalization and P/S conversion, the symbol stream is demodulated to recover the original high-speed input.

3.4   Simulation Results

Before we execute the GA, we should understand that for fitness functions of Eq. (3.3) and Eq. (3.5), the GA is not directly used to find the optimal solution for sidelobe suppression. Therefore, it is possible that for any of the two fitness functions above, the GA returns the best-possible solution for the result of the fitness function. However, this solution may not provide a good sidelobe suppression. Therefore, we need to run the GA several times for one fixed DC serial and choose the solution that gives the best sidelobe suppression value. Also, we know that the GA takes a long time to converge to a final solution, and we need to make a trade-off between the suppression we want to get and time it will take.

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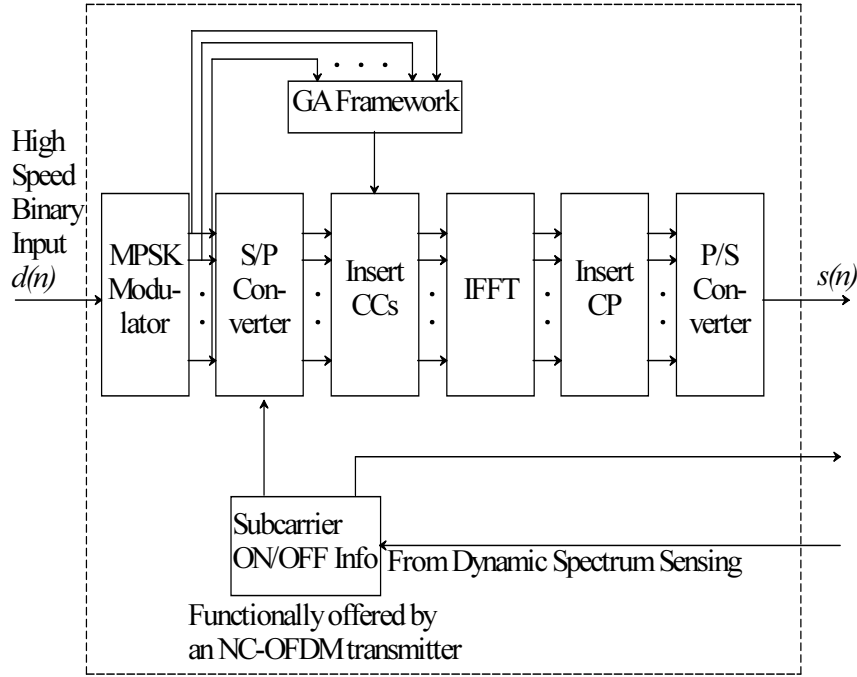
(a) An OFDM-based transmitter employing the CC technique with GA framework
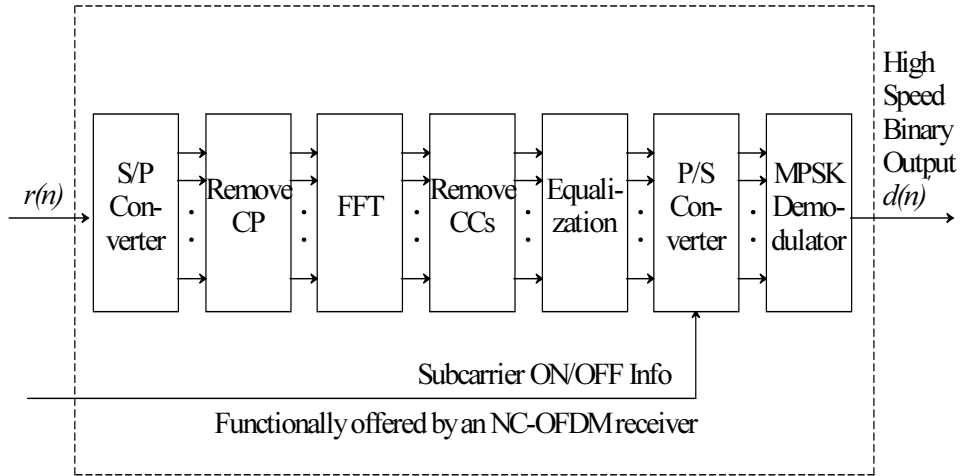
(b) An OFDM-based receiver employing the CC technique with GA framework

Figure 3.2: Schematic of an OFDM-based cognitive radio transceiver employing genetic algorithm for cancellation carriers technique for OFDM sidelobe suppression.

Since the sidelobe power reduction values from each GA process vary greatly, we need to perform a sufficient number of loops for a fixed DC to get the best-possible solution. For BPSK, when there are 64 DCs and 4 CCs (2 CCs on both sides of the OFDM spectrum) and all the amplitudes of the DCs are '1' for 20 populations, 100 generations, and 50 execution loops, we can get a 32.9001 dB [1] reduction and it takes 5.6237 s [2] for each loop. When we set the generations as 1000, we can get a 30.5233 dB reduction and for each loop it takes 56.6948 s. In this case, we got to know that fewer generations can give us a good enough sidelobe reduction and it greatly saves on execution time. Simulation results are obtained for all the other DC possibilities. Figure 3.3 shows the change of fitness value as GA is running. There are 69 variables here since the number of CCs is also a variable and here in this case we fix the number of CCs into four. The upper part of Figure 3.3 shows a final 39.012 dB sidelobe reduction. The lower part shows the final values of the variables, including amplitudes of 4 CCs and 64 DCs (all '1') and the number of CCs - four (fixed). As shown in Figure 3.3, when the amplitudes of DCs are all '1', GA reach the best solution after less than 20 generations. The left 80 generations do nothing but get the same result. So we need to set the number of GA generations to a best fit number which not only helps us to find the optimal solution, but also is formed within a reasonable amount of time. Finally we decided to set population size as 20, generation as 100, and run of 50 loops for each fixed DC amplitude sequence. In addition, note that GA in this paper is set to find the minimum result of fitness function, as shown in Figure 3.3.

Furthermore, in order to improve sidelobe reduction results and to save on execution time, we can use the results obtained from the original versions of the algorithms from the heuristic CC algorithm and the optimization-based CC algorithm as an initial population of GA [10]. In this way, the final suppression values based on these algorithms can be obtained. We can also know how much improvement we can make for these two algorithms and how good they are.

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[1]Genetic algorithm toolbox in MATLAB is used in the simulations.

[2]Time measurements in this thesis are calculated in MATLAB using "tic" and "toc" functions.
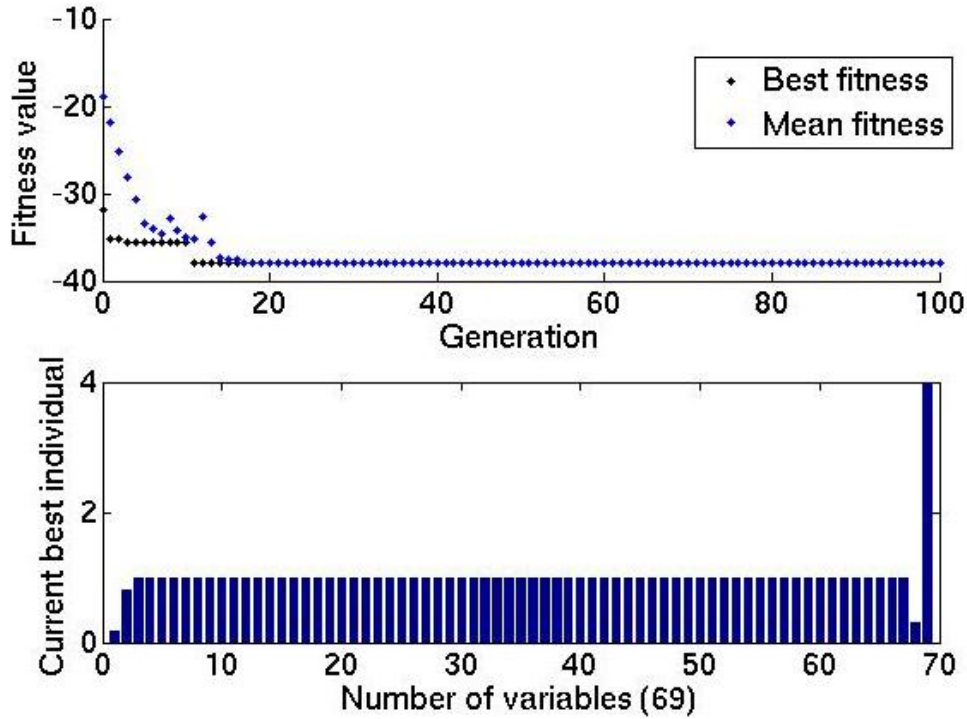
Figure 3.3: GA execution process for 64 DCs with all '1' amplitudes and 4 CCs.

Table 3.1: Comparison for 64 DCs with all '1' amplitudes and 4 CCs in execution time and sidelobe suppression

	Execution Time(s)	Reduction Value(dB)
GA with Fitness Function 1	5.6237	32.9001
GA with Fitness Function 2	21.674918	36.2892
GA with Fitness Function 3	24.224552	39.6330
The heuristic CC algorithm	0.579559	20.7937
The optimization-based CC algorithm	0.130298	38.9560

3.4.1 GA with Random Initial Population

First, the original algorithms from [6], [7] and the three GA implementations with different fitness functions are compared. Note that for the current GA approaches, the initial populations are not from the heuristic CC algorithm and the optimization-based CC algorithm, but random initial population.

Table 3.1 shows the results of execution time and reduction values for different

Table 3.2: Comparison for 64 DCs with randomly generated amplitudes (fixed) and 4 CCs in execution time and sidelobe suppression

	Execution Time(s)	Reduction Value(dB)
GA with Fitness Function 1	6.32636	8.2600
GA with Fitness Function 2	21.706329	9.2977
GA with Fitness Function 3	40.009986	9.4097
The heuristic CC algorithm	0.567055	9.3186
The optimization-based CC algorithm	0.325014	9.3149

Table 3.3: Average sidelobe suppression comparison for 100 different DCs amplitude sequences, each sequence consists of 64 DCs (amplitude randomly generated) and 4 CCs

	Average sidelobe reduction (dB)
GA with Fitness Function 3	11.7447
The heuristic CC algorithm	11.6411
The optimization-based CC algorithm	10.3924

approaches. With 64 DCs using all '1' amplitudes being considered and 2 CCs being inserted on each side of the spectrum, we set the population size as 20, the generation as 100, and execute 50 loops. For the execution time, we can find that the GA takes much more time than either pure algorithm. This is expected since the GA is more computationally complex than the other two algorithms and the number of generations decides the execution time. We can also find that the optimization-based CC algorithm is faster than the heuristic CC algorithm since the MATLAB function to solve linear least squares problems is executable function. If these two algorithms are implemented more fairly in other languages, such as C, the heuristic CC technique should be faster since it avoids complex computations in the optimization-based CC algorithm.

With respect to sidelobe reduction, we can see that the GA general approach yields the highest sidelobe suppression. Thus, compared to the other two original algorithms, the GA can provide the best solution for OFDM sidelobe suppression even with random initial population.

Table 3.2 is the results for a random generated DC amplitude serial. In this case, all five approaches are employed to the OFDM signals whose amplitudes of all subcariers are randomly generated using either '1' or '−1'. We see that the GA can still give us the best solution in all the approaches. Also, combined with Table 3.1, we can see that GA with general fitness function is the best among three different GA approaches. This has been proved in different tests using random DCs. However, the reduction value got from GA with general fitness function is only slightly better than the heuristic CC algorithm or the optimization-based CC algorithm.

Table 3.3 shows the comparison of different approaches using 100 different random DC amplitude serials. There are 64 DCs and 2 CCs on each side of OFDM spectrum. For the GA approach, we set the population size as 20 and generation size as 100 and each certain DC will execute 50 loops. The sidelobe reduction value is the average value for all different DC serials. We can see from Table 3.3 that the GA with general fitness function works the best, the heuristic CC algorithm is in the second place and the optimization-based CC algorithm is in the third place. Also, the advantage of GA compared to the heuristic CC algorithm is relatively small.

Figure 3.4 shows the effect of OFDM sidelobe suppression after employing 4 cancellation carriers with GA framework. The black lines represent the original OFDM spectrum and the blue lines represent the spectrum after CCs are inserted. An average value of 11.7447 dB sidelobe reduction is produced by using the GA with general fitness function. This shows that the CC technique employing a GA framework is effective in suppressing the OOB interference.

3.4.2   GA with Initial Population Seeds

Compared to either the heuristic CC algorithm or the optimization-based CC algorithm, the GA framework for CC is evidently slower. Using results from these two algorithms as the initial population of GA is a good way to save time and improve the suppression effect. In addition, in this way, GA can definitely get a better solution, which means we no longer need to do many loops for a fixed DC amplitude serial.

Figure 3.5 shows the *complementary cumulative distribution function* (CCDF)
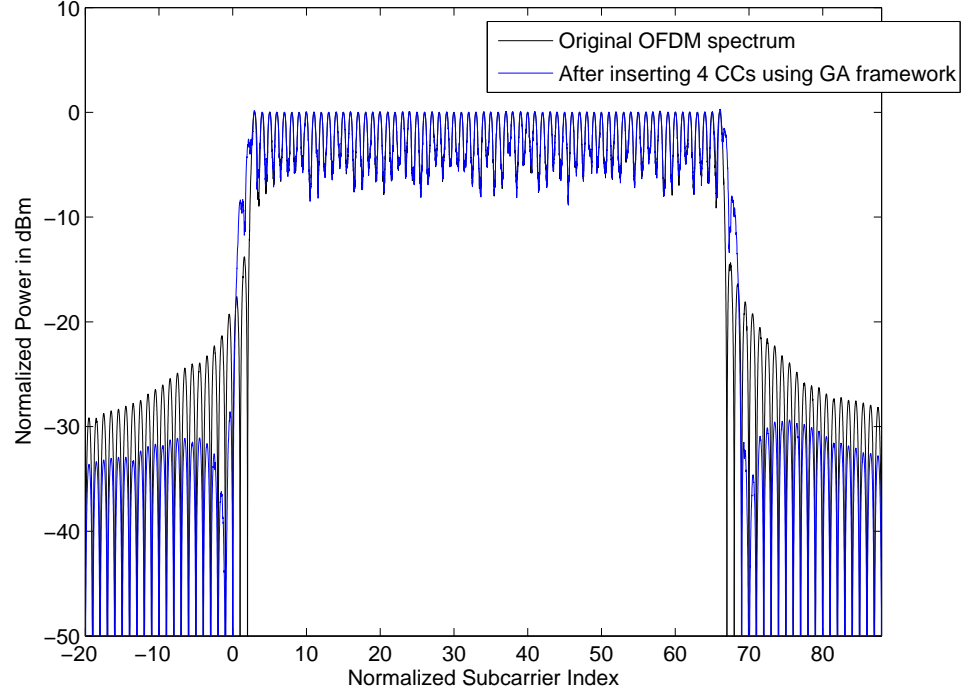
Figure 3.4: Averaged BPSK-OFDM spectrum with and without inserting cancellation carriers (CCs).

plot of the results for different approaches. From the left to the right are respectively GA based on heuristic algorithm results, original heuristic algorithm, GA based on optimization-based algorithm, original optimization-based algorithm. In this figure, a BPSK-OFDM system with 64 DCs and 4 CCs (2 CCs on each side) is considered. The simulations was performed over 100 different DC serials and the average condition is given. In this case, we choose a GA framework with general fitness function which can give us the best-possible solution among three fitness functions and we set the population size as 20 and generation as 100. From Figure 3.5, it can also be observed that by inserting two CCs on each side of the spectrum, the original heuristic CC algorithm performs better than the original optimization-based algorithm. After using GA and setting the results from these two algorithms as initial population, we can get better solutions. The GA using the results from the original heuristic algorithm as initial population performs the best and it can provide a tiny improvement over the original heuristic CC algorithm. After using the GA, the original optimization-based
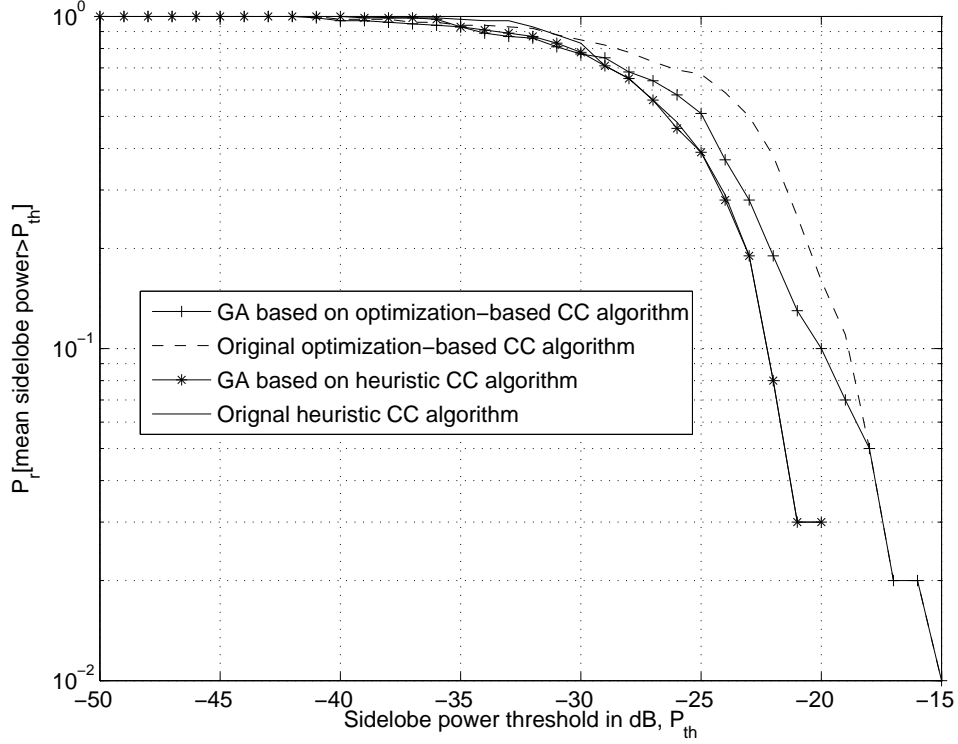
Figure 3.5: Complementary cumulative distribution function (CCDF) plot.

CC algorithm can be improved too, although it cannot be so good as using GA for the heuristic CC algorithm.

3.4.3 Combine CC with Data Throughput

Subsection 3.4.1 and Subsection 3.4.2 show that for the CC technique using GA framework, we can get the best solution among all existing CC techniques. Moreover, the GA is very flexible and we can put different numbers of CCs on each side of the OFDM spectrum. For the original heuristic algorithm and the original optimization-based algorithm, whenever one CC is added, we need to rewrite part of the codes, while using GA we can easily change the number of CCs since the number of CCs is also a variable in our fitness function. So we can investigate how many CCs we need to get the best sidelobe suppression. Suppose the total number of carriers is 16 and DC carriers have amplitude of all '1'. Using GA with general fitness function, we

can see that to get the best sidelobe suppression, we need to set more than 10 out of 16 carriers into cancellation carriers, which means when there are more CCs, we can get higher OOB power reduction. However, although we can get satisfying OOB power reduction, 10 out of 16 carriers are used for CCs is not acceptable at all, since so many CCs will greatly decrease the throughput.

So we need to find a trade-off between sidelobe suppression and data throughput. Using GA we can easily realize this. We can write a fitness function for throughput and combine fitness functions of CCs and throughput together. The fitness function of throughput is very simple and it can be expressed as the number of DCs multiplying the data each DC carries. Note we need to set initial weighing factors before simply adding these two fitness functions together since we need to make sure that the results of them are in the same order of magnitude. Still for totally 16 carriers including DCs and CCs, when we try to balance the two fitness functions, we will find that $4 - 5$ carriers are used for CCs and $68\% - 75\%$ carriers are used for signal transmission. If we put more emphasis on throughput, for example the throughput is twice as important as the sidelobe suppression, we can see that $3 - 4$ carriers will be used for CCs and $75\% - 81\%$ carriers will be used for signal transmission. Therefore, it is clear that by using the GA, we can easily get a decent OOB power reduction. In the meanwhile, the throughput can be restricted to be above a fixed goal.

3.5   Chapter Summary

In this chapter, the cancellation carriers technique for OFDM sidelobe suppression using genetic algorithms is proposed. Simulation results show that using genetic algorithm for cancellation carriers can achieve a significant reduction of the sidelobe power. Moreover, compared to other existing cancellation carriers algorithms, using genetic algorithm for cancellation carriers can provide the best solution with a cost of higher computation complexity. This high computation complexity can be solved by using look-up table which is stored in memory or just considering the subcarriers at the edge of the OFDM signal in stead of all the subcarriers since those in the center do not have much impact on the sidelobes. Finally, the genetic algorithm framework can

also conveniently help us to combine different techniques together, such as throughput to realize different requirements.

Chapter 4

Proposed Sidelobe Suppression Technique for NC-OFDM Signals Using Modulated Filter Banks and Cancellation Carriers

In this chapter, we propose a sidelobe reduction approach for NC-OFDM transmission systems that employing a combination of modulated filter banks and cancellation carriers technique. In particular, the filter banks serve to further isolate different frequency components of the secondary transmissions. Without loss in generality, we specifically choose raised-cosine filters for this work, where the center frequencies of these filters are modulated to the locations of NC-OFDM *data carriers* (DCs). The combination of modulated filter banks with the CC technique can provide a reduction in the sidelobe levels greater than the individual reductions of either technique. Furthermore, we developed an algorithm based on simulation results to determine the number of OFDM data carriers that can be transmitted in a given spectrum space.

4.1 Raised-cosine Filter

The raised-cosine filter is a good candidate to be used for OFDM sidelobe suppression due to its ability to minimize *intersymbol interference* (ISI) and relatively straightforward implementation. The ideal raised-cosine filter impulse response is defined as [11]:

$$h(t) = \text{sinc}\left(\frac{t}{T}\right) \frac{\cos\left(\frac{\pi \beta t}{T}\right)}{1 - \frac{4\beta^2 t^2}{T^2}} \tag{4.1}$$

where T is the reciprocal of the symbol rate.

The frequency response of an ideal raised-cosine filter consists of unity gain at low frequencies, a raised-cosine function in the middle frequencies, and significant attenuation at high frequencies. The width of the middle frequencies are defined by the roll-off factor β, where $0 < \beta < 1$. The term β is a measure of the *excess bandwidth* of the filter, *i.e.*, the bandwidth occupied beyond the *Nyquist bandwidth* of $\frac{1}{2T}$. Mathematically, the frequency response of a raised-cosine filter can be written as [12]:

$$H(f) = \begin{cases} T, & |f| \leq \frac{1-\beta}{2T}, \\ \frac{T}{2}\left[1 + \cos\left(\frac{\pi T}{\beta}\left[|f| - \frac{1-\beta}{2T}\right]\right)\right], & \frac{1-\beta}{2T} < |f| \leq \frac{1+\beta}{2T}, \\ 0, & \text{otherwise.} \end{cases} \tag{4.2}$$

However, usually one raised-cosine filter is employed to suppress OOB radiation. For an NC-OFDM system, this is insufficient due to the numerous disjoint transmission bands being used by a single transmission. Since there may be M spectral blocks of OFDM subcarriers that could be located anywhere in the frequency domain, we need M different raised-cosine filters at these locations. Using the Fourier Transform pair $h(t) \leftarrow \mathscr{F} \rightarrow H(f)$, we can modulate $H(f)$ to the center frequency f_c by multiplying h(t) by a factor of $e^{2\pi f_c t}$. Therefore, the new raised-cosine filter impulse response becomes:

$$h_{new}(t) = \text{sinc}\left(\frac{t}{T}\right) \frac{\cos\left(\frac{\pi \beta t}{T}\right)}{1 - \frac{4\beta^2 t^2}{T^2}} e^{2\pi f_c t} \tag{4.3}$$

and the frequency response is $H(f - f_c)$ based on Eq. (4.2).

4.2   Proposed Approach Employing Both Modulated Filter Banks and CCs

Modulated filter bank can be employed to enable NC-OFDM sidelobe suppression [13]. In an NC-OFDM system, the subcarriers are "on" or "off" based on the monitory results of the transmission spectrum [14]. This means that the subcarriers can only be "on" in unoccupied spectrum. A *filter bank* is an array of band-pass filters that separates the input signal into several components, each one carrying a single frequency subband of the original signal. These subbands can be recombined at the receiver to recover the original signal [15]. The filter bank serves to isolate different frequency components in a signal. In this work, we employ the raised-cosine filter as the prototype filter for our modulated filter bank. For an ideal raised-cosine filter, the frequency response is symmetric and the center frequency is located at zero. However, these raised-cosine filters need be modulated to the locations of the NC-OFDM DC blocks. Moreover, the original data will not be distorted by keeping a unified reciprocal of the data rate T for raised-cosine filters. In addition, we need to ensure that the spectrum is efficiently used and there is no interference with other transmissions. As a result, the sidelobe power of our signal must be suppressed to as low as -60 dBm for data transmission or -30 dBm for audio transmission at the edge of our OFDM spectrum.

For M different DC blocks, we need M raised-cosine filters, each one with a different center frequency and a different *bandwidth* (BW). Therefore, the frequency response of the ith raised-cosine filter is $H(f - f_{ci})$ based on Eq. (4.2).

Figure 4.1 shows the frequency response of two raised-cosine filters and four CCs for an NC-OFDM system. The dashed lines show two raised-cosine filters for two blocks of OFDM DCs and the solid lines are OFDM DCs (all one amplitude case) and sidelobes. Raised-cosine filters must be designed to make sure that they will not distort the OFDM DCs. CCs are inserted as the first step for sidelobe suppression and the two raised-cosine filters provide further optimization. We observe that *raised-cosine filter* 1 and *raised-cosine filter* 2 are modulated to the frequency locations
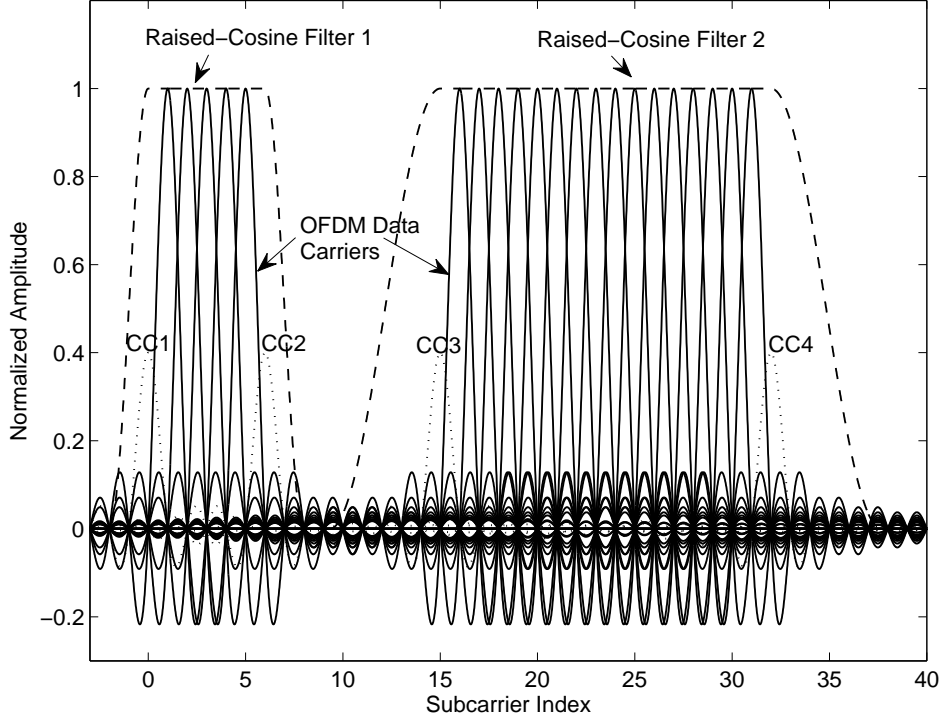
Figure 4.1: An illustration of proposed modulated raised-cosine filters implementation for spectrally non-continuous waveforms.

corresponding to the two non-contiguous blocks of DCs. The number of DCs is defined as N_{DC} and we can get that the bandwidth occupied by DCs is $(N_{DC} + 1)\pi$. The part of the raised-cosine filter that keeps a constant amplitude is designed to cover the whole DCs part, which means that $BW = \frac{1-\beta}{T}$ equals to $(N_{DC} + 1)\pi$. In addition, the amplitudes of this part of the raised-cosine filter need to be unified, which keeps DC amplitudes the same as before raised-cosine filters are applied. The OOB radiation is suppressed by the part of the raised-cosine filter that $|f - f_c| \geq \frac{1-\beta}{2T}$. Moreover, the number of the raised-cosine filters we need is the same as the number of OFDM DC blocks.

4.3   NC-OFDM Framework Using Proposed Approach

Inserting two CCs on each side of the OFDM spectrum, we know that a 5 dB to 15 dB sidelobe power reduction can be achieved based on the number of DCs [1]. The combination of modulated filter banks with the CC technique with a GA framework can provide a better suppression than using any of the technique alone.

A general schematic of the NC-OFDM transceiver is shown in Figure 4.2 employing both the CC technique and modulated filter banks. A high speed data stream, $d(n)$ is modulated using *M-ary phase shift keying* (MPSK). The modulated data stream is split into M slower data streams using a *serial-to-parallel* (S/P) converter. In the presence of primary user transmissions, which are detected using DSA and channel estimation techniques, the secondary OFDM user turns off the subcarriers in their vicinity resulting a non-continuous transmission. Of the remaining active subcarriers, a small fraction is used for cancelling out the OOB interference arising from the OFDM symbols used in the secondary signal transmission. The IFFT is then applied to these modulated signals. A *cyclic prefix* (CP) whose length is greater than the delay spread of the channel is inserted to mitigate the effects of the ISI. Following the *parallel-to-serial* (P/S) conversion, data streams are passed through M different raised-cosine filters based on the number of DC blocks M. The outputs of these raised-cosine filters are summed and then the baseband OFDM signal is passed through the transmitter's *radio frequency* (RF) chain, to amplify the signal and upconvert it to the desired frequency.

At the receiver, the reverse operations are performed, namely, mixing the bandpass signal to downconvert it to a baseband signal, then applying S/P conversion, discarding the CP and applying FFT to transform the time domain signal to frequency domain. As the symbols over the CCs do not carry any information, they are discarded. After performing channel equalization and P/S conversion, the symbol stream is demodulated to recover the original high-speed input.
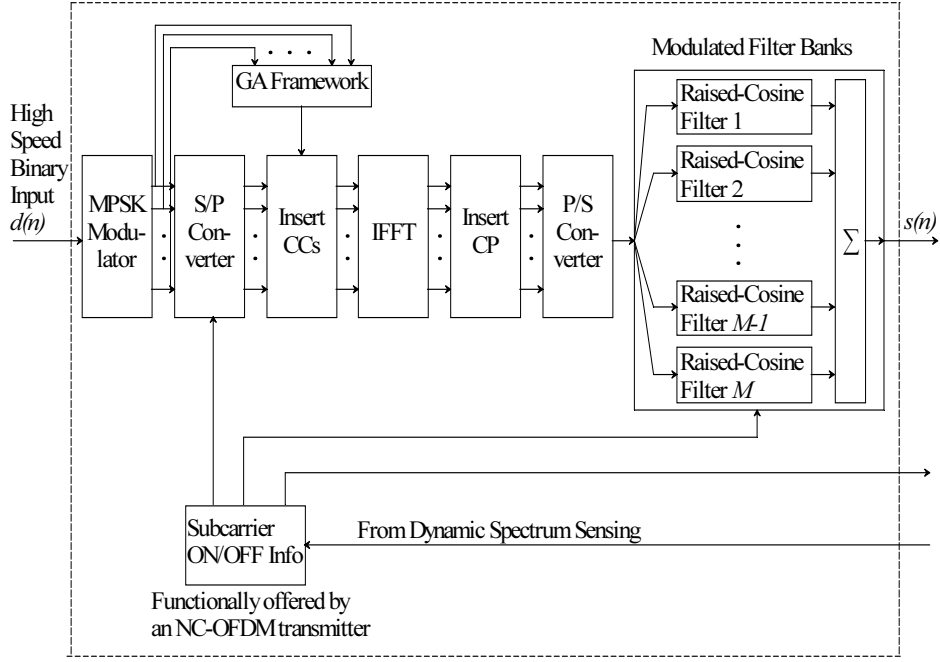
(a) An OFDM-based transmitter employing MFB and CC
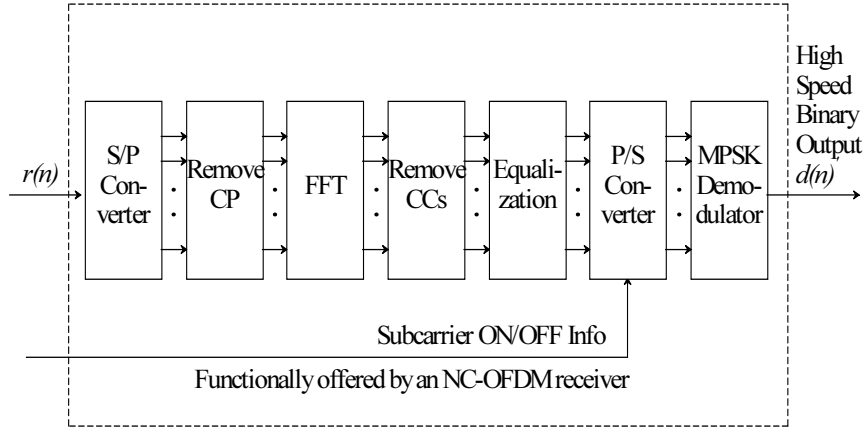
(b) An OFDM-based receiver employing MFB and CC

Figure 4.2: Schematic of an OFDM-based cognitive radio transceiver employing modulated filter banks and cancellation carriers technique for OFDM sidelobe suppression.

4.4 Simulation Results

Figure 4.3 shows the simulation results after employing modulated filter banks and the CC technique for a BPSK modulated NC-OFDM system. From the top down,

the first line is the original NC-OFDM spectrum and the second line represents the effect after inserting four CCs. The third line is the effect after using two raised-cosine filters with a roll-factor of 0.25 and the fourth line represents the results after using both modulated filter banks and the CC technique. There are two OFDM DC blocks and the first one has 25 DCs and the second one has 60 DCs. Based on the locations of these two blocks in the frequency axis, two raised-cosine filters are implemented by moving their center frequencies to required locations. If we only use the CC technique employing heuristic CC algorithm and there are two CCs inserted on each side of the OFDM blocks, there is a reduction of about 7 dB. If we only use two raised-cosine filters with $\beta = 0.25$, the sidelobe can be suppressed to $-60 \ dBm$ in a small spectrum space away from data carriers. It is clear that modulated filter banks performs much better than the CC technique because of the slope of the sidelobe power density decreases after using raised-cosine filters. Moreover, we can try to combine the CC technique and raised-cosine filters and simulation results show that this way contributes to a fantastic solution. For this combination, a even smaller spectrum space is needed for the sidelobe power to decrease to $-60 \ dBm$ and it performs better than only using raised-cosine filters, although the improvement is limited. In addition, if the system is for audio transmission, the combination provides a much better solution to suppress the sidelobe power down to $-30 \ dBm$.

We need a quantitative comparison between these different techniques. Figure 4.4 shows the simulation results. From the top down, the first line represents the original OFDM spectrum and the second line represents the effect after inserting four CCs. The third line is the effect after using two raised-cosine filters with a roll-factor of 0.25 and the last line represents the simulation results after using the combination of raised-cosine filters and the CC technique. The x-axis is the number of DCs and the y-axis represents the average spectrum distance away from DCs in subcarrier index for the sidelobe to go down to $-60 \ dBm$. The average value is produced from one hundred different combinations of amplitudes (BPSK modulation) for a fixed number of DCs. It is clear that for the original OFDM spectrum or even the OFDM spectrum after inserting CCs, too much space is needed in frequency domain for the sidelobe to be suppressed to $-60 \ dBm$. However, modulated filter banks can extremely decrease
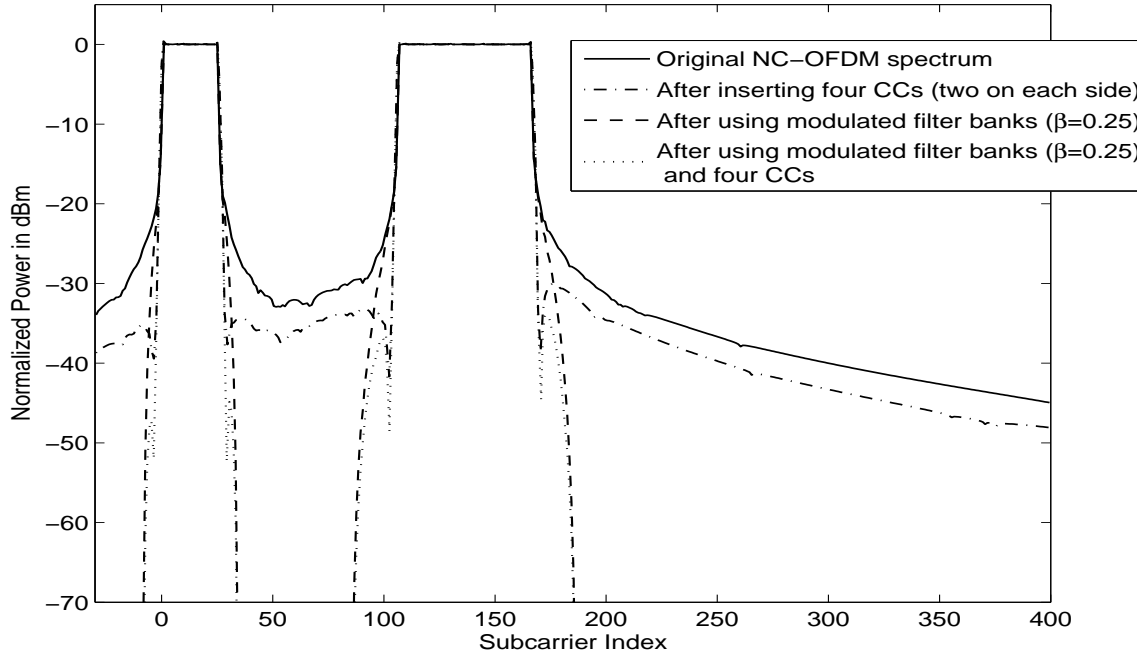
Figure 4.3: Normalized power spectrum of a BPSK-modulated NC-OFDM system.

the needed spectrum space for the sidelobe power to reach -60 dBm. Notice that in Figure 4.4 the lower two lines almost overlap, which means the simulation results for the pure raised-cosine filters and the the combination of raised-cosine filters and the CC technique is quite close. This makes sense since in Figure 4.3 we have already found that the combination of raised-cosine filters and the CC technique can provide only limited improvement over the pure raised-cosine filters for the sidelobe power going down to $-60 \ dBm$ or even lower.

4.4.1 Comparison of Different Number of CCs Combined with Modulated Filter Banks

The more cancellation carriers we use, the higher sidelobe suppression we can achieve [1]. We need to find out how the number of CCs combined with modulated filter banks influence OFDM sidelobe level. Figure 4.5 shows the comparison of different number of cancellation carriers combined with a raised-cosine filter with a roll
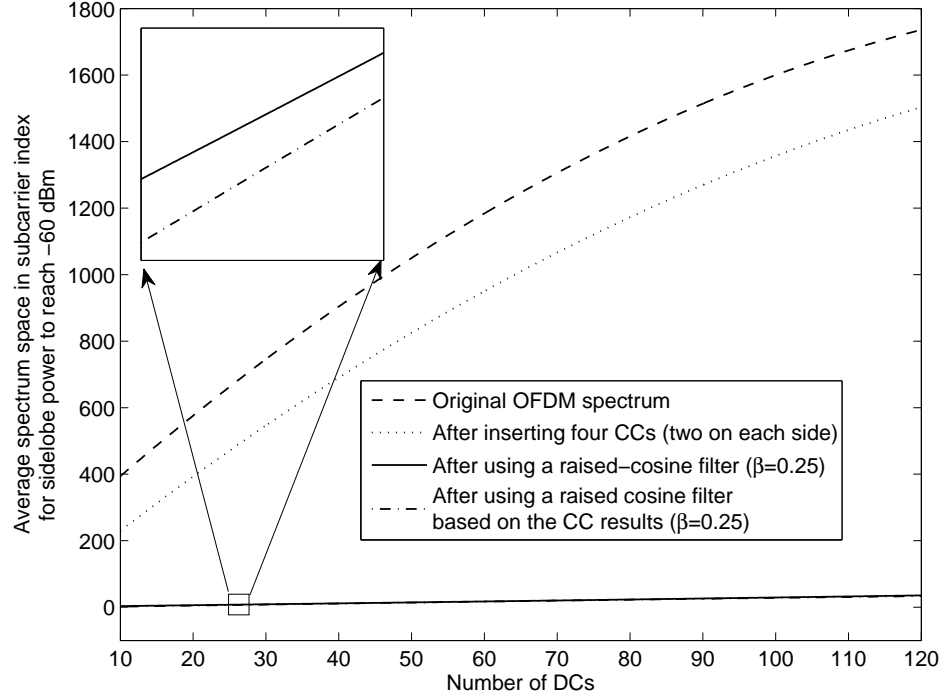
Figure 4.4: Comparison of the spectrum space in subcarrier index needed for sidelobe power reaching -60 dB in BPSK-modulated OFDM system.

off factor of 0.25. From the top down, the lines respectively represent original OFDM spectrum power, spectrum power after using only a raised-cosine filter, spectrum power after using a raised-cosine filter and 2 CCs, spectrum power after using a raised-cosine filter and 4 CCs, spectrum power after using a raised-cosine filter and 6 CCs, spectrum power after using a raised-cosine filter and 8 CCs. We can find that the more CCs we use, the lower sidelobe we will get. However, the spectrum space between the main OFDM spectrum and the $-70\ dBm$ sidelobe, which represents the unoccupied part of the spectrum, almost remains the same. Therefore, we should choose a reasonable number of CCs, such as 8 for 64 OFDM subcarriers which means the number of CCs is 12.5% of the number of OFDM subcarriers, in order to get a tradeoff between maximizing sidelobe reduction and decreasing bit error rate. As less power is available for data transmission, the *signal-to-noise ratio* (SNR) is decreased. When a larger amount of the transmission power is available for the CCs, a better
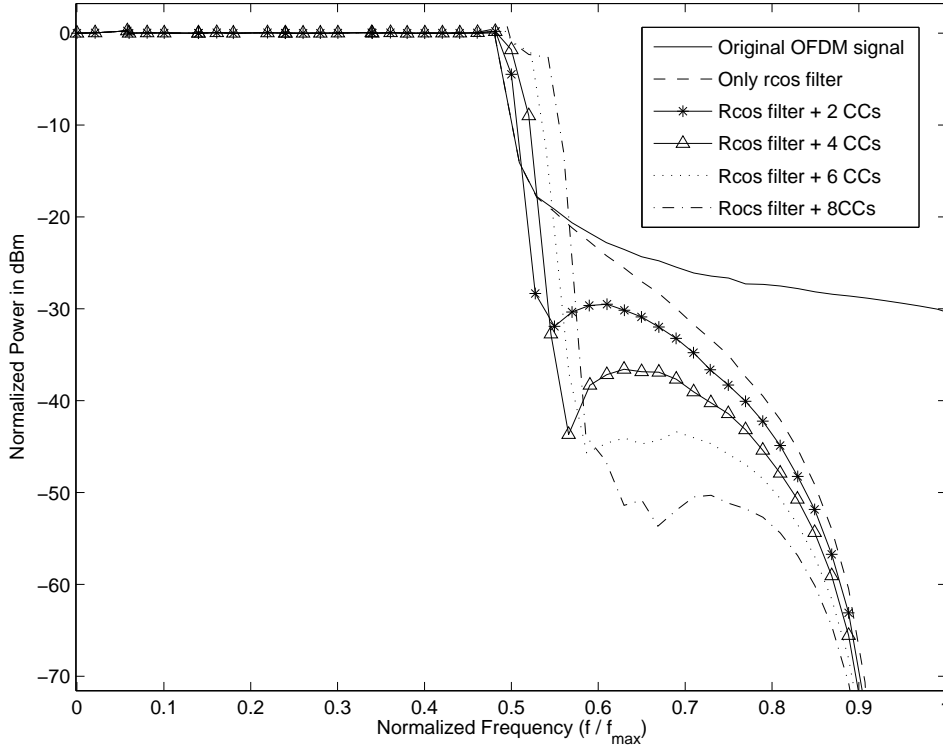
Figure 4.5: Comparison of different number of CCs combined with a raised-cosine filter with a roll off factor of 0.25.

Table 4.1: Comparison for different number of CCs combined with a raised-cosine filter with a roll off factor of 0.25

	-40 dBm	-55 dBm	-70 dBm
Optim-based (0CCs) + rcos filter	0.3	0.38	0.411
Optim-based (2CCs) + rcos filter	0.25	0.35	0.409
Optim-based (4CCs) + rcos filter	0.2	0.32	0.406
Optim-based (6CCs) + rcos filter	0.1	0.30	0.4
Optim-based (8CCs) + rcos filter	0.1	0.28	0.396

suppression is achieved, but at the same time system performance degrades.

Table 4.1 shows the effect of different number of CCs using optimization-based CC algorithm combined with a raised-cosine filter. The values represent the unoccupied normalized spectrum for the sidelobe to be suppressed to a certain value employing different number of CCs combined with a raised-cosine filter. We can find in Table
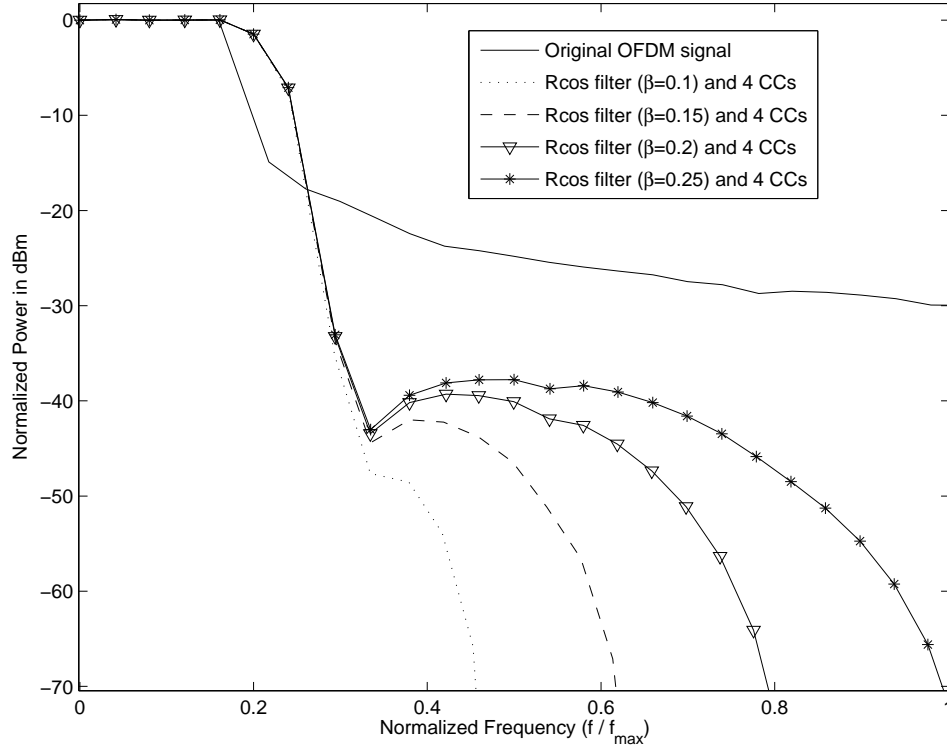
Figure 4.6: Comparison of the OFDM sidelobe power after employing raised-cosine filters with different roll off factors.

4.1 that the more CCs we use, the better performance we can achieve. The difference is especially clear when the sidelobe is only required to be suppressed to -40 dBm.

4.4.2 Comparison of Different Values of the Roll Off Factor of Raised-Cosine Filter

The roll off factor decides the bandwidth of the raised-cosine filter as well as the raised-cosine function at higher frequencies in frequency domain. Figure 4.6 shows how the roll off factor β influences the effect of sidelobe suppression. From the top down, the lines respectively represent spectrum power of the original OFDM spectrum, spectrum power after employing two CCs at each side and a raised-cosine filter with $\beta=0.25$, spectrum power after employing two CCs at each side and a raised-cosine filter with $\beta=0.2$, spectrum power after employing two CCs at each side and

Table 4.2: Comparison for different roll off factor values for a raised-cosine filter combined with 4CCs

	-40 dBm	-55 dBm	-70 dBm
Rcos filter β=0.25 + 4CCs	0.45	0.75	0.8
Rcos filter β=0.2 + 4CCs	0.3	0.55	0.6
Rcos filter β=0.15 + 4CCs	0.18	0.4	0.42
Rcos filter β=0.1 + 4CCs	0.15	0.25	0.24

a raised-cosine filter with β=0.15, spectrum power after employing two CCs at each side and a raised-cosine filter with β=0.1. The same as before, one hundred different BPSK-modulated OFDM amplitudes combination is simulated and the average result is shown. The amplitude of these subcarriers can be either '1' or '0'. In addition, two CCs are inserted at each side of the OFDM spectrum. In Figure 4.6, after comparing the first line with the other lines, we can clearly find that these two CCs produce higher sidelobe at the edge of OFDM main spectrum. After using a raised-cosine filter with different roll off factors, the effects of the sidelobe suppression are different. For example, when β is 0.25, we need about 80% of the whole normalized spectrum for the sidelobe power to be suppressed to -70 dBm. However, if β is 0.15, only 60% of the normalized spectrum is needed for the sidelobe power to be suppressed to -70 dBm. The smaller β is, the amount of the spectrum unoccupied because the sidelobe power needs to suppressed to -70 dBm is smaller. Nevertheless, a small roll off factor is not easy to realize in practice and when we design a raised-cosine filter for OFDM sidelobe suppression, we need to try our best to make the roll off factor as small as possible.

Table 4.2 compares the effect of different roll off factors combined with 4 CCs. The values in the table are the unoccupied normalized spectrum for the sidelobe to be suppressed to a certain value employing different roll off factors for a raised-cosine filter combined with 4 CCs. It is very clear that a raised-cosine filter with a smaller roll off factor works much better.

4.5 Proposed Algorithm Based on Simulation Results for NC-OFDM Transmissions

Since the combination of raised-cosine filters and the CC technique provides the best solution for sidelobe suppression, we can develop an algorithm based on simulation results to determine the number of OFDM DCs that can be transmitted in a given spectrum space based on DSA results.

4.5.1 Origination of the Proposed Algorithm

In Figure 4.7, x-axis represents the number of DCs and y-axis represents the spectrum space away from DCs in subcarrier index for sidelobe to reach -60 dBm after using both the CC technique and modulated filter banks. From the top down, the third line shows the average spectrum space in subcarrier index using both raised-cosine filters and the CC technique to suppress the sidelobe power to -60 dBm, which is the same as in Figure 4.4. However, in an NC-OFDM system, we need to make sure that the sidelobe power at the edge of our given spectrum should be at most -60 dBm. This means the interference with the other transmissions must be small enough for digital data transmission. Therefore, we need to consider the worst case and in this situation the OOB radiation is the highest in a fixed number of OFDM DCs. For BPSK-modulated OFDM, this means alternative '1's and '-1's , as shown in the second line from the top down in Figure 4.7. It is clear that the spectrum space needed for the worst case is larger than the average value. In order to make the whole algorithm simple and reduce high computation complexity, we decided to make approximate relationship between the number of DCs and the spectrum space needed to go down to -60 dBm in the sidelobe region for the worst case. After analyzing the simulation results, we can get:

$$d_1 = 0.3113 N_{DC} - 0.1795 \tag{4.4}$$

where d_1 represents the spectrum space away from OFDM DCs in subcarrier index needed to suppress the sidelobe power to -60 dBm and N_{DC} represents the number
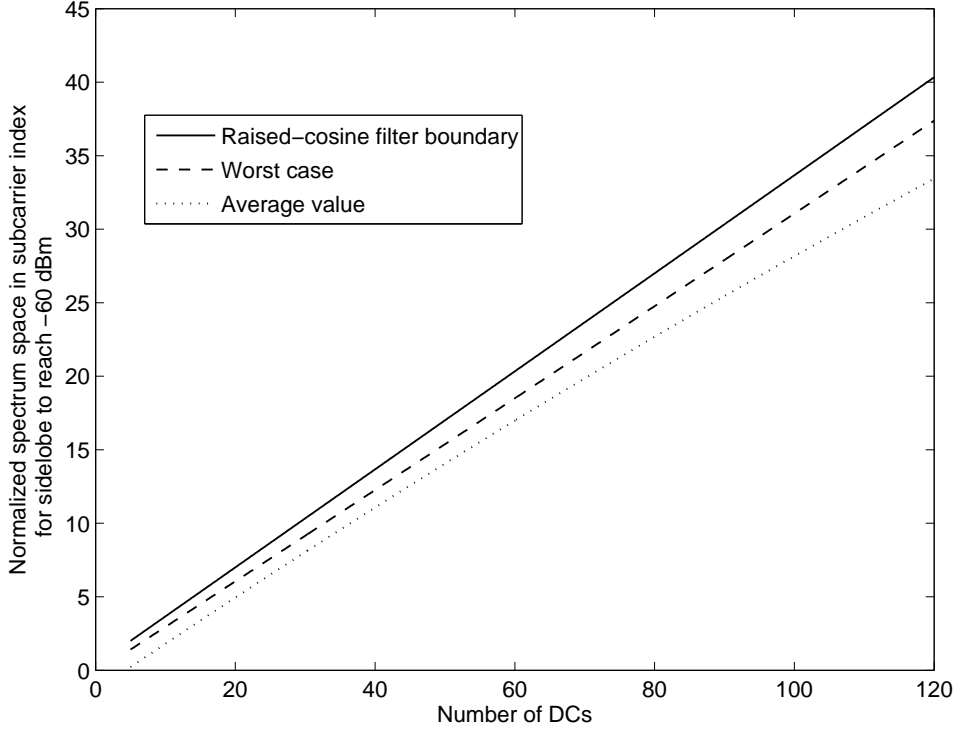
Figure 4.7: Spectrum space in subcarrier index vs the number of DCs.

of DCs.

Another concern is the raised-cosine filter boundary. For an ideal raised-cosine filter, when the frequency is high enough, the frequency response will go down to zero. Before that, there is a non-zero region in frequency domain that is used for sidelobe suppression in our case. The boundary is the point of intersection of these two regions in frequency domain. If the sidelobe power is suppressed to $-60\ dBm$ before the non-zero part of the raised-cosine filter goes to zero, the remaining part of this non-zero region will cause interference with other transmissions. This non-zero region may decrease the signal power of other transmissions since the amplitude of this region of raised-cosine filters is designed to between zero and one. To achieve zero interference, the boundary of raised-cosine filter should be in our given spectrum space.

For a raised-cosine filter, we already know the bandwidth that covers DCs is

$\frac{1-\beta}{T} = (N_{DC} + 1)\pi$. Therefore, we can get the following relationship:

$$T = \frac{1 - \beta}{(N_{DC} + 1)\pi}. \tag{4.5}$$

The spectrum space in subcarrier index between the raised-cosine filter edge and OFDM DCs' edge is $\frac{1+\beta}{2T} - \frac{1-\beta}{2T} = \frac{\beta}{T}$. Using Eq. (4.5), the spectrum space between the raised-cosine filter boundary and DCs' edge can be given as

$$d_2 = \frac{\beta}{1 - \beta}(N_{DC} + 1). \tag{4.6}$$

This relationship is shown in the first line in Figure 4.7 from the top down.

We can also find that the first line and the second line will intersect at some points in Figure 4.7. Therefore, in the algorithm we need to consider both the raised-consine filter boundary case and the worst case for the sidelobe power to be suppressed to -60 dBm. Suppose our given spectrum in subcarrier index is D, and then we know $D = 2d + N_{DC} + 1$, where d represents the spectrum space away from DCs in subcarrier index needed to suppress the sidelobe power to -60 dBm. Using Eq. (4.4) or Eq. (4.6), we can determine the number of DCs based on the already known spectrum space. For Eq. (4.4) and Eq. (4.6), the one provides a smaller value of the number of DCs will be chosen in the algorithm.

4.5.2 Flow Chart of the Proposed Algorithm

Figure 4.8 shows the flow chart of the proposed algorithm. First, DSA results provide the usage situation of the whole spectrum and we get to know that there are M spectrum spaces unoccupied, where we can transmit our OFDM signal. Suppose each of the occupied spectrum space has a bandwidth of D_i, where $i = 1, 2, ..., M$. The algorithm will employ M different raised-cosine filters and modulate them in the frequency domain to the required locations based on DSA results. For the ith spectrum space, given the bandwidth D_i, the algorithm will use both Eq. (4.4) and Eq. (4.6) to calculate the number of DCs. The smaller number got from these two equations will be chosen to make sure there is no interference with other transmissions. After the proposed algorithm is applied, the signal will be passed through the blocks shown in Figure 4.2.
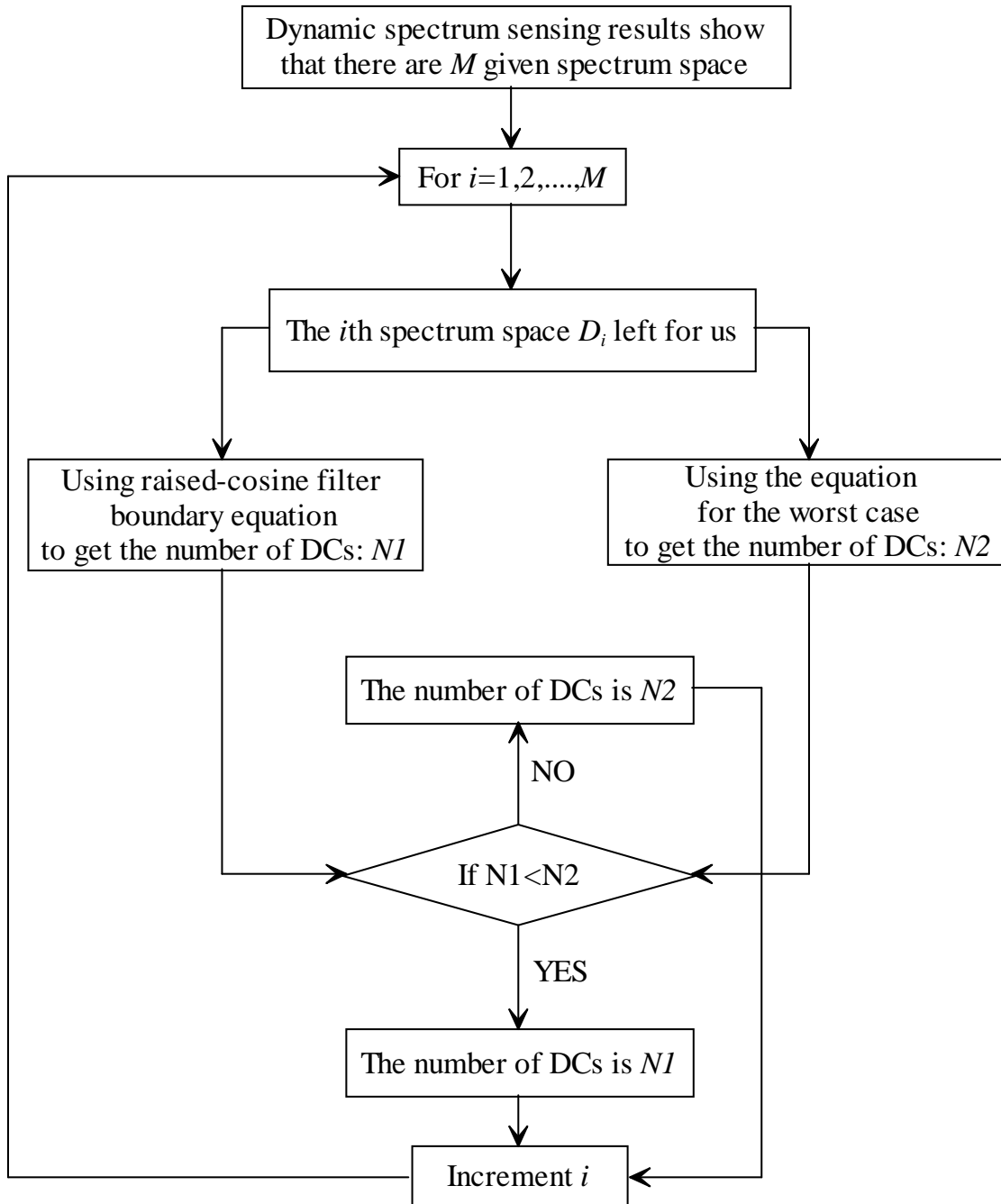
Figure 4.8: The proposed algorithm to determine the number of OFDM data carriers that can be transmitted in a given spectrum space.
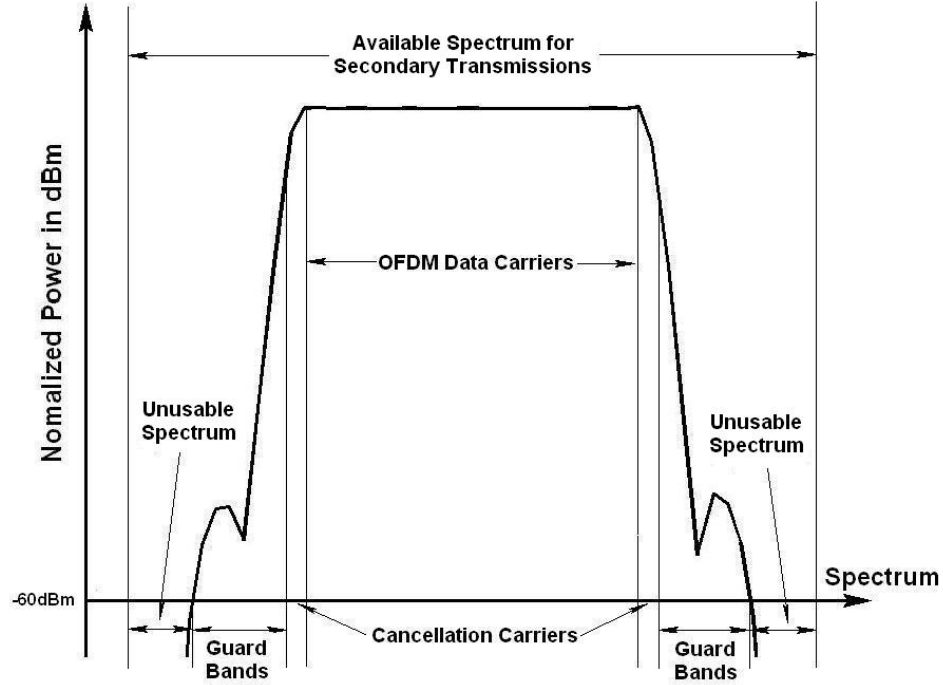
Figure 4.9: The compositions of the given spectrum, including OFDM DCs, 4 CCs, guard bands and unusable spectrum.

4.5.3 Simulation Results after Using the Proposed Algorithm for OFDM Sidelobe Suppression

Figure 4.10 shows the simulation results after using the proposed algorithm in a BPSK-modulated NC-OFDM system. The NC-OFDM signal is transmitted in the given spectrum space and the sidelobe power at the edge has been suppressed to below -60 dBm (shown as "*" in the figure). In Figure 4.10(a) there are two spectrum spaces to transmit NC-OFDM signal and in Figure 4.10(b) there are three. The proposed algorithm automatically choose the number of OFDM DCs that can be transmitted in each spectrum space. The rectangular part of the spectrum is the spectrum occupied by other transmissions, e.g. first users, and the spectrum space left is used for us to transmit NC-OFDM signal. At the edge of the given spectrum, the sidelobe power is suppressed to at most -60 dBm. The "*" point in Figure 4.10 shows the boundary between our NC-OFDM signal transmissions and transmissions of other users and
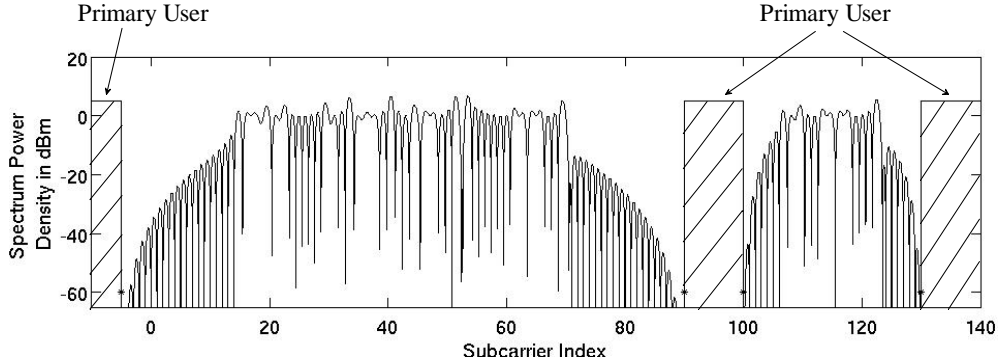
(a) NC-OFDM transmission in two non-continuous spectrum spaces.
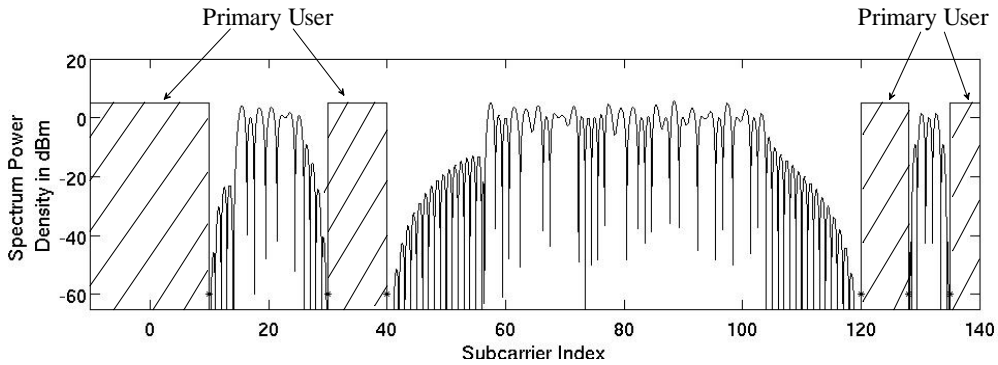
(b) NC-OFDM transmission in three non-continuous spectrum spaces.

Figure 4.10: The frequency response after using the proposed algorithm for a BPSK-modulated NC-OFDM system.

we can find that the spectrum power is suppressed to at most -60 dBm. Based on simulation results, 60% in average of the spectrum space will be used to transmit OFDM signals and the left spectrum are used for cancellation carriers, guard bands and a small part of waste. Figure 4.9 shows the components of our given spectrum after using the proposed algorithm to determine the number of OFDM DCs. The proposed algorithm only considers the worst case or the boundary of the raised-cosine filter, which means that generally there is a small part of the spectrum, called unusable spectrum, wasted. In the middle are OFDM DCs with 2 CCs on the left and right hand side and the number of the DCs is determined by the algorithm. After using modulated filter banks and the CC technique, some spectrum space called guard bands is needed to make sure the spectrum power density is suppressed to -60 dBm.

The spectrum left are the unusable part which is a waste. The unusable spectrum occupies 4% in average of the whole given spectrum space. This value is calculated using one hundred different random combinations of DC amplitudes (1 and -1 for BPSK modulation) based on a fixed number of DCs. This unusable can also be seen in Figure 4.7 as the difference between the average value and the bigger spectrum space needed in the other two cases. This waste is necessary since we need to make sure that our transmissions will not interfere with the neighboring transmissions. Although our algorithm is simple in order to reduce high computation complexity, it does provide a good solution for NC-OFDM application in a shared spectrum. More importantly, there is no interference with other transmissions at the cost of a waste of a small part of the given spectrum in the spectrum allocation policy.

4.6   Chapter Summary

In this chapter, the modulated filter banks approach for OFDM sidelobe suppression is proposed. Moreover, the combination of modulated filter banks and the cancellation carriers technique is applied. Simulation results show that using these two techniques can achieve a significant reduction of the sidelobe power and by changes the parameters, such as the number of cancellation carriers, the value of roll off factors, we can achieve an optimum solution. Finally, based on the simulation results, an algorithm is developed to determine the number of OFDM data carriers that can be transmitted in a given spectrum space in a spectrum sharing policy.

Chapter 5

Adaptive Allocation Combined With Sidelobe Suppression for OFDM-based Cognitive Radio Systems

Although the modulation and demodulation stages of a *multi-carrier modulation* (MCM) system are usually more complex relative to a single carrier system, MCM systems possess a number of advantages due to their "divide-and-conquer" nature in the frequency domain by transmitting the data across the channel at a lower data rate in several frequency subcarriers, and the process of distortion compensation can be made simpler by treating each subcarrier separately [20]. Since the channel usually does not have a flat frequency response, it is easier to compensate for the channel distortion on a per-subcarrier basis rather than on the entire received signal. Moreover, since the channel distortion may not be equivalent for all subcarriers, adapting the transmission parameters per subcarrier (*i.e.*, signal constellation and transmit power levels) would allow for increased throughput while guaranteeing a prescribed error performance. For instance, by subdividing a frequency-selective fading channel frequency response into a collection of relatively flat subchannels, each subchannel then has a different amount of distortion and a different instantaneous SNR value. Power

loading is one method for improving system performance by tailoring the subcarrier power levels, thus changing the subcarrier SNR and BER values. Another method called bit loading is to assign different number of bits into different subcarriers to realize objectives, such as throughput maximization while the constraint could be a prescribed upper bound on the mean BER. Since the effectiveness of these loading algorithms are heavily dependent on the quality of the channel state information, power allocation is usually performed in tandem with bit allocation. In addition, as we know from Chapter 2, out-of-band radiation is always a problem for OFDM-based cognitive radio systems. In this chapter, a combined optimization employing power loading, bit loading and sidelobe suppression is proposed. In the following two sections, two popular types of allocation algorithms, power loading and bit allocation, are introduced.

5.1 Power Loading

Power allocation is a powerful technique for enhancing system performance when the multicarrier system operates in a frequency selective fading channel. A frequency selective channel combined with additive white noise will yield varying SNR values across frequency. In this situation, the allocation of a non-uniform amount of power across the transmission spectrum could yield an increase in performance. In the context of multicarrier systems, the modification of the transmit power levels can be performed on a subcarrier basis rather than in a continuous fashion across frequency.

There exist a substantial number of power allocation algorithms for multicarrier systems, most of which employ a total power constraint, *i.e.*,

$$\pi_{total} = \sum_{i=0}^{N-1} \pi_i, \tag{5.1}$$

where π_{total} is the total power allowed for the system. This implies that for any subcarrier that is "switched off" or nulled, the power that was allocated to it can be transferred to the remaining active subcarriers. However, such a strategy can result in a possible violation of regulatory requirements for the frequency band of operation [20].
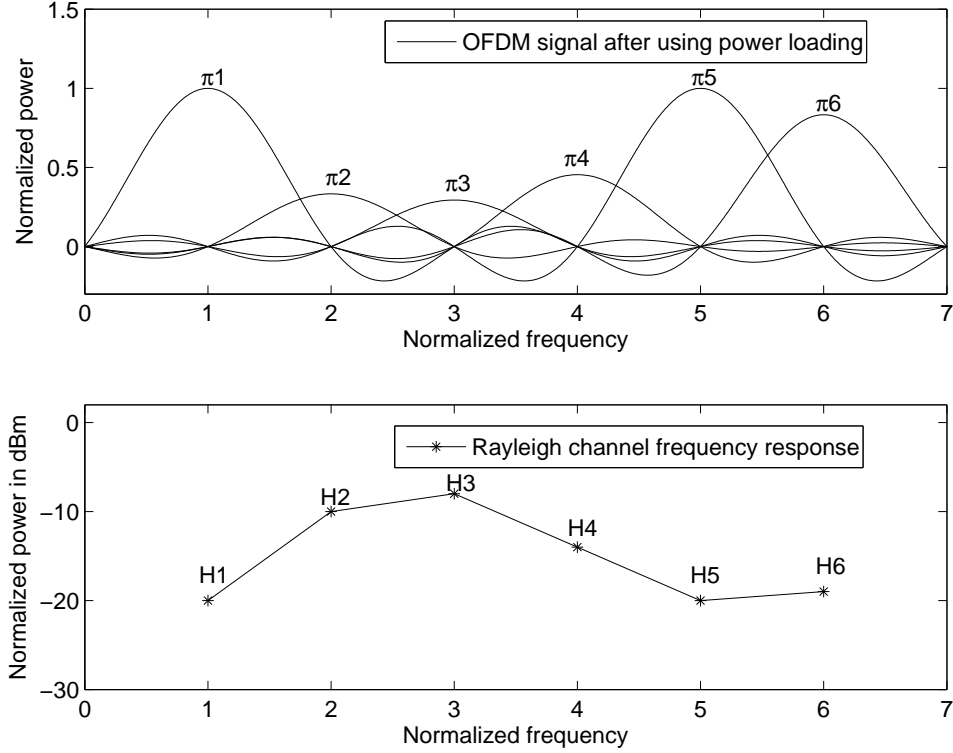
Figure 5.1: Illustration of power loading for OFDM systems given channel information.

Suppose the channel is subdivided into N disjoint approximately flat subchannels with complex gains $H_i, i = 0, ..., N - 1$. Furthermore, let the transmit power level for the subcarriers be specified as $\pi_i, i = 0, ..., N - 1$. Therefore, if the additive noise is white with variance σ^2 and the equalizer at the receiver is a single complex gain per subcarrier, the SNR of subcarrier i can be defined by:

$$\gamma_i = \frac{\pi_i |H_i|^2}{\sigma^2}, \tag{5.2}$$

where γ_i is the SNR of the ith subcarrier and $|H_i|^2 \leq 1$ is always true due to path loss [20]. In addition, for OFDM-type systems with a sufficiently long cyclic prefix, Eq. (5.2) becomes increasingly accurate as N increases. However, for other multicarrier schemes, this approximation may be less accurate if other sources of distortion, such as ISI, are not adequately suppressed.

Figure 5.1 shows how power loading works. In the lower part of Figure 5.1, one
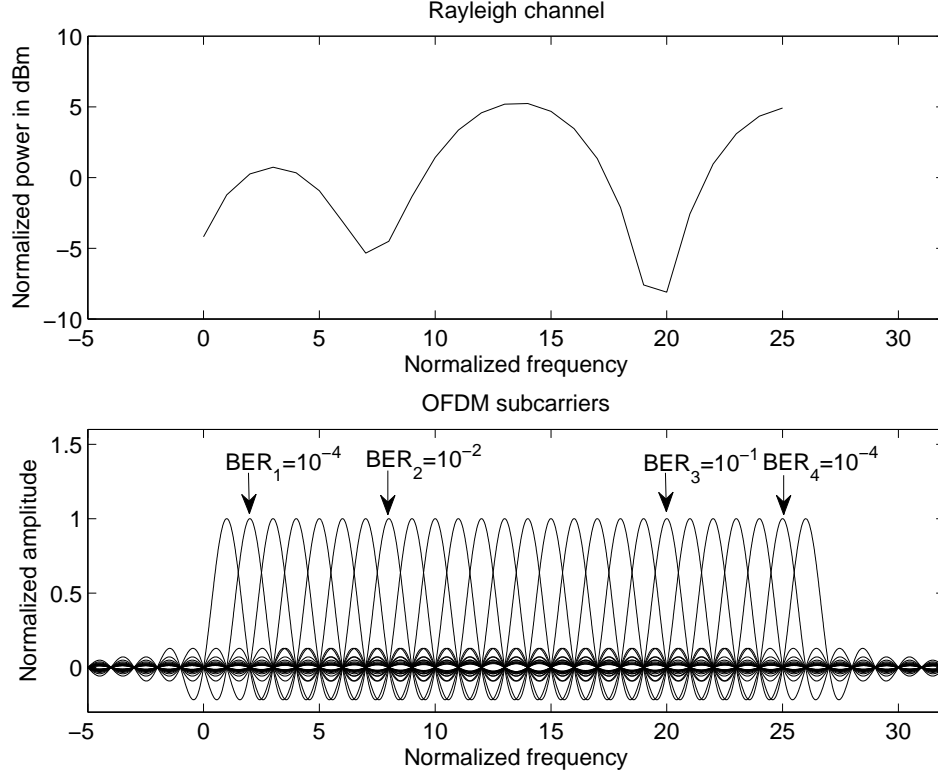
Figure 5.2: Illustration of bit loading for OFDM systems given channel information.

snapshot of the frequency response of a Rayleigh channel is shown. The upper part shows the OFDM subcarriers after using power loading. We can find that in order to maintain a constant SNR, higher power of OFDM subcarrier is needed where the the channel is more attenuated. In the same way, lower power of OFDM subcarriers is needed where the channel response is higher.

5.2   Bit Allocation

Most OFDM systems use the same signal constellation across all subcarriers, where the commutator allocates bit groupings of the same size to each subcarrier. However, their overall error probability is dominated by the subcarriers with the worst performance [20]. To improve performance, adaptive bit allocation can be employed, where the signal constellation size distribution across the subcarriers varies according to the

measured *bit error rate* (BER) values. In extreme situations, some subcarriers can be turned off or nulled if the subcarrier BER values are poor. The term *bit allocation*, also known as *bit loading* or *adaptive modulation*, defines a process for assigning a modulation scheme to each subcarrier, given a set of available modulation schemes, to achieve a performance objective while satisfying some prescribed constraint. For example, the objective could be throughput maximization while the constraint could be a prescribed upper bound on the mean BER.

Figure 5.2 shows why bit loading is necessary. One snapshot of a given frequency-selective channel is shown in the upper part of Figure 5.2. If we assign the same of bits to each OFDM subcarrier, which means each subcarrier uses the same modulation scheme, we can find the *bit error rate* (BER) values for different subcarriers are different. Due to the impact from the channel, the subcarrier BER is affected and the subcarriers that have high BERs are excluded if necessary, to keep the overall system performance in good condition. In Figure 5.2 some subcarriers have BER values as high as 10^{-2} and these subcarriers should be assigned lower bits to improve the performance, or their high BER values will greatly influence the performance of the whole system.

5.3   Proposed Combined Approach For Power Loading, Bit Loading and Sidelobe Suppression

We can combine power loading, bit allocation and sidelobe suppression for OFDM-based cognitive system. As shown in Algorithm 1, first, we need to find out the power threshold that can be assigned to each sidelobe. Notice that the center OFDM subcarriers have much lower impact on the OFDM OOB radiation than those at the edge, as shown in Figure 5.3. The result in Figure 5.3 is produced after randomly generating 1000 different OFDM subcarrier sequences and the average result is shown. Suppose N_{DC} is the total number of OFDM subcarriers. When the amplitudes of the $N_{DC}/2$ subcarriers in the center are ten times bigger and the other subcarriers hold the line, the sidelobes only sightly increase. However, when the amplitudes of the

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Algorithm 1 Proposed algorithm employing power loading, bit allocation and side-lobe suppression for OFDM-based cognitive radio systems.

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1. Given one snapshot of the frequency selective fading channel, find the power threshold that can be assigned to each subcarrier.

2. Assign different power levels to different subcarriers so that the SNR is constant more or less given that $\pi_i < \pi_{\tau i}(i = 1, 2, ...)$.

3. Assign different number of bits to different subcarriers to maximize the throughput given that $BER_i < BER_\tau(i = 1, 2, ...)$.

4. Use modulated filter banks to suppress the out-of-band radiation of OFDM signal.
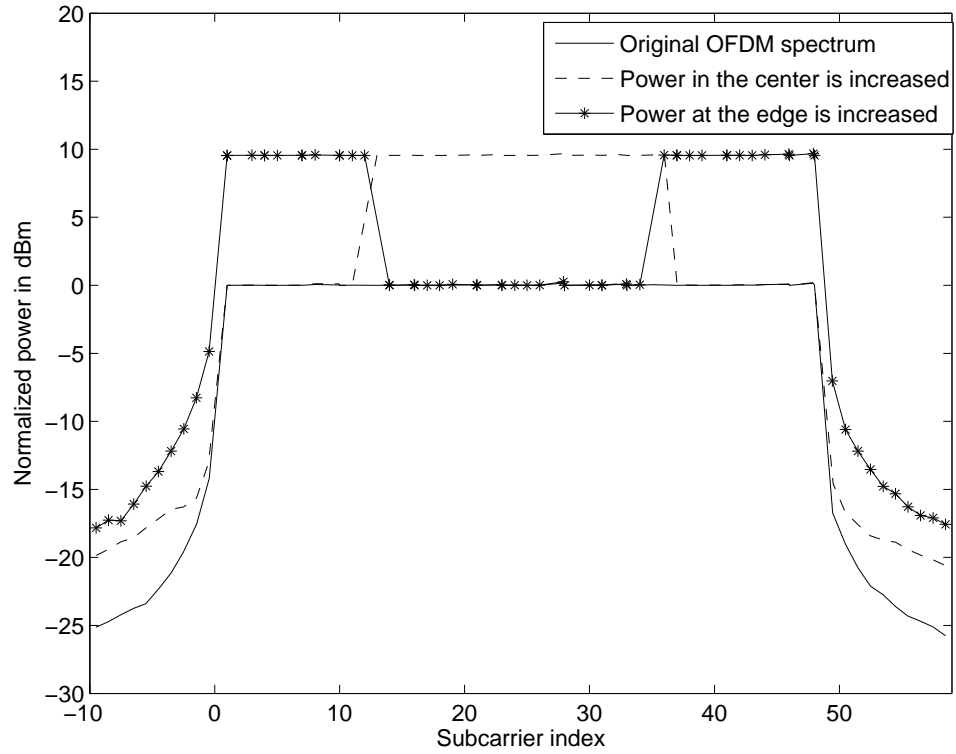

Figure 5.3: Illustration of the influence of sidelobe if part of the OFDM subcarriers have higher power than others.

$N_{DC}/2$ subcarriers at the edge are ten times bigger and the other subcarriers hold the line, the out-of-band radiation substantially increases. In addition, the first and second sidelobes increase a lot if the amplitudes of subcarriers at the edge of the
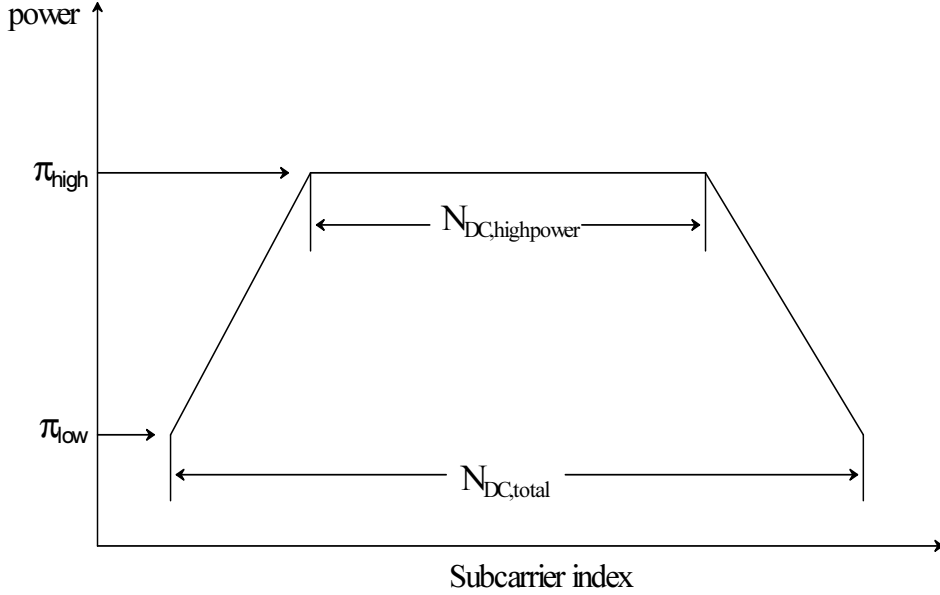
Figure 5.4: The threshold for power loading.

OFDM spectrum increase. This will greatly reduce the effect of sidelobe suppression using modulated filter banks. Thus, when the power of the subcarriers at the edge of the OFDM spectrum is increased, it produces much higher sidelobe than that if the power of the subcarriers in the center is increased. Based on this fact, the center subcarriers can be assigned more power than those at the edge. We designed a trapezoid threshold in which the center subcarriers can have higher power than those at the edge, as shown in Figure 5.4. The ratio between the highest power and the lowest power is defined as k and $k = \frac{\pi_{high}}{\pi_{low}}$. The value of k cannot be too high, or those signal which has lower power may be clipped. In addition, the ratio between the number of OFDM subcarriers that have highest power level $N_{DC,highpower}$ and the total number of OFDM subcarriers $N_{DC,total}$ is defined as μ and $\mu = \frac{N_{DC,highpower}}{N_{DC,total}}$. This value is also an important factor that can determine the OOB radiation situation of OFDM signals and influence the sidelobe suppression effect.

Then we can assign power to different OFDM subcarriers based on Eq. (5.2) and those have the lowest channel frequency response are assigned the most amount of power in order to keep a constant SNR. However, due to the power threshold, any

power that is higher than the threshold should be reduced. Therefore, the SNR values of different subcarriers cannot be exactly the same, but the difference between the minimum value and the maximum value can be reduced. In addition, the OFDM subcarriers at the center can be assigned more power than others, since they will not cause much increasing of OOB radiation.

Third, we begin to assign different number of bits into each subcarrier using bit allocation. We want the throughput as high as possible, which means that the total number of bits that are assigned to all subcarriers as high as possible. However, we cannot afford too high BER value. The subcarrier that has the highest BER will dominate the system performance. So those subcarriers that have high BERs need to reduce the order of modulation scheme, such as from 16-QAM to 4-QAM, to maintain a reasonable BER. To compute the probability of bit error for all subcarriers, closed-form expressions are employed. For instance, the probability of bit error for BPSK is given by:

$$P_{2,i}(\gamma_i) = Q(\sqrt{2\gamma_i}) \tag{5.3}$$

while the probability of symbol error for QPSK (M_i=4), square 16-QAM (M_i=16), and square 64-QAM (M_i=64) is given by:

$$P_{M_i,i}(\gamma_i) = 4(1 - \frac{1}{\sqrt{M_i}})Q(\frac{3\gamma_i}{M_i - 1})(1 - (1 - \frac{1}{\sqrt{M_i}})Q(\frac{3\gamma_i}{M_i - 1})) \tag{5.4}$$

where $log_2(M_i)$ gives the number of bits to represent a signal constellation point. To obtain the probability of bit error from the symbol error of Eq. (5.4), we can use the approximation $P_i \approx P_{M_i,i}/log_2(M_i)$ [20].

Finally, modulated filer banks can be used to suppress the high OOB radiation of OFDM signal to make sure that there is no interference with other neighboring transmissions. The detailed information about implementation of modulated filter banks has been discussed in Chapter 4.
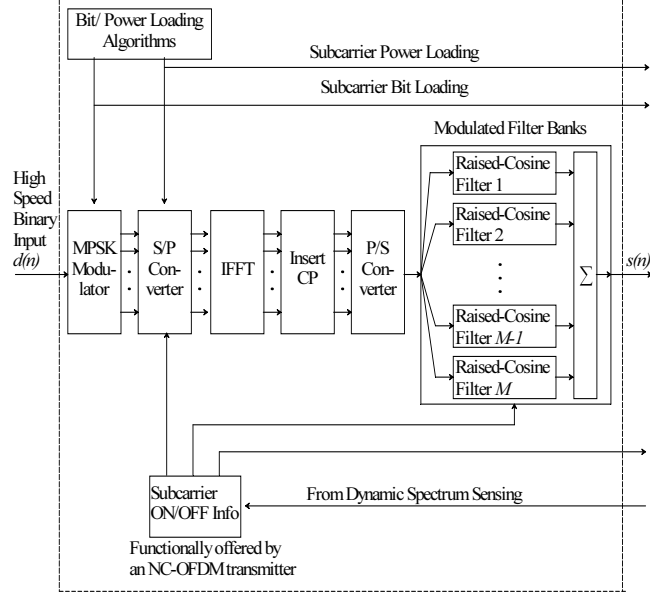
5.4   System Framework

Figure 5.5 shows a general schematic of an OFDM-based cognitive radio transceiver employing sidelobe suppression, power loading and bit allocation. A high speed data

stream, *d(n)* is modulated using *M-ary phase shift keying* (MPSK). The modulated data stream is split into N slower data streams using a *serial-to-parallel* (S/P) converter. Bit loading and power loading is used here to determine the power level of each subcarrier and the number of bits each subcarrier can be assigned. In the presence of primary user transmissions, which are detected using *dynamic spectrum access* (DSA) and channel estimation techniques, the secondary OFDM user turns off the subcarriers in their vicinity resulting in a non-contiguous transmission. The *inverse fast fourier transform* (IFFT) is then applied to these modulated signals. A *cyclic prefix* (CP) whose length is greater than the delay spread of the channel is inserted to mitigate the effects of the *intersymbol interference* (ISI). Following the *parallel-to-serial* (P/S) conversion, data streams are passed through M different raised-cosine filters based on the number of OFDM DC blocks M. The outputs of these raised-cosine filters are summed and then the baseband OFDM signal is passed through the transmitter's *radio frequency* (RF) chain, to amplify the signal and upconvert it to the desired frequency.

At the receiver, the reverse operations are performed, namely, mixing the bandpass signal to downconvert it to a baseband signal, then applying S/P conversion, discarding the CP and applying *fast fourier transform* (FFT) to transform the time domain signal to frequency domain. After performing channel equalization and P/S conversion, the symbol stream is demodulated based on bit loading and power loading information to recover the original high-speed input signal.

5.5   Simulation Results

Figure 5.6 shows the simulation results for power loading and sidelobe suppression. Figure 5.6(a) shows one snapshot of the frequency response of a Rayleigh channel. This frequency-selective fading channel is a slow time-varying channel and it is produced using MATLAB built-in function based on autoregressive models according to the work proposed by Kareem E. Baddour [41]. In this snapshot, the AR model order is 100, the number of samples is 50, the maximum doppler frequency is 150 Hz, the symbol frequency is 3 ksps and the added bias, which depends on the Doppler rate,

(a) An OFDM-based transmitter employing sidelobe suppression, power loading and bit allocation.
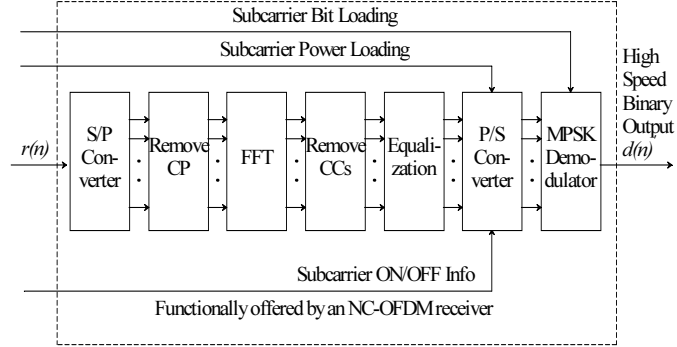

(b) An OFDM-based receiver employing sidelobe suppression, power loading and bit allocation.

Figure 5.5: A general schematic of an OFDM-based cognitive radio transceiver employing sidelobe suppression, power loading and bit allocation.

is 0.00000001 [41]. This snapshot is a very bad case since there is a 20 dB difference between the highest and lowest of the channel frequency response. In order to get a constant SNR of 25 dB, given the noise variance of 0.1, the power that can be assigned to the OFDM signal is calculated and shown in Figure 5.6(b). However, some
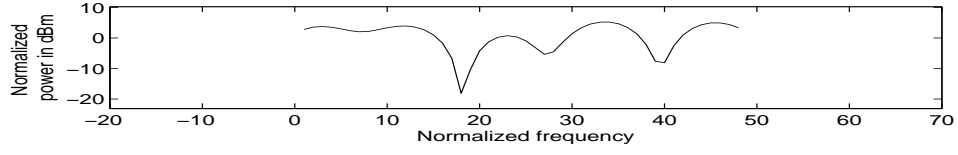
(a) Rayleigh channel.
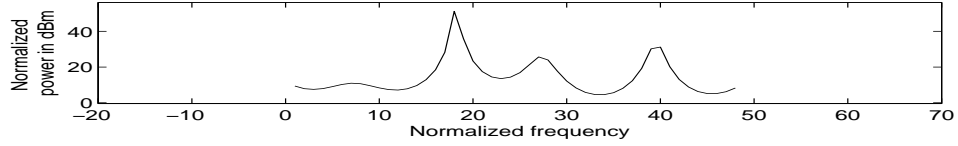
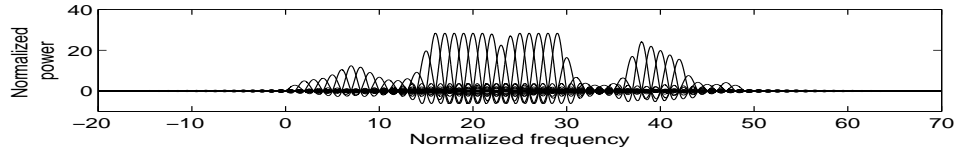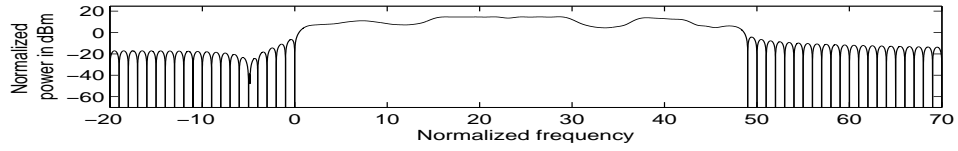(b) Power assigned to each subcarrier in order to keep a constant SNR.
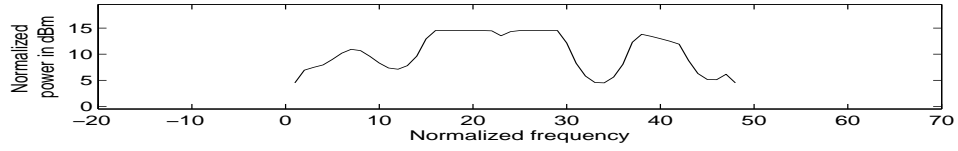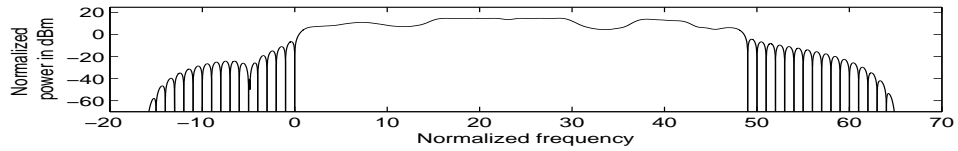

(c) Power assigned to each subcarrier after applying the threshold.

(d) OFDM subcarriers with different power levels.

(e) OFDM spectrum after using power loading.

(f) OFDM spectrum after using power loading and modulated filter banks.

Figure 5.6: Simulation results after using power loading and modulated filter banks.
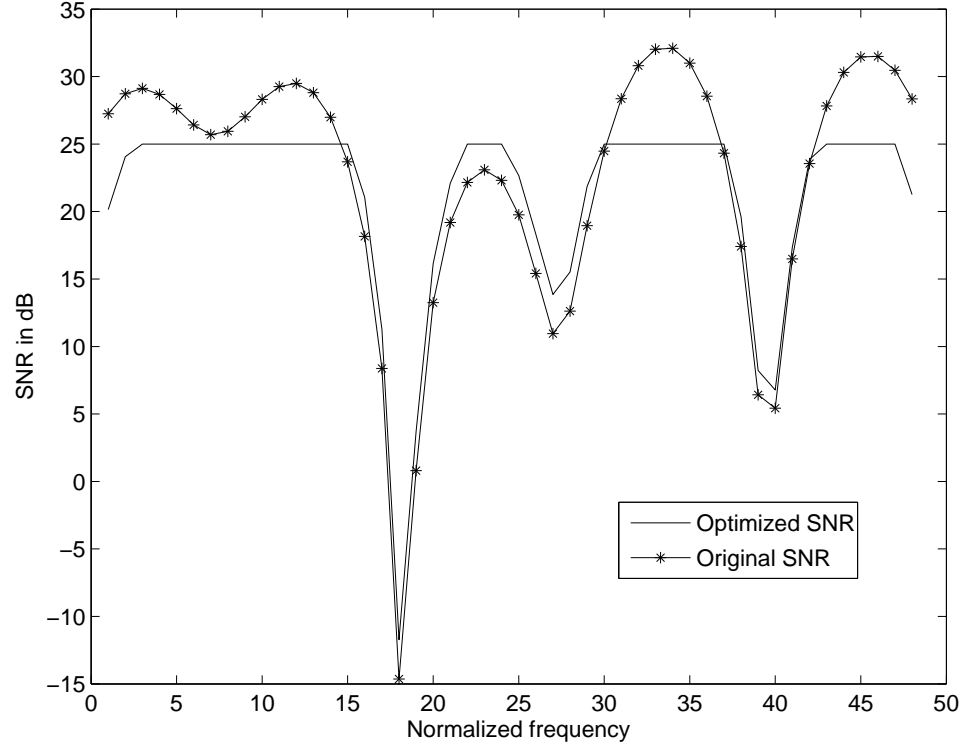
Figure 5.7: SNR before and after using power loading.

power levels are much higher than the power threshold and after applying the power threshold, the difference between different power levels that are assigned to different OFDM subcarriers is smoothed, as shown in Figure 5.6(c). The value of k in the power threshold, which is the ratio between the highest power and the lowest power, is 10 in this case. The number of OFDM subcarriers that have highest power levels are half of the total number of OFDM subcarriers, so μ=0.5. Figure 5.6(d) shows the OFDM subcarriers. These subcarriers have different power levels and the power levels are the same as in Figure 5.6(c). In Figure 5.6(e), the OFDM power spectrum is shown and we can find very high sidelobe. In order to reduce this out-of-band radiation, a raised-cosine filter with a roll off factor of 0.25 is chosen for the modulated filter banks which are used for OFDM sidelobe suppression and the sidelobe has been suppressed to -70 dBm very efficiently, as shown in Figure 5.6(f).

In Figure 5.7, SNR before and after using power loading is compared. We can
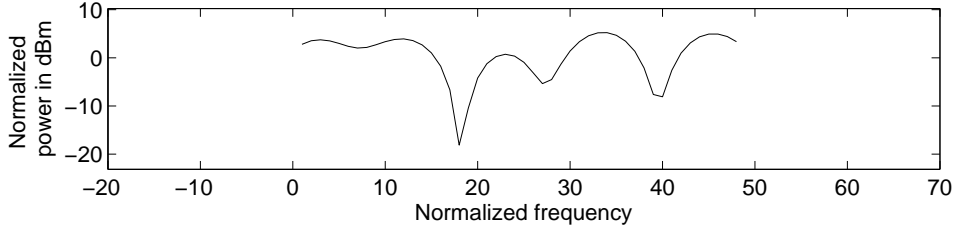
(a) Rayleigh channel.
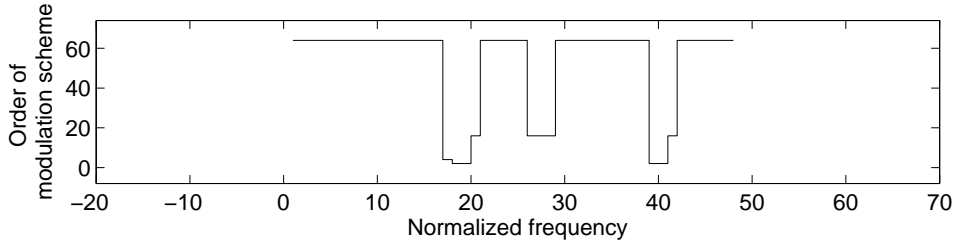
(b) The orders of different modulation schemes after using bit allocation.
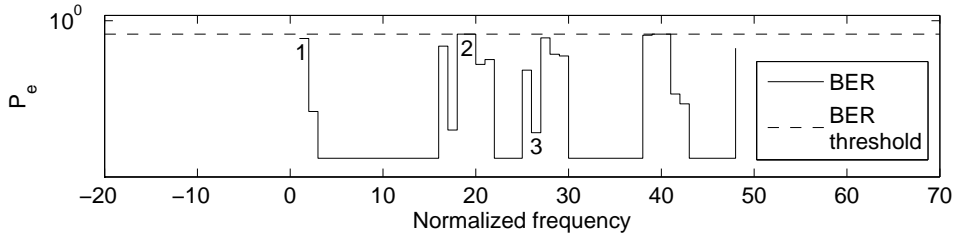
(c) BER after using bit allocation.

Figure 5.8: Simulation results after using bit loading.

see that after using power loading, the difference between the maximum SNR and minimum SNR is decreased. However, we cannot realize a constant SNR because of the power threshold. Without this power threshold, the power levels of some subcarriers may be much higher than the rest subcarries. Thus, sidelobes with much lower power levels will be clipped.

Figure 5.8 shows the simulation results after using bit loading. In Figure 5.8(a), the same snapshot of the channel as in Figure 5.6(a) is shown. In 5.8(b), after employing bit allocation, different OFDM subcarriers choose different modulation schemes, including BPSK, 4-QAM, 16-QAM and 64-QAM. Compare Figure 5.8(a) and Figure

5.8(b), we can find that where the channel has lower frequency response, the OFDM subcarriers will choose lower-order modulation schemes and smaller number of bits will be assigned. Since we want to make the throughput as big as possible, the reason why some subcarriers choose low-order modulation schemes, such as BPSK, is that we cannot let BER be too high, since lower-order modulation scheme provides BER. In Figure 5.8(c), BER values of different subcarriers are shown. The dashed line represents the BER threshold. We can see that all the subcarriers have BER values smaller than the threshold, which is 10^{-5} in this case. Some subcarriers, such as subcarrier "2" in Figure 5.8(c), whose BER values are as high as 10^{-5}, have employed BPSK to reduce their BER values with a cost of lower number of bits per subcarrier. Some other subcarriers, such as subcarrier "1" in Figure 5.8(c), whose BER values are also as high as 10^{-5}, have employed 64-QAM to achieve the highest data throughput, although they can use lower-order modulation scheme to reduce their BERs. Some other subcarriers, such as subcarrier "3" in Figure 5.8(c), employ middle-order modulation schemes and have not high BERs. Higher-order modulation scheme will cause a BER higher than the threshold, thus, they have to stick to this modulation scheme to achieve the highest data throughput ensuring their BERs are lower than threshold. From the above simulation results, we can see again that the basic principle of bit loading is to achieve the highest data throughput as far as the BER values is lower than the threshold.

5.6   Chapter Summary

In this chapter, a combined optimization for OFDM-based cognitive radio systems in frequency-selective fading channel is proposed, employing power loading, bit loading and sidelobe suppression techniques. Simulation results show that this unified approach can optimize the system by meeting different requirements, such as data throughput maximization, BER below the threshold and a constant SNR in all OFDM subcarriers. Only one snapshot of the frequency-selective fading channel is shown in the simulation results since we assume this is a slow time-varying channel. The algorithm needs to be re-executed with the fading of the channel.

Chapter 6

Conclusion

In this thesis, effort has been made to optimize the OFDM-based cognitive radio systems, including out-of-band radiation suppression which reduce the interference with other neighboring transmissions, and bit loading and power loading, which improve the performance in a frequency-selective fading channel. The techniques that have been developed in this thesis are:

- A cancellation carrier technique using genetic algorithm framework, which performs by inserting cancellation carriers on both sides of the OFDM spectrum to suppress sidelobe and this genetic algorithm framework can be conveniently combined with other optimization requirements.

- A combined approach employing modulated filter banks and cancellation carriers for OFDM sidelobe suppression, wherein a fast and simple algorithm has been developed based on simulation results to determine the number of OFDM subcarriers that can be transmitted in a given spectrum space.

- A combined approach employing bit loading, power loading and sidelobe suppression to optimize the performance of OFDM-based cognitive raido systems in a frequency-selective fading channel environment.

The proposed techniques can provide a lot of benefits to society. Modern society depends on wireless networks in order to facilitate ubiquitous access to the Internet,

Table 6.1: A list of the proposed techniques in this thesis.

Proposed techniques	Positive	Negative
Cancellation carriers employ genetic algorithm for OFDM sidelobe suppression	1. Improve the performance of cancellation carriers. 2. Can combine different optimization requirements.	1. High computation complexity. 2. Can only achieve 15 dB reduction.
Modulated filter banks and cancellation carriers for OFDM sidelobe suppression	Sidelobes can be suppressed to -60 dBm very efficiently avoiding interference with neighboring transmissions.	A small part of the spectrum is wasted.
Unified optimization employing bit loading, power loading and sidelobe suppression	Improve the system performance meeting several optimization requirements.	The algorithm is not powerful enough.

other human users, and both essential services and modern conveniences. Therefore, conducting research into distributed wireless networks performing dynamic bandwidth allocation, which could be employed in many emerging applications, is important. The optimization techniques and technology resulting from the proposed activities will also assist the public safety, emergency services, and first responders communities in enabling better communications access to the network, which could potentially translate into additional human lives being saved. Furthermore, the proposed architecture can also be employed in commercial data networking devices, such as vehicular communication networks, in order to further enhance the quality-of-life through ubiquitous wireless access.

The proposed three techniques are listed in Table 6.1 and positive aspects and negative aspects are presented. As a result of this research, five peer-reviewed publication have been produced:

- Zhou Yuan, Alexander M. Wyglinski, "On Sidelobe Suppression for Multicarrier-Based Cognitive Radio Transceivers", Submitted to the IEEE Transactions on Vehicular Technology, December 22, 2008.

78

- Zhou Yuan, Srikanth Pagadarai, and Alexander M. Wyglinski, "Sidelobe Suppression of OFDM Transmissions using Genetic Algorithm Optimization", Proceedings of the IEEE Military Communications Conference, San Diego, CA, USA, November 2008.

- Zhou Yuan and Alexander M. Wyglinski, "Cognitive Radio-Based OFDM Sidelobe Suppression Employing Modulated Filter Banks and Cancellation Carriers", Submitted to the International Conference on Cognitive Radio Oriented Wireless Networks and Communications, Hannover, Germany, March 3, 2009.

- Zhou Yuan, Alexander M. Wyglinski, "Uniform Optimization for OFDM-based Cognitive Radio Systems", Submitted to IEEE Transactions on Vehicular Technology (TVT) special issue on "Achievements and the Road Ahead: The First Decade of Cognitive Radio", May 2009.

- Srikanth Pagadaiai, Zhou Yuan and Alexander M. Wyglinski, "Feasibility of NC-OFDM Transmission in Dynamic Spectrum Access Networks", Submitted to the IEEE Military Communications Conference, Boston, MA, USA, 2009.

6.1 Future Work

There exists a number of areas for future work related to what has been presented in this thesis.

- The existing algorithms including those presented in this thesis do not utilize the statistical relationship between the random symbols carried by the subcarriers and the resulting sidelobe power levels. An understanding of such a relationship would greatly help in designing better techniques with better sidelobe suppression.

- A sidelobe suppression technique based on varying the data rates of the subcarriers that are closer to the edges of the OFDM spectrum can be developed. The premise of this algorithm is, if the subcarrier that are closer to the edge

of the OFDM spectrum have slower data rates, then the subcarrier bandwidth would be smaller and the sidelobes emerging from them would also be smaller, leading to low sidelobe power levels.

- Power amplifier at the transmitter may influence the effect of sidelobe suppression since the sidelobes are also amplified. Analysis is needed about this kind of influence.

- The combined optimization approach employing bit loading, power loading and sidelobe suppression can be analyzed by changing the parameters, such as the power threshold including the ratio between highest power to lowest power k and the percentage of subcarriers that are permitted to have higher power in the center of the OFDM spectrum, or the BER threshold BER_τ, to obtain the optimum performance for an OFDM-based cognitive radio system in a fading channel.

- It would be interesting to the proposed techniques implemented on a cognitive /software-defined radio hardware platform. The Universal Software Radio Peripherals (USRP) in Wireless Innovation Laboratory, which are high-speed USB-based board for making software-defined radios, can be a good candidate for implementation of the proposed techniques.

Bibliography

[1] Zhou Yuan, Srikanth Pagadarai, and Alexander M. Wyglinski,"Sidelobe Suppression of OFDM Transmissions using Genetic Algorithm Optimization", Proceedings of the IEEE Military Communications Conference, San Diego, CA, USA, June 2008.

[2] Zhou Yuan, Alexander M. Wyglinski, "On Sidelobe Suppression for Multicarrier-Based Cognitive Radio Transceivers", Submitted to the IEEE Transactions on Vehicular Technology, December 22, 2008.

[3] Zhou Yuan and Alexander M. Wyglinski, "Cognitive Radio-Based OFDM Sidelobe Suppression Employing Modulated Filter Banks and Cancellation Carriers", Submitted to the International Conference on Cognitive Radio Oriented Wireless Networks and Communications, Hannover, Germany, March 3, 2009.

[4] Srikanth Pagadarai and Alexander M. Wyglinski, "A Quantitative Assessment of Wireless Spectrum Measurements for Dynamic Spectrum Access", Submitted to the International Conference on Cognitive Radio Oriented Wireless Networks and Communications, Hannover, Germany, March 3, 2009.

[5] David E. Goldberg, "Genetic Algorithms in Search, Optimization and Machine Learning," Addison-Wesley Longman Publishing Co., Inc., New York, USA, 1989.

[6] Srikanth Pagadarai, Rakesh Rajbanshi, Alexander M. Wyglinski, and Gary J. Minden, "Sidelobe Suppression for OFDM- Based Cognitive Radios Using Con-

stellation Expansion", Proceedings of the IEEE Wireless Communications and Networking Conference, Las Vegas, NV, USA, April 2008.

[7] Sinja Brandes, Ivan Cosovic, and Michael Schnell, "Sidelobe suppression in OFDM systems by insertion of cancellation carriers", Proceedings of the 62nd IEEE Vehicular Technology Conference - Fall, vol. 1, pp. 152-156, September 2005.

[8] Srikanth Pagadarai, "Sidelobe Suppression for OFDM Based Cognitive Radios in Dynamic Spectrum Access Networks", M.S. thesis, University of Kansas, Lawrence, KS, USA, August 2007.

[9] Federal Communications Commission, "Spectrum Policy Task Force Report", EE Docket No. 02-135, 2002.

[10] Timothy Newman, Rakesh Rajbanshi, Alexander M. Wyglinski, Joseph B. Evans, and Gary J. Minden, "Population Adaptation for Genetic Algorithm-based Cognitive Radios," Proceedings of 2nd International Conference Cognitive Radio-Oriented Wireless Networks and Communnications, August 2007.

[11] John G. Proakis, "Digital Communications", McGraw-Hill, pp. 532-536, 1989.

[12] John R. Barry, David G. Messerschmitt, Edward A. Lee, "Digital Communication", Springer, 2003.

[13] Behrouz Farhang-Boroujeny, "Filter bank spectrum sensing for cognitive radios", IEEE Transactions on Signal Processing, vol. 56, issue 5, pp. 1801-1811, May 2008.

[14] Dinesh Datla, Rakesh Rajbanshi, Alexander M. Wyglinski, and Gary J. Minden, "Parametric Adaptive Spectrum Sensing Framework for Dynamic Spectrum Access Networks", Proceedings of the Second IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks, Dublin, Ireland, April 2007.

[15] P. P. Vaidyanathan, "Multirate Systems and Filter Banks", Prentice Hall, 1993.

82

[16] Timo A. Weiss, Fredrich K. Jondral, "Spectrum Pooling: An Innovative Strategy for Enhancement of Spectrum Efficiency", IEEE Communications Magazine, Radio Communications Supplement, pp. S8 - S14, March 2004.

[17] Friedrich K. Jondral, "Software Defined-Radio - Basics and Evolution to Cognitive Radio", Invited paper, EURASIP Journal on Wireless Communications and Networking, No. 3, pp. 275 - 283, 2005.

[18] Jospeph Mitola III, "Cognitive Radio for Flexible Mobile Multimedia Communications", IEEE International Workshop on Mobile Multimedia Communications, Novermber 1999.

[19] Ivan Cosovic, Sinja Brandes, and Michael Schnell, "Physical Layer Design Challenges of an OFDM Based Overlay System," IST Mobile & Wireless Communication summit, June 2006.

[20] Alexander M. Wyglinski, "Physical Layer Loading Algorithms for Indoor Wireless Multicarrier Systems", Ph.D. Thesis, McGill University, Montreal, QC, Canada, November 2004.

[21] Ivan Cosovic, Sinja Brandes, and Michael Schnell, "Subcarrier Weighting: A Method for Sidelobe Suppression in OFDM Systems," IEEE Communication Letters, vol. 10, No. 6, June 2006.

[22] Richard van Nee, Ramjee Prasad, "OFDM for Wireless Multimedia Communications", Boston, London: Artech House, 2000.

[23] Timo A. Weiss, Joerg Hillenbrand, Albert Krohn and Friedrich K. Jondral, "Mutual Interference in OFDM-based Spectrum Pooling Systems," Proceedings of IEEE Vehicular Technological Conference, vol. 4, pp. 1872-1877, May 2004.

[24] A. Dhammika S. Jayalath, Chintha Tellambura, "Reducing the Out-of-band Radiation of OFDM Using an Extended Guard Interval", IEEE Vehicular Technology Society 54th, Volume 2, pp 829-833, October 2001.

[25] Alexander M. Wyglinski, "Effects of Bit Allocation on Non-contiguous Muticarrier-based Cognitive Radio Transceivers", Proceedings of the 64th IEEE Vehicular Technology Conference, September, 2006.

[26] Rakesh Rajbanshi, Alexander M. Wyglinski, and Gray J. Minden, "An Efficient Implementation of the NC-OFDM Transceivers for Cognitive Radios", Proceedings of the IEEE International Conference on Cognitive Radio Oriented Wireless Networks Communication, June 2006.

[27] Leonard J. Cimini, "Analysis and Simulation of a Digital Mobile Channel Using Orthorgonal Frequency Division Multiplexing", IEEE Transactions on Communications, vol. COM-33, pp. 665-675, July 1985.

[28] Rakesh Rajbanshi, "OFDM-basd Cognitive Radio for DSA Networks", Ph.D. disstertation, University of Kansas, Lawrence, KS, USA, May 2007.

[29] Srikanth Pagadarai and Alexander M. Wyglinski, "Novel Sidelobe Suppression Technique for OFDM-Based Cognitive Radio Transmission", Proceedings of the IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks, Chicago, IL, USA, October 2008.

[30] Joseph Mitola III, Gerald Q. Maguire Jr., "Cognitive Radio: Making Software Radios More Personal", IEEE Personal Communications, vol. 6, no. 4, pp. 13-18, 1999.

[31] John A.C. Bingham, "RFI Suppression in Multicarrier Transmission Systems", Proceedings of IEEE Global Telecommunication Conference, pp. 1026-1030, November 1996.

[32] IEEE 802.11a, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: High-speed Physical Layer in the 5 GHz Band", IEEE, Tech. Rep., 1999.

[33] Danijela Cabric, Ian D. ODonnell, Mike Shuo-Wei Chen, and Robert W. Brodersen, "Spectrum Sharing Radios", IEEE Communication Magzine, vol. 2, pp. 30-45, 2006.

[34] Kaveh Pahlavan and Prashant Krishnamurthy, "Principles of Wireless Networks - A Unified Approach", pp 82, Prentice Hall, 2002.

[35] Irving Kalet, "The multitone channel", IEEE Transactions on Communications, vol. 37, pp. 119C124, Febuary 1989.

[36] Tomoaki Yoshiki, Seiichi Sampei, and Norihiko Morinaga, "High Bit Rate Transmission Scheme with a Multilevel Transmit Power Control for the OFDM Based Adaptive Modulation Systems", Proceedings of 53rd IEEE Vehicular Technology Conference C Spring, vol. 1, pp. 727C 731, Rhodes, Greece, May 2001.

[37] Michael J. Marcus, "Unlicensed Cognitive Sharing of TV Spectrum: The Controlversy at the Federal Communications Commission", IEEE Communications Magazine, vol. 43, no. 5, pp. 24-25, May 2005.

[38] V.D. Chakravarthy, Z. Wu, A. Shaw, M.A. Temple, R. Kannan and F. Garber, "A General Overlay/Underlay Analytic Expression Representing Cognitive Radio Waveform", Waveform Diversity and Design Conference, 2007.

[39] Peter S. Chow, John M. Cioffi, and John A.C. Bingham, "A Practical Discrete Multitone Transceiver Loading Algorithm for Data Transmission Over Spectrally Shaped Channels", IEEE Transaction Communications, vol. 43, pp. 773C775, March 1995.

[40] E. Baccarelli, A. Fasano, and A. Zucchi, "On the Loading of Peak-energy-limited Multicarrier Systems Transmitting Over Spectrally-shaped Crosstalk-impaired DSLs", Proceedings of the IEEE International Conference Communications, vol. 1, pp. 310C314, Helsinki, Finland, June 2001.

[41] Kareem E. Baddour, "Autoregressive Modeling for Fading Channel Simulation", IEEE Transactions on Wireless Communications, July 2005.