EXPERIMENTAL EVALUATION OF LONG TERM EVOLUTION-BASED NC OFDM SECONDARY-TO-SECONDARY INTERFERENCE

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ABSTRACT OF THE THESIS

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Scarcity of spectrum resources, inefficient spectrum usage and the inflexibility of the current spectrum assignment are few of the major roadblocks in the development of new wireless communication standards. Secondary spectrum sharing has become a viable solution to alleviate this problem. Secondary users are unlicensed devices that use opportunistic spectrum access to identify vacant frequency bins and thereby utilize the spectrum. For advanced wireless communication standards like the Long Term Evolution (LTE) which primarily calls for higher data rates, evaluation of design parameters for ensuring efficient coexistence of heterogeneous secondary users and guaranteeing acceptable minimum level of performance becomes essential. Additionally, the understanding of the interference between secondary users occupying adjacent frequency bands for their transmission is imperative.

This thesis focuses on the coexistence of secondary users in the same band assuming that the primary spectrum is found available. By implementing two Non Contiguous Orthogonal Frequency Division Multiplexing (NC-OFDM) based secondary transmitters on a real time platform, the design parameters that need to be considered to ensure efficient coexistence have been identified and investigated. The performance degradations observed at a particular secondary link due to presence of another interfering secondary link occupying adjacent frequency bands for its transmission have also been studied. This thesis also focuses on implementation of algorithms to modify the existing NC-OFDM transmission at the secondary transmitter end to reduce its interference effects on the other secondary links operating within the same band. The focus is on an LTE-based Secondary Non Contiguous Orthogonal Frequency Division Multiplexing Transceiver on a Real Time Platform developed by National Instruments . The various blocks needed to design a real time LTE based communications links are discussed. An experimental LTE-to-LTE interference analysis based on the Real Time Platform and the designed system is presented.

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Dedication

To my parents, teachers and friends

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Chapter 1

Introduction

1.1 Background

One of the major roadblocks in designing new wireless communication standards is the issue of whether the current spectrum availability allows for the usage of transmission specifications as desired by the standard. The available Radio Frequency (RF) spectrum is scarce and new emerging wireless technologies should try to achieve the best performance under given bandwidth constraints. However, the allocated spectrum has been heavily underutilized owing to current spectrum allocation policies. The Federal Communications Commision(FCC) has recently released a set of frequency bands for opportunistic access to ensure tighter control and to promote emerging wireless communication standards. Dynamic Spectrum Access is one of the techniques to achieve coexistence between two or more nodes sharing the same bandwidth. The FCC defines two types of links that can use the same chunk of spectrum. The primary links are licensed devices that are allocated the spectrum based on their needs and all the other links will have to modify their transmission process to suit the bandwidth utilization of the primary. The secondary link can be defined as any other unlicensed device that can utilize the spectrum by opportunistic spectrum access and will have to modify its transmission giving priority to the primary link.

Given that the primary has already been allocated its share of the spectrum, the question arises as to how would the other secondary users utilize the remaining spectrum. The first issue is the fact that two or more secondary users may see the same spectrum opportunity. This issue could be solved using advanced spectrum sensing algorithms and designing protocols to avoid collision. The other major issue is that of secondary links occupying adjacent frequency bins and interfering with each other.

This evaluation is important as it sheds light on parameters what need to be considered while designing secondary links. The aim of this thesis was to design a secondary transceiver operating under LTE [1] specifications and evaluate secondary to secondary coexistence. A part of this thesis also focuses on the implementation of a novel transmission technique named Interference Avoidance by Partitioned Frequency- and Time-domain processing(IA-PFT)[4] [6] which aims to further increase the performance of the secondary links in consideration.

1.2 Cognitive Radio Technology and Software Defined Radio

Cognitive Radio can be termed as a paradigm for wireless communication in which the network or the node itself modifies its transmission or reception parameters to execute its tasks efficiently without causing hinderance to other users operating within the same wireless environment. In other words, a Cognitive Radio System must possess the capability to perform opportunistic access to enable coexistence of primary and secondary users.

The most important part of Cognitive Radio Technology is the notion of a Software Defined Radio [13]. A Software defined radio is a smart radio in which the various components of a radio which are typically implemented in hardware are instead implemented by means of software on a Real Time Operating System or a Personal Computer. Typical characteristics of an SDR are wideband RF converters, Digital-to-Analog Converters (DAC), Analog-to-Digital Converters (ADC), multiband frontend antennas and a general purpose processor, which handles the fundamental signal processing. A Software Defined Radio (SDR) can be programmed to handle various transmission and reception functionalities. Some of the transmission functionalities are Adaptive Channel Modulation, changing the transmit power to adapt to the existing environment, calculation of channel parameters,etc. A SDR can also perform various receiver based functionalities like identification of channel modulation, error detection and correction, spectrum sensing etc. A basic SDR may consist of a Real time Embedded Controller with embedded FPGA modules , ADC /DAC and an RF daughter card. In the experiments performed for the thesis, a similar setup has been used.

1.3 Need for Secondary-to-Secondary Interference Evaluation

In Dynamic Spectrum Access, the primary user has always been considered as the one with the greatest priority and the secondary links modify their transmitted spectrum to suit the primary user needs. However, the primary user occupies a very small part of the available spectrum and the remaining portion has to be shared among secondary users. Opportuinistic spectrum access can be realized by using both decentralized spectrum allocation or using a central entity to monitor and control the sharing of the spectrum among secondary users. The centralized control technique leads to more reliability and ensures lesser secondary to secondary interference as secondary links are allocated the spectrum based on what the central governing node sees. However, this technique is more complicated as the entire allocation technique would break down if the central governing unit fails to function. Also, the vacant frequency bins perceived by the central governing technique may be different due to the fact that the central entity may not detect the presence of a coexisting secondaries at respective frequency bins and regard them as vacant. This is popularly known as the hidden node problem. The decentralized spectrum allocation technique depends only upon what the relevant secondary users percieve for spectrum allocation, and thus, will lead to better usage of vacant frequency bins. Under this technique, multiple secondary networks may interfere with each other if they see the same specrtrum opportunity. This kind of interference can be solved using smart spectrum sensing and utilization techniques. Assuming that this problem has been solved, there exists an issue of co-channel interference between secondary links occupying adjacent frequency bins. Measurement of performance becomes important in this case as the transmitting secondary will have to ensure that its transmission does not affect the other secondary users operating in adjacent bands.

Chapter 2

Coexistence of Heterogenous Secondary Links using DSA

2.1 Channel Model

The channel model that has been assumed for the wireless environment is that of Additive White Gaussian Noise (AWGN). According to the AWGN channel specifications, the received signal y(t) can be expressed as an addition of the transmitted signal x(t) and white Gaussian noise w(t). If we sample the received signal y(t) according to the relation t=nT where n=0,1,....N-1, we can express y(n) as

$$y(n) = x(n) + w(n) \tag{2.1}$$

2.2 Types of Dynamic Spectrum Access (DSA) techniques to achieve Secondary-to-Secondary Coexistence

According to FCC regulations, the operator of an unlicensed RF device will need to cease operation upon notification that the device is causing harmful interference. The primary users have more priority than secondary users in spectrum access. This thesis focuses on coexistence of secondary users assuming that the primary users have been granted their requested share of the spectrum. The first step of DSA is spectrum sensing to identify the positions of the vacant frequency bins. In this thesis, it has been assumed that the positions are known, as the purpose of the thesis was to evaluate performance and parameters for coexistence. Once spectrum sensing is performed, the SDR has to modify the transmitted spectrum to suit the wireless environment. Assuming that the underlying system is OFDM, there are many ways to modify the secondary transmission. Some of the ways which are relevant to the thesis are explained as follows.

2.2.1 DSA using On/Off keying

This type of secondary transmission is the most basic technique to enable primary secondary coexistence. Whenever a primary signal is detected, the secondary OFDM ceases to transmit. When there is no primary, it uses the complete band. However, this method is not efficient as it does not employ efficient usage of available spectrum. The main purpose of DSA is to solve the spectrum scarcity problem and this is not completely addressed by this technique.

2.2.2 DSA using secondary Non Contiguous OFDM transmission (NC-OFDM)

In this case, the secondary transmission is not stopped but modified when the primary signal is detected. When there is no primary user active, the secondary transmission is so modified to null out the secondary sub-carriers in the frequency bins that are occupied by the primary transmission. This kind of modified OFDM transmission is called Non Contiguous OFDM transmission (NC-OFDM). Non Contiguous OFDM transmission operates in the following manner:

- Initially, the secondary receiver to scan the spectrum to detect presence of used frequency bins. Various signal detection schemes can be used for this purpose, the simplest being energy detection.

- The receiver identifies the frequency bins that are occupied by any other user and generates a mask of 1s and 0s. A 1 indicates availability of the frequency bin and a 0 indicates the non-availability of the frequency bin. This can be pictorially represented in Fig. 2.1

- The secondary transmitter simply multiplies the spectrum mask with the complex symbol sequence hence notching out the sub-carriers that may interfere with the other transmissions.

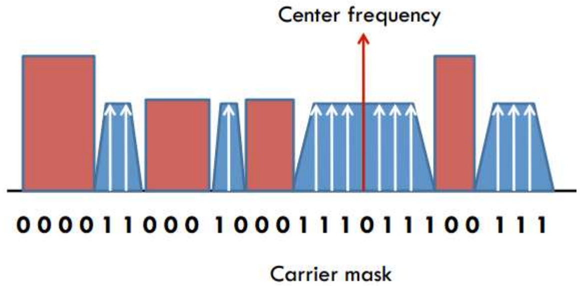


Figure 2.1: Spectrum mask calculated based on availability of frequency bins [7]

The pitfall of this method is that even though the sub-carriers are being notched out at the appropriate locations, there is spectral leakage from the sub-carriers adjacent due to the notch. Thus, the suppression gain is not adequate and it may lead to interference with the secondary user occupying those particular frequency bins.

2.2.3 DSA using IA-PFT modified NC-OFDM

As discussed before, the suppression gain at the notch is not adequate for regular NC-OFDM. Interference Avoidance by Partitioned Frequency and Time-domain Processing is a novel technique to increase the suppression within the null band with respect to a particular Secondary NC OFDM transceiver. It employs various signal processing algorithms in the time and frequency domain to help achieve more suppression in the null band. The IA-PFT theory has been explained further in section 2.3 of the thesis.

2.3 IA-PFT theory

As discussed before, due to poor filter characteristics of the baseband transceiver and due to spectral leakage from adjacent sub-carriers with respect to the notch, the suppression gain within the notch is not adequate. This may lead to reduction in the performance of the secondary link occupying adjacent resource blocks for transmission. IA-PFT is a novel technique proposed by NEC-Laboratories, Japan [6] that basically modifies the Non Contiguous OFDM symbol both in the Time and the Frequency domain to achieve further suppression gain. It is composed of two parallel operations namely Time Windowing and Carrier Cancellation. As the name suggests, Time Windowing is performed on the OFDM samples in the time domain after the IFFT block in the OFDM sequence of operations whereas Carrier Cancellation is performed after the sub-carrier mapping before the IFFT block. A detailed description of both these techniques is as follows.

2.3.1 Carrier Cancellation by adding Active Interference Cancellation tones to the NC OFDM transmission

Active Interference Cancellation (AIC)[5] [7] [8] is a technique that proposes to add two or more extra sub-carriers besides the existing sub-carriers that lie in the user band. The purpose of adding these tones is to cancel out the interference due to sidelobes of the existing sub-carriers. Assuming the secondary link has estimated the unused frequency bins and determined the positions of the sub-carriers that have to be nulled, the spectrum can be pictorially represented in Fig. 2.2. As indicated in the figure, spectrum can be divided into two complementary parts. The part of the spectrum that has been utilized by the secondary to transmit data can be labelled as the Information band whereas the part of the spectrum which may contain sub-carriers that arise due to the sidelobe interference of the information bearing - of the secondary link can be labelled as the Interference band. AIC removes one or more of these additional tones and replaces them with a new set of tones called AIC tones that effectively aid in nulling out the sidelobe interference caused by the information bearing sub-carriers.

The first step of the AIC technique is to compute the sidelobe interference in the Interference band. AIC computes the sidelobe interference in the interference band by turning off the interference tones and replacing them with AIC tones. The complex symbol sequence **X** is upsampled in the frequency domain by a factor of M.

Suppose X(k) where k=0,....,N-1, represents the original frequency domain data symbols where N is the FFT size. The time domain data signal is as follows

$$x(n) = \sum_{k=0}^{N-1} \mathrm{X}(k) exp(j2\pi \frac{nk}{N}) \tag{2.2}$$

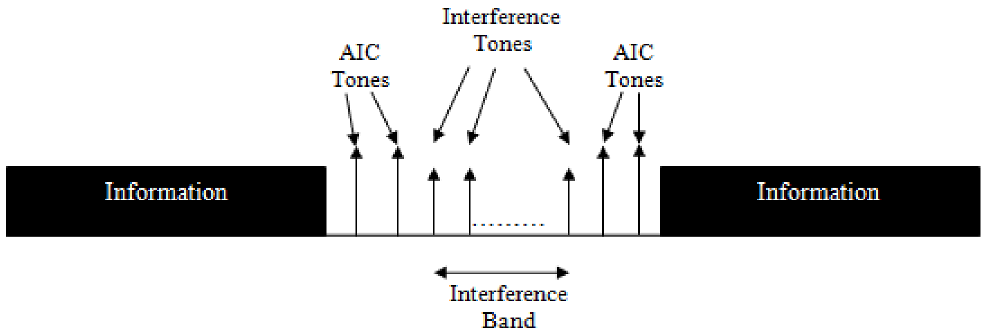


Figure 2.2: Spectrum showing positions of Interference and AIC tones

If the corresponding spectrum is upsampled by a factor of M, the new upsampled sequence Y is given by

$$\mathrm{Y}(l) = \frac{1}{N}\sum_{n=0}^{N-1} x(n)exp(-j2\pi\frac{nl}{NM}) \tag{2.3}$$

Using the above equations , the following relationships can be determined

$$\mathrm{Y}(l) = \frac{1}{N}\sum_{k=0}^{N-1}\sum_{n=0}^{N-1} \mathrm{X}(k)exp(-j2\pi\frac{n}{N}(k-\frac{l}{M})) \tag{2.4}$$

Or

$$\mathbf{Y} = \frac{1}{\mathrm{N}}\mathbf{PX} \tag{2.5}$$

Where

$$\mathbf{X} = [\mathrm{X}(0)....\mathrm{X}(\mathrm{N})]' \tag{2.6}$$

P represents the upsampling matrix which when multiplied with any complex sequence, the upsampled version of the respective complex sequence would be generated.

$$\mathrm{P}(l,k) = \sum_{n=0}^{N-1} exp(-j2\pi\frac{n}{N}(k-\frac{l}{M})) \tag{2.7}$$

To compute the AIC tones that need to be added, the number of Interference tones adjacent to the information bearing tones has to be selected as a design choice. One can assume that the interference tones nearest to the information bearing sub-carriers will have more sidelobe interference but this may not be entirely true. Suppose the Interference tones considered start from $(p)^{th}$ to $(p + N_i - 1)^{th}$ sub-carrier. where N_i stands for the number of interference tones considered. We can define a nulling matrix **T** of size N by N. The matrix **T** is a sparse diagonal matrix and its diagonal elements contain zeros at all the positions except at the positions of the information bearing sub-carriers where they are ones. The interference generated by these sub-carriers can be computed as

$$d_l = \mathbf{P}_s \mathbf{T} \mathbf{X} \tag{2.8}$$

Where $\mathbf{P}_s$ is a submatrix of $\mathbf{P}$ by taking its row corresponding to the upsampled spectrum in the interference band i.e from M(p+1)th to M(p+N_i-1)th rows of $\mathbf{P}$. The new set of sub-carriers say h that need to be placed to cancel out the interference due to d_l can be computed as

$$\mathbf{P}_n h = -d_l \tag{2.9}$$

$\mathbf{P}_n$ is a submatrix of $\mathbf{P}_s$ corresponding to the Interference tones and the AIC tones. The size of $\mathbf{P}_n$ is (M(N_i-1)+1) by (N_i+2). Finally to compute h we can formulate a least squares expression. Since $\mathbf{P}_n$ is not a square matrix one can use the pseudoinverse equation to compute h as

$$h = -(\mathbf{P}'_n \mathbf{P}_n)^{-1} \mathbf{P}'_n d_l \tag{2.10}$$

Addition of these AIC tones has to be performed for the either ends of the Interference bands. AIC tone insertion leads to cancellation of interference at the sides of the Interference bands and thus leads to suppression gain. This technique is performed at the sub-carrier level and thus has to be added before performing IFFT in the OFDM sequence of operations.

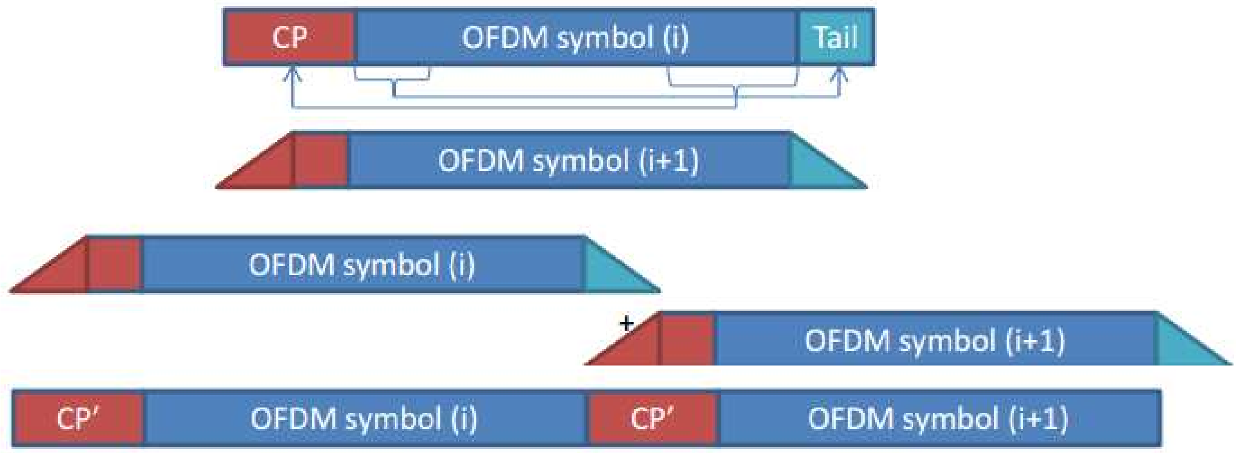
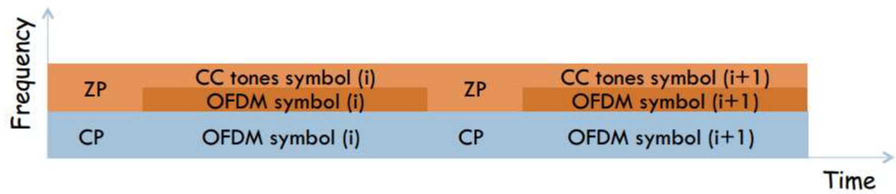


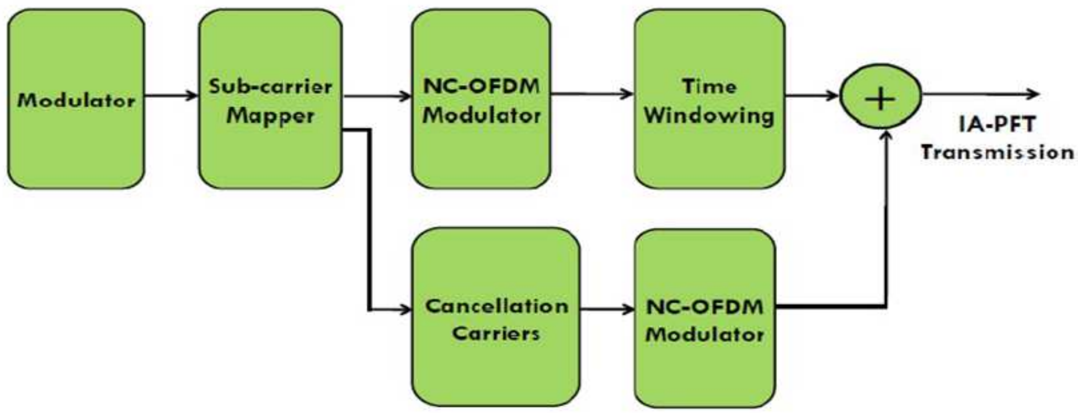
Figure 2.3: Steps to illustrate Time Windowing process [7] [8]

2.3.2 Time Windowing using Raised Cosine filtering

Time Windowing performs raised cosine filtering of the OFDM samples after the IFFT block. Typically LTE [1] or any other communication standard recommends addition of cyclic prefix to OFDM symbol for a variety of reasons like eliminating Intersymbol Interference, Symbol Synchronization, etc. In addition to the cyclic prefix, Time Windowing specifies addition of another set of samples at the end of the OFDM symbol. These samples are termed as overlap and they are generally equal to the first few samples of the original OFDM symbol excluding the cyclic prefix.Thus, the modified OFDM symbol contains the cyclic prefix attached to the front and the overlap attached at the end. The size of the overlap is a design criterion and can be varied depending upon the required suppression gain. The first few samples corresponding to the overlap size of the modified OFDM symbol are raised cosine filtered with a positive ramp and the last few samples are raised cosine filtered with a negative ramp. The samples corresponding to the overlap portion of the modified OFDM symbol are added to the first few samples of the succeeding OFDM symbol and the overlap is discarded. In essence, the modified OFDM symbol on which time windowing is performed is similar to the original OFDM symbol with exception of the first few samples of the cyclic prefix which have been modified. Thus there is an interdependence of every OFDM symbol with the preceding OFDM symbol. Figure 2.3 illustrates the Time Windowing process.



(a) Zeropad for CC part and addition of Cyclic Prefix for TW part



(b) Combination of TW part and CC part

Figure 2.4: Combination step [8] [7]

The Time Windowing and the Carrier Cancellation blocks together constitute the IA-PFT operation. The OFDM symbol is split into two complementary symbols. The first symbol contains all the sub-carriers including the cyclic prefix except for a selected information bearing sub-carriers adjacent to the interference band where they are nulled out. This selection is purely a design choice and varies according to the designers needs.Time Windowing operation is performed over this symbol. The other set has the cyclic prefix zeropadded and contains only the selected number of information bearing sub-carriers. All the other sub-carriers are zeroed out. The Carrier Cancellation operation is performed over this symbol. Assuming linearity of the IFFT both these operations are combined together.

The resultant IA-PFT modified NC-OFDM symbol should be similar to the NC-OFDM symbol with the exception that on observing the spectrum of the symbol the IA-PFT modified symbol shows more suppression in the interference band. The combination step is pictorially represented as shown in Fig 2.4. Fig 2.5 shows the final

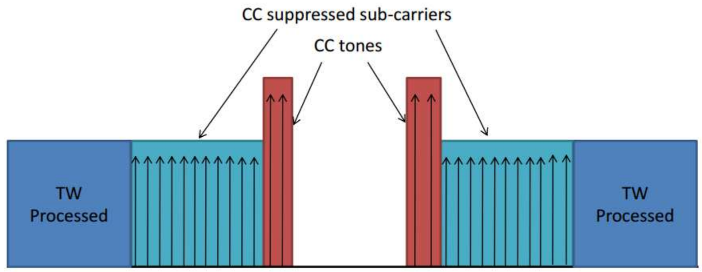


Figure 2.5: IA-PFT modified NC-OFDM symbol [7]

IAPFT modified NC OFDM symbol.

Chapter 3

Design and Implementation of the Secondary Transceiver System

3.1 Real time system implementation concerns

3.1.1 Need for a real time system

A real time system can be defined as a system which guarantees response within strict time constraints. It is generally a misconception that real time systems should necessarily have a fast response time. That is not entirely true. A non real time system may be fast but does not guarantee a fixed response time when it is triggered. Some of the attributes of a real time system are as follows:

- Loop Cycle time: Loop Cycle time is defined as the execution time of a block within a single loop.
- Jitter: The jitter in the system characterizes the variation in the execution time as opposed to the desired response time.
- Priority: If a real time system is given many tasks, priority defines the importance of a particular task in relation to the other tasks.

Thus a real time system must have the notion of a fixed response time with less jitter and defined priority. The aim of this thesis is to evaluate secondary-to-secondary interference in an LTE-esque environment. LTE specifications demand both stringent timing considerations and operation within a defined Bandwidth. So, to ensure that experiments are performed with LTE specifications taken into consideration, a real time system implementation becomes essential.

3.1.2 Using LabVIEW RT/FPGA as a platform for real time systems

National Instruments-based LabVIEW RT/FPGA [9] [12] was chosen to be the platform for the implementation of a LTE-esque communication system. The choice of LabVIEW was based on its efficiency and simplicity of use. LabVIEW provides a graphical environment and has an extensive Math, DSP and RF Communications libraries which enable easier transition from design to implementation. LabVIEW provides a stable real time environment for communication systems development. Certain important features required by the RT system are satisfied by various features of the LabVIEW development environment. For highly time constrained operations the FPGA environment can also be used. LabVIEW FPGA environment provides for higher clock rates and can be programmed to run time sensitive tasks. FPGA programming in LabVIEW is easier since it does not involve the need for VHDL/Verilog programming. Using a block diagram approach, LabVIEW provides a higher level of abstraction, and hence, FPGA coding becomes relatively less complicated. LabVIEW provides certain interesting and important tools relevant to a real time System. Some of these tools are described as follows:

- Timed Loop

  As explained before Timing is a very important consideration in a real time system. In any real time system, various tasks have to be executed repeatedly according to specified time considerations. The allocation of resources and processor cycles to each of these operations becomes important. Timed loops take care of the timing and priority of each of these tasks. Timed loop can be defined as a structure that ensures that the sequence of functional blocks within itself is executed at a specified rate. A timed loop is as shown in Fig.3.1. Each timed loop has various controls and indicators. Using a faster or slower clock, one can change the execution time to suit the requirements of the system design. One can also set the priority level of a particular timed loop depending on importance of the operation. Timing errors are also indicated using Boolean logic indicators which further help in debugging. In the figure, the execution time is specified to be 1

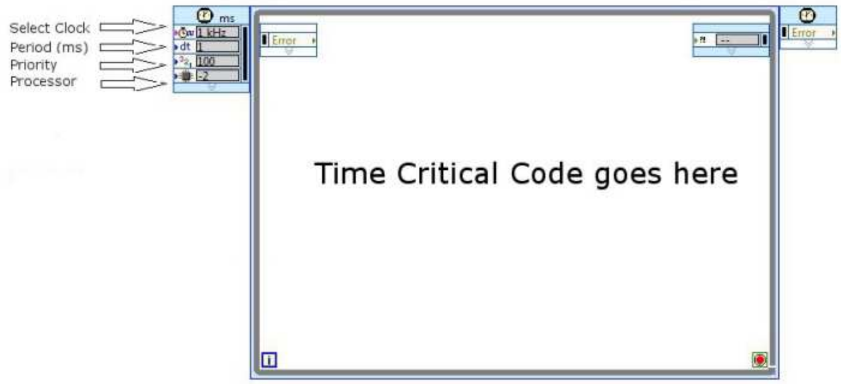


Figure 3.1: Timed loop in LabVIEW

ms. So if the execution time exceeds the specified limit, the Timed Out Indicator glows enabling the user to consider restructuring the code for faster execution.

- DMA

DMA stands for Direct Memory Access. In any FPGA-based code, queuing becomes a very important component of the design. In order to transfer high amounts of data at high rates between the target and the host as would be the case of a communication system, the best way to buffer data is to use DMA. DMA in LabVIEW can be implemented using FIFOs(First in First out) [12]. The use of a FIFO is to buffer samples generated by a previous block and release samples required by the second block, as and when, the succeeding block is ready. For instance, assuming that the first block operates at 20 MSamples/sec and the succeeding block operates at a lower rate say 10 Msamples/sec. If the two blocks were wired together directly without using FIFOs, the second it would lead into a sample overflow problem as the second block will not be able to keep up with the operation of the first block. However, if a FIFO is used between the two blocks , the FIFO will be able to buffer samples at a higher rate and release samples as and when the second block is ready to process them and this will ensure a systematic flow of samples between the two blocks. FIFOs are thus used to interface between two blocks operating at different rates. The depth of the FIFO defines

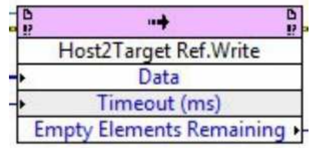


Figure 3.2: A typical FIFO method node in LabVIEW

the number of elements that the FIFO can buffer. Depending upon the difference in the rate of operation between the two blocks, the depth of the FIFO can be set. The timed out indicator enables the user to identify if the FIFO times out if an output request is sent. The FIFO parameters are set using FIFO method nodes in LabVIEW. A FIFO can be programmed to be storing samples or transmitting them depending upon the need of the task. One can also monitor the status of a FIFO using the specified method node. Figure 3.2 shows a FIFO method node in LabVIEW.

- Shared Variable

  LabVIEW provides a shared variable structure which enables sharing of data between the host and the target and between various sub operations within the same host/target. These structures become very important in case of operations like Bit Error Rate measurements that can be performed at the host by processing samples obtained from various blocks mapped to the target.

3.2 LabVIEW RT/FPGA platform usage concerns

3.2.1 Designing and compiling an FPGA code

FPGA code design in LabVIEW follows a higher level of abstraction and thus, is relatively easier to design the flow of logic as compared to VHDL/Verilog based coding. The LabVIEW FPGA module coding is slightly different than the normal host based coding and will prove to be efficient if particular incremental steps are followed to code. The design flow that has been found to be more efficient is shown in Fig. 3.3.

The first step towards coding any FPGA based code is the defining the architecture of the code i.e. defining its functionality, inputs, outputs, etc. Once that is mapped

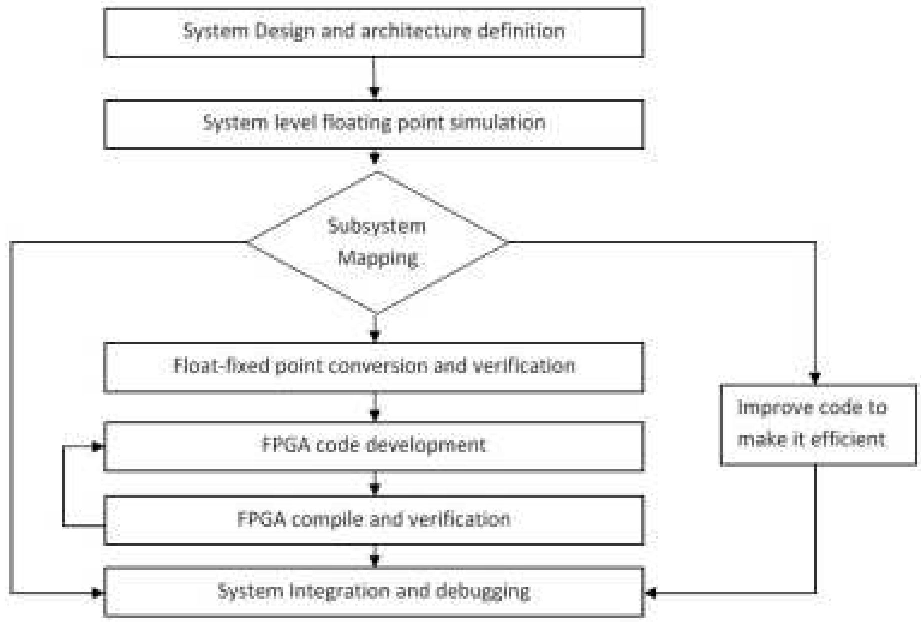


Figure 3.3: Typical design flow for development of FPGA code [9] ©National Instruments, Inc

out, the next step is to perform a system level floating point simulation that verifies the functionality. As indicated earlier, since the coding in FPGA is slightly different than a system based code, the next step is the perform mapping of sub-blocks into an FPGA based sub blocks. Since LabVIEW FPGA works with fixed point representation as opposed to floating point representation, it is important to decide the representation of data that is to be used. The next step is coding and compiling. Compiling an FPGA code in LabVIEW follows a systematic approach to convert an FPGA code to bit level logic that can be programmed into the FPGA chip. The FPGA module first compiles the FPGA code, and this graphical code is translated to VHDL code. The Xilinx ISE Compiler compiles this VHDL code and creates the circuit. The compiler then works on optimizing the implementation. After compilation, a bitstream is generated and this bitstream is loaded on the system at run-time and the whole system is executed with the crucial components loaded onto the FPGA for faster and efficient execution. Refer to the Fig 3.4 for a pictorial description of the process. The final step is checking for errors in the code and optimizing the performance using pipelining, high throughput

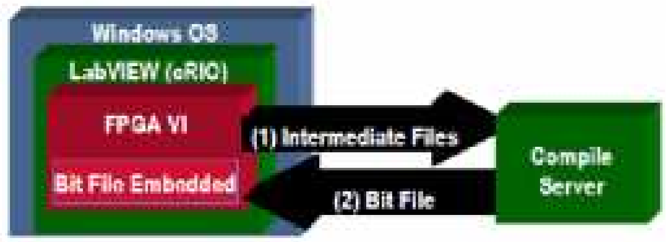


Figure 3.4: FPGA compile server [9] ©National Instruments, Inc

block usage, etc.

3.3 System Design

3.3.1 System Parameters

The aim of this thesis was to evaluate secondary-to-secondary coordination and coexistence. To serve this purpose more effectively, the realization of an LTE-esque communications system was crucial. A LTE based secondary NC-OFDM transceiver was designed and implemented for this purpose. From the LTE standard specifications, the underlying system is OFDM. Fig 3.5 shows some of the LTE specifications. The secondary transceiver design specifications that have been implemented for the system are as follows:

- Bandwidth: 20 MHz
- SubFrame duration: 1 ms
- No. of Sub-carriers: 1200
- Sub-carrier spacing: 15kHz
- Sub-carrier Mapping : Quadrature Phase Shift Keying (QPSK)
- Use of 1 Reference Carrier every 5 data carriers for equalization and channel estimation

Transmission BW		1.25 MHz	2.5 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Sub-frame duration		0.5 ms					
Sub-carrier spacing		15 kHz					
Sampling frequency		192 MHz (1/2 x 3.84 MHz)	3.84 MHz	7.68 MHz (2 x 3.84 MHz)	15.36 MHz (4 x 3.84 MHz)	23.04 MHz (6 x 3.84 MHz)	30.72 MHz (8 x 3.84 MHz)
FFT size		128	256	512	1024	1536	2048
OFDM sym per slot (short/long CP)		7/6					
CP length (usec/ samples)	Short	(4.69/9) x 6, (5.21/10) x 1	(4.69/18) x 6, (5.21/20) x 1	(4.69/36) x 6, (5.21/40) x 1	(4.69/72) x 6, (5.21/80) x 1	(4.69/108) x 6, (5.21/120) x 1	(4.69/144) x 6, (5.21/160) x 1
	Long	(16.67/32)	(16.67/64)	(16.67/128)	(16.67/256)	(16.67/384)	(16.67/512)

Figure 3.5: LTE specifications [1]

3.3.2 Hardware Setup

It is important to discuss the Hardware Setup before discussion of the transceiver design as most of the design choices depend upon the Hardware Setup. The setup consists of a Windows based Host machine containing the LabVIEW user interface. The real time machine is a National Instruments-based PXIe-8133 Real Time Controller with support for LabVIEW Real Time Module (LabVIEW RT). The LabVIEW system code is built on the Host machine and is ported on to the RT controller using Ethernet. The RT controller has two Xilinx Virtex-5 based FPGA chips interfaced to itself. The FPGA chips can be programmed using LabVIEW FPGA module which can be controlled using the Host interface. Each FPGA chip streams data to an NI-based Baseband Transceiver kit. The Baseband Transceiver module contains two 16 bit DACs and 14 bit ADCs operating at a sampling rate of 100 MSamples/sec for both I and Q components (50 Complex MSamples/sec overall). The Baseband transceiver talks to the RF daughter board via an NI-based Interposer. The RF daughter board is the Ettus XCVR 2450 which operates at center frequency of 2.45-2.49/4.9-5 GHz and is capable of a maximum transmit power of 20 dBM. The hardware setup for experiments conducted in this study is shown in Fig 3.6.

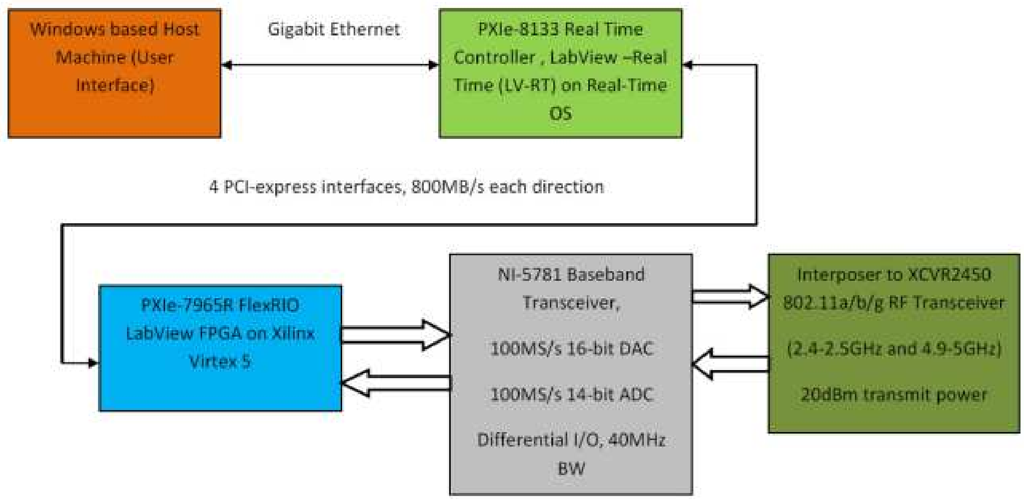


Figure 3.6: Hardware setup for implementation of system design

3.3.3 Secondary transceiver block diagram description

As discussed above, the aim was to design a NC OFDM transceiver having LTE parameters. The underlying system was OFDM with some modification for suppression. An important design consideration in utilizing LabVIEW RT/FPGA platform is to determine what blocks in the OFDM sequence of operations go into the RT and FPGA. As discussed before, the FPGA is more efficient than the RT with regards to meeting timing constraints and resource allocation. However, The FPGA chip has limited resources and thus the system design has to overcome this space constraint and maximize overall efficiency of the system. In other words, selection of blocks that go into the FPGA /RT has to be carefully made and should try to meet the LTE standard specifications as closely as possible. The block diagram of the system design is as shown in Fig. 3.7.

Secondary Transmitter The upper stream shows the transmitter end and the lower stream shows the receiver end of the OFDM system. As shown in the figure, all the sub blocks have been classified to be working at the Host, RT or the FPGA platform. The secondary transmitter has the Data Bit generator, QPSK modulation block and the Reference Symbol generation mapped into the RT whereas the Reference Data Multiplexer, IFFT zeropad block, IFFT block and the Sample Rate Conversion

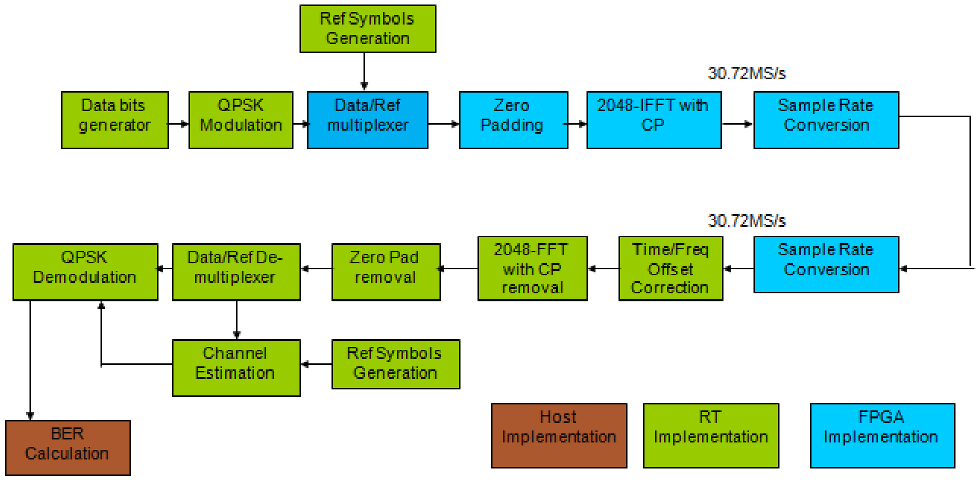


Figure 3.7: Secondary NC-OFDM transceiver block diagram

block mapped to the FPGA module.

The LabVIEW RF communications library provides a Fibonacci PN sequence generator which is capable of producing random bits every iteration. The seed input can be varied depending upon the design needs. These bits are mapped into QPSK symbols using the QPSK modulation block. The symbol map can also be varied according to the design needs. LTE specifes insertion of 1 reference sub-carrier every 5 data sub-carriers. These sub-carriers are fixed and generated in the RT controller itself. The receiver uses these reference sub-carriers for channel estimation purposes. Both the reference and data carriers are streamed to the FPGA target using independent FIFO blocks. This step is quite important when it comes to the system design. Since the target may operate at a different rate as compared to the RT controller, it is required to queue the data and the reference samples using seperate FIFOs. The FPGA target reads these FIFOs as required by the system operation. It is important to ensure that the FIFO does not overflow or underflow. This can be taken care of by employing time critical loops in the RT which ensure samples are streamed out at a definite rate.

Once the symbols are streamed into the FPGA module, the Ref/Data Multiplexer block employs a counting mechanism to intersperse the data and the reference sub-carriers. As per LTE standards, there should be 1 reference sub-carrier every 5 data sub-carriers. For every OFDM symbol, LTE specifies 1000 data sub-carriers and 200 reference sub-carriers for a bandwidth of 20 MHz. Once these sub-carriers are interleaved, we get 1200 sub-carriers per OFDM symbol. Since an IFFT of size 2048 is used, these 1200 symbols must be zeropadded on either side. This is performed by the Zeropadding block. The design uses the Xilinx IP(Intellectual Property) to realize the IFFT module. This is done to ensure efficiency and robustness. It also inserts a cyclic prefix of length 512 sub-carriers to ensure lesser Inter Symbol Interference and also for OFDM symbol synchronization. The baseband transceiver (ADC/DAC) in the hardware setup works at 50 complex Msamples/sec. However, the sampling rate obtained by the system at the end of the IFFT block is 30.72 complex MSamples/sec. If this is directly fed to the DAC, it will lead to undersampling of the DAC and the DAC will tend to insert garbage samples to overcome the rate difference. Thus, resampling is required. This is done using the sample rate conversion blocks which upsamples the output of the IFFT to ensure a rate of 50 complex MSamples/sec.

FPGA module design for NC OFDM transmitter We have discussed the design for a basic OFDM transmitter. The NC OFDM transmitter design is relatively straightforward and just involves nulling out the sub-carriers at the positions of used frequency bins. In our experiments, it has been assumed that the positions of the vacant frequency bins are previously known to the Secondary transceiver and thus the only changes in the design relative to the OFDM transmitter would be zeroing out the sub-carriers occupying used frequency bins of the spectrum in the QPSK modulation and reference symbols generation blocks in the OFDM transmitter.

Design of IA-PFT-based NC OFDM transmitter IAPFT involves two major operations - Carrier Cancellation and Time Windowing. The Time Windowing is performed at after the IFFT block, and hence, requires modifications in the FPGA module. The insertion of AIC tones of the Carrier Cancellation operation have to be done at the RT controller owing to the design choice since the Reference and the Data Symbols generation is performed at the RT end. However, for the IA-PFT design, the

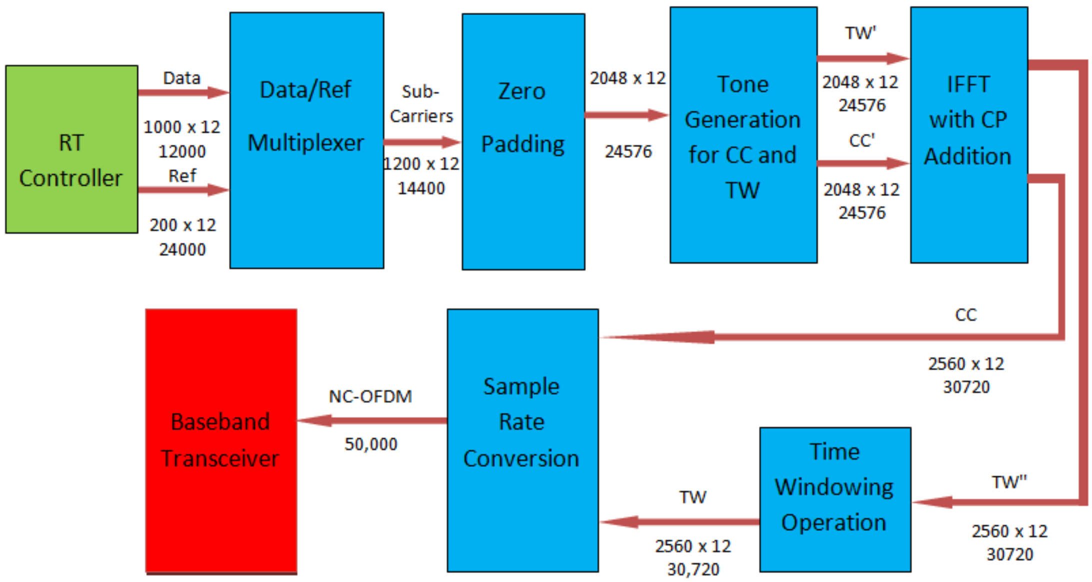


Figure 3.8: FPGA module design for IA-PFT implementation

NC OFDM symbol is divided into two complementary sub-streams: one for the Time Windowing and the other for the Carrier Cancellation process. These operations are performed at the FPGA end. Refer to Fig 3.8 for the FPGA module implementation block diagram for IA-PFT.

The numerical figures shown in each stream represents the number of samples streamed through various blocks in 1 ms. the goal is to achieve a rate 50 MSamples/sec which is the sampling rate of the DAC. Pipelining is implemented in the entire FPGA module to ensure timing constraints are well met. As shown in the figure, the Reference Symbols and Data Symbols are streamed into the Data/ref Multiplexer block using FIFOs. After interspersing the data and the reference according to the system parameters, the Symbols are zeropadded on either ends to make up a length of 2048 per symbol to match the IFFT size. Once zeropadding is performed, the CC and the TW tones are separated based on the number of sub-carriers in the information band on either side of the interference band to be considered for generation of AIC tones. The AIC tones for the CC stream are generated separately on the RT controller end on the basis of the theory discussed before. IFFT is performed on both these streams parallely and the Cyclic Prefix is zeroed out for the CC to ensure linearity. Time

Windowing using raised cosine filtering is performed on the TW stream. The CC and the TW sets are streamed out at a rate 30,720 Msamples/sec after this stage. These streams are added together at the Sample Rate Conversion block and upsampled to a rate of 50 complex Msamples/sec (100 Msamples/sec for both I and Q), the rate which is required by the baseband transceiver. These describe the modifications that need to be made to the existing NC OFDM transmission for building an IA-PFT based NC OFDM transmission.

Secondary Receiver The receiver design has been completely mapped on the RT controller with the exception of the sample rate conversion block owing to ease of design. The samples are acquired at the RF end by the XCVR daughter board, and transfers received I/Q samples to the ADC on the NI-5781 Baseband Transceiver, which converts this RF signal into baseband spectrum. These samples are downsampled at the FPGA end using a resampler to regain the rate of 30,720 Msamples/sec. A FIFO is used to queue these samples which wait on processing by the RT controller. To perform Time/Frequency Offset estimation, the design uses the Maximum-Likelihood Estimnation technique described by [11]. Once each OFDM symbol is isolated by this method, the Cyclic Prefix is removed and an 2048 pt FFT is performed to recover the sub-carriers. The sub-carriers recovered are composed of both data and reference symbols interspersed with each other. A demultiplexing operation is performed to isolate the data and the reference symbols. The reference symbols are used for channel estimation. The channel estimation block uses the least squares estimation technique described by [11] to obtain channel coefficients . These channel coefficients are used to estimate the original data symbol set that had been transmitted. The data carriers so obtained are QPSK symbols following a Gray Coding scheme. Using the sign of each symbol, bits are recovered at the receiver end. The BER calculations are performed over the recovered bits for error performance measurement.

Chapter 4

Experiments and Results

4.1 Experimental setup for the evaluation of secondary-to-secondary interference on a National Instruments-based Real Time Controller

The goal is to evaluate Secondary-to-Secondary Coordination and Coexistence. The performance measure for any system is best understood using Bit Error Rate measurements. Most of the experimental results in this thesis focus on the use of BER measurements. Two Secondary Transceiver systems were implemented on a National Instruments-based Real Time PXIe controller setup. The frequency band used for transmission and reception was the 2.4 GHz ISM band. This is the Wifi Band and the experiments performed were affected marginally by the spurious transmissions by Wifi nodes/hotspots. The experimental setup is shown in Fig. 4.1

The figure shows two secondary links. One of the Secondary Transceivers was used as the interfering link and the range of the secondary transceiver can be represented by the pink area. The other secondary transceiver is the one whose performance was evaluated in presence of the interfering secondary. The design used for both these transceivers has been explained before in section 3.3 of this thesis. The transmission power of the interfering secondary was varied to see the performance degradations in the secondary link under consideration. Experiments based on increasing the guard band between the considered secondary NC OFDM spectrum and the interfering secondary NC-OFDM spectrum were also carried out and the changes in the performance were observed. CC tones were added to the interfering secondary transmission and the changes in the suppression gain in the notch were also observed.

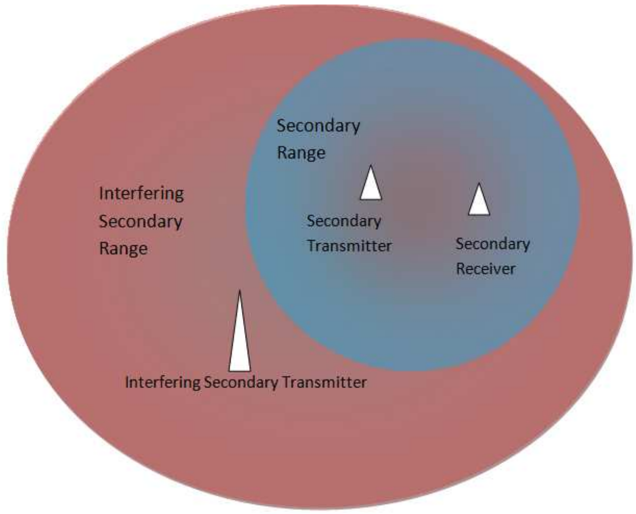


Figure 4.1: Experimental setup to evaluate secondary to secondary coexistence

4.2 Effect of increasing the Interfering Secondarys' transmission power on the Bit Error Rate of a coexisting secondary link

In these experiments, the secondary link whose performance has to be evaluated was utilizing bandwidth corresponding to 10 Resource Blocks (2 MHz). The interfering secondary had a transmission bandwidth of 100 Resource Blocks(20 MHz). Both the transmitters were operating within the 2.4 GHz ISM band. It has been assumed that the interfering secondary is aware of the positions of the frequency bins occupied by other secondary users and it suppresses its corresponding sub-carriers accordingly. The coexistence of both these secondary links in the spectrum can be pictorially represented in Fig.4.2 . The guard band between the heterogeneous secondary links has been assumed to be having the size of 1 Resource block on either sides. When the interfering secondary transmission power increased, the difference in the received power spectral density of the received secondary signal and the interfering secondary link reduces. Under presence of no interfering secondary, the observed constellation and spectrum at the secondary receiver can be shown in Fig. 4.3.

As we increase the interfering secondary transmit power, it has been observed that the constellation keeps getting worse and when the received interference power increases beyond a threshold, the secondary receiver starts losing synchronization and leads to a poorer performance. The spectra and the constellation plots observed on increasing the interfering transmission have been shown in Fig 4.5. To quantify these effects a performance measurement of the Secondary link in terms of Bit Error Rate became necessary. The received SNR of the secondary link in consideration was kept constant and the transmit power of the Interfering Secondary was varied. The Bit Error Rate curve for the secondary link is as shown in figure. In order to obtain an optimal range of BER values, a total of 396,000 bits were used for calcluation. It is observed that as the interfering link power is increased, the BER increases. The BER curve for the secondary link is as shown in Fig. 4.6.

4.3 Effect of varying guard band between the interfering link spectrum and the spectrum of the secondary link under consideration

To evaluate coexistence of secondary links, it is important to draw out certain transmission parameters. The guard band that needs to be maintained between the spectra of secondary links is an important parameter that needs to be measured to ensure proper coexistence. Experiments were performed to vary the guard band between two secondary links whose transmissions occupied adjacent frequency bins. As the guard band increases, it has been observed that the interference effects by other secondary transmissions on a particular secondary link diminish. The observed spectra and constellation plots at the secondary receiver for different guard band spacing with respect to the interfering secondary transmission have been shown in Figs. 4.7, 4.8, 4.9. Again the Interfering Secondary Transmission power was increased and its effects were observed on the other secondary link for different guard band spacings. The family of BER curves of the secondary link for different guard bands seen in the linear range are shown in Fig. 4.10.

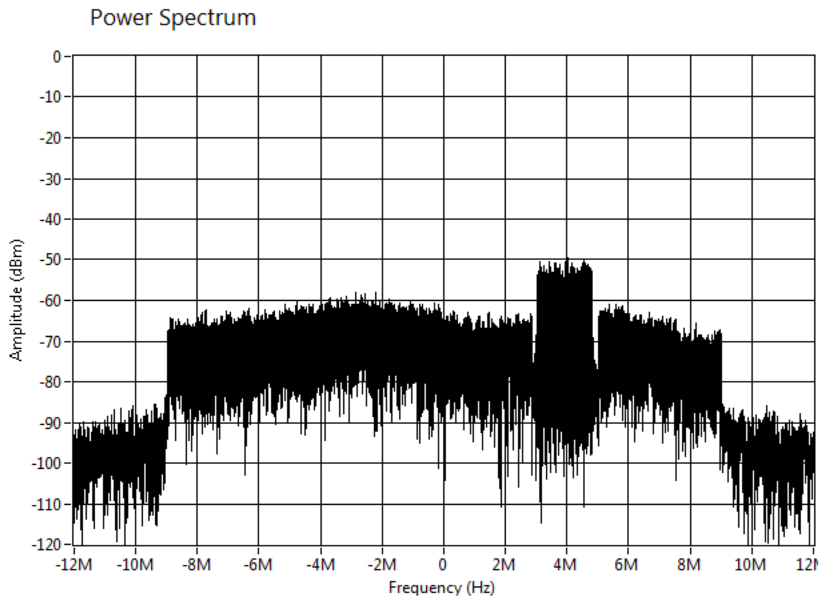
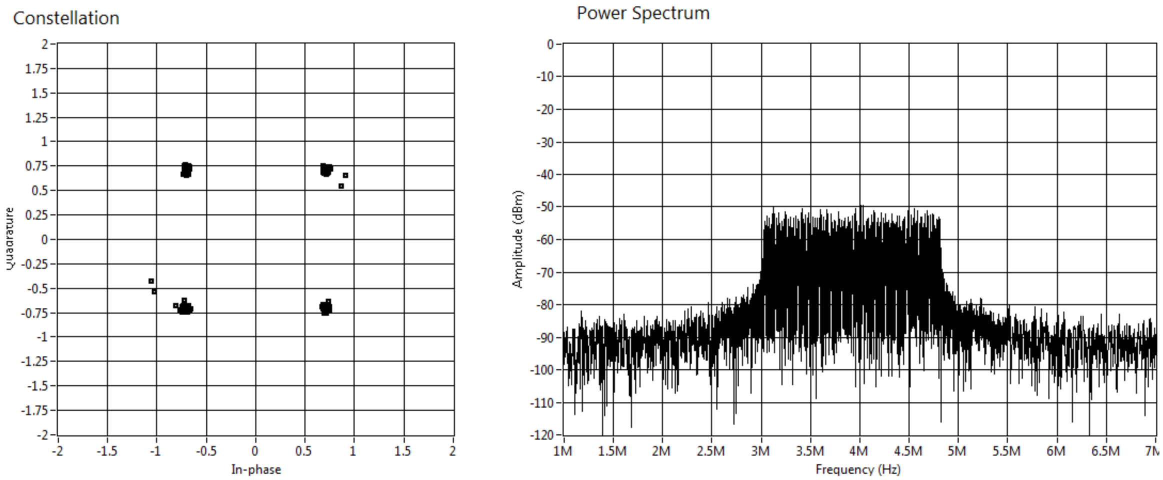


Figure 4.2: Spectrum showing coexistence of two secondary users within the same 20 MHz band

4.4 Effect of using modified Secondary Transmission techniques on the suppression

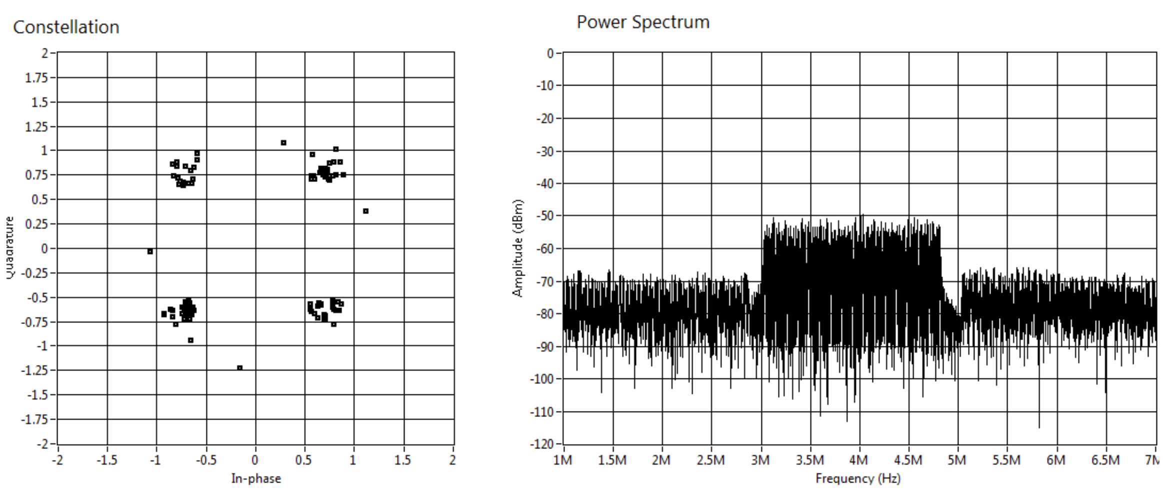
In order to ensure better suppression gain in the Interference Band, modified NC OFDM transmission techniques like the IA-PFT had been simulated on a MATLAB platform. The size of the FFT used was 2048 with a Cyclic Prefix of 512. The notch was assumed to be having a size of 12 Resource Blocks (RBs) corresponding to 144 carriers. Two AIC tones were used on either side to suppress sidelobe interference from the information band. These AIC tones were calculated considering sidelobe interference of 10 information bearing sub-carriers on either side of the interference band. Time Windowing was performed using a total overlap size of 300 samples. The results show a clear suppression of 10-12 dB as compared to the regular NC -OFDM technique. The spectra can be shown in Figs. 4.11 and 4.12.



(a) Secondary Receiver Constellation in the presence no interfering secondary

(b) Secondary Receiver Spectrum in the presence of interfering secondary

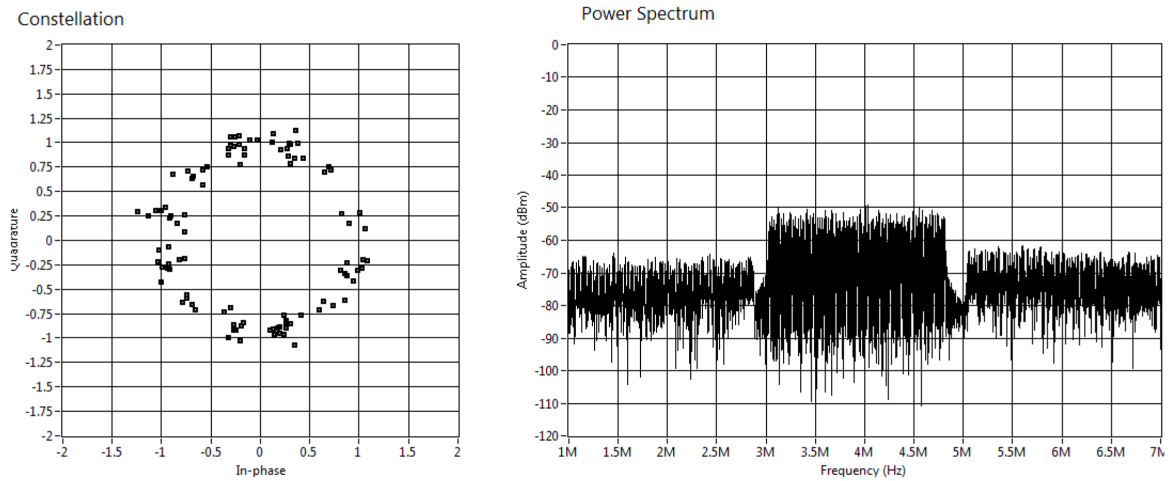
Figure 4.3: Spectrum and constellation for absence of Interfering Secondary



(a) Secondary Receiver Constellation in the presence of Interfering Secondary with average received power of -72dBM

(b) Secondary Receiver Spectrum in the presence of Interfering Secondary with average received power of -72dBM

Figure 4.4: Spectrum and constellation in presence of Interfering Secondary



(a) Secondary Receiver Constellation in the presence of Interfering Secondary with average received power of -66dBM

(b) Secondary Receiver Spectrum in the presence of Interfering Secondary with average received power of -66dBM

Figure 4.5: Spectrum and constellation in presence of Interfering Secondary

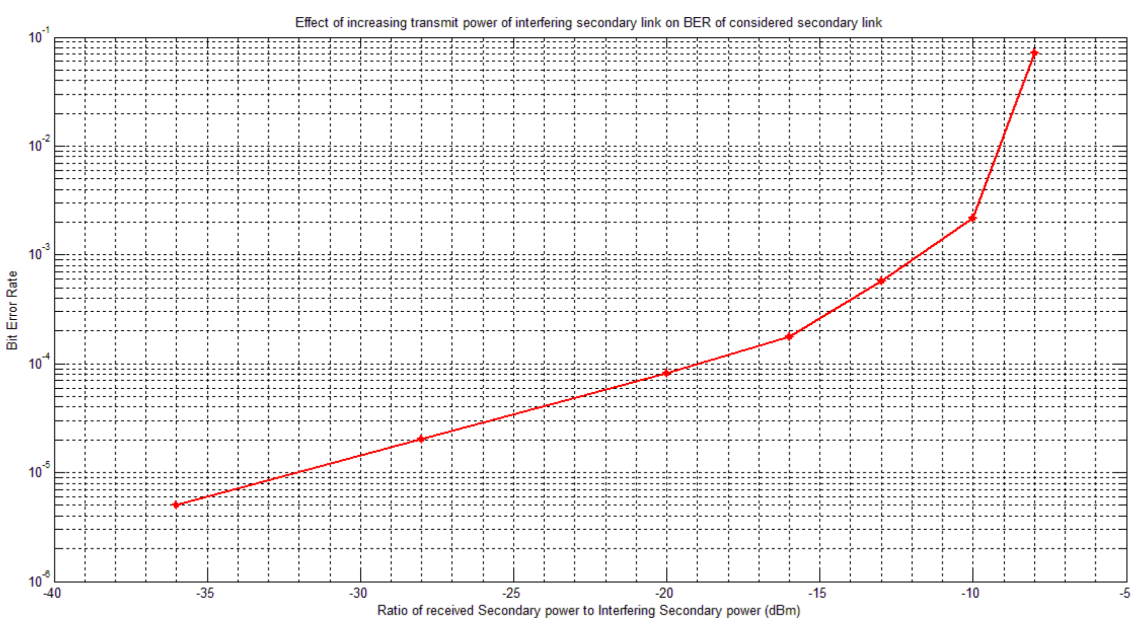
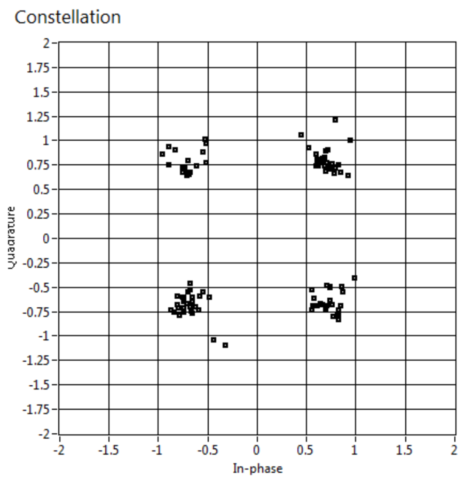
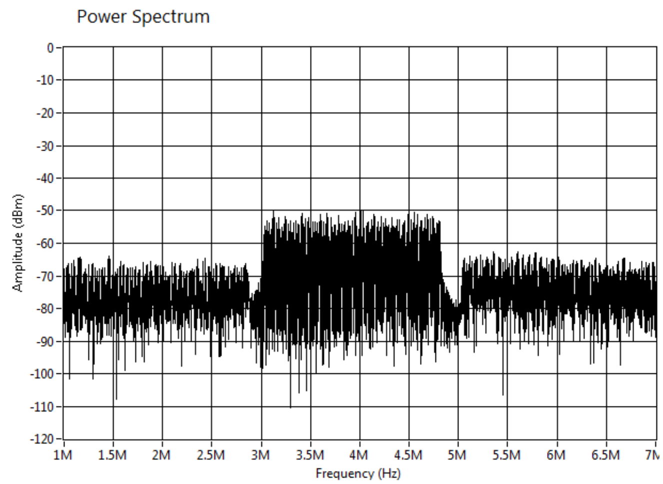


Figure 4.6: Bit Error Rate curve showing performance of Secondary link against varying interfering secondary transmit power in a wireless environment

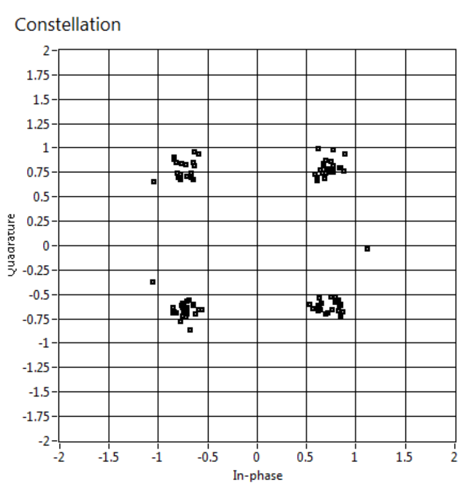


(a) Secondary Receiver Constellation for guard band spacing of 1 RB

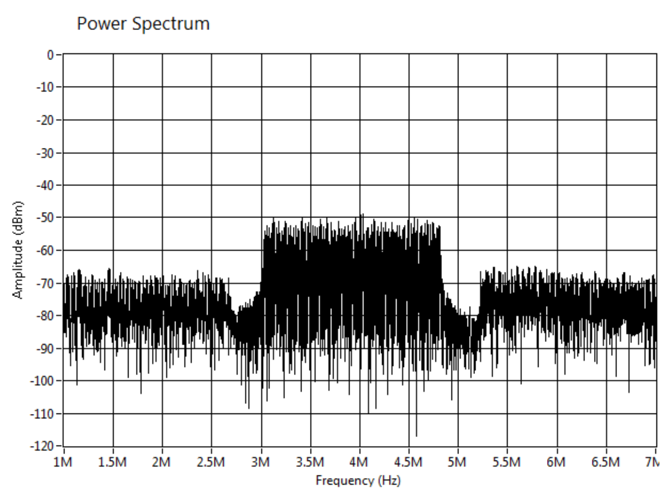


(b) Secondary Receiver Spectrum for guard band spacing of 1 RB

Figure 4.7: Spectrum and constellation at the secondary receiver for a guard band of 1 RB

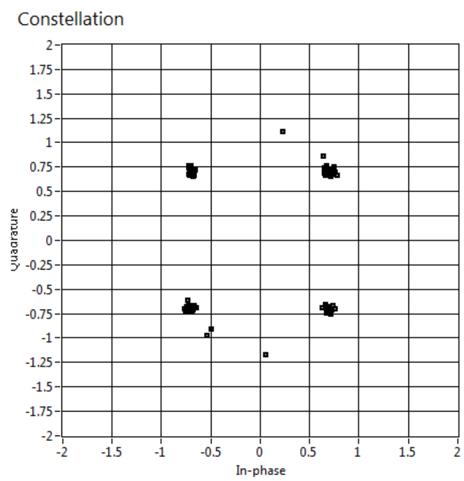


(a) Secondary Receiver Constellation for guard band spacing of 2 RBs

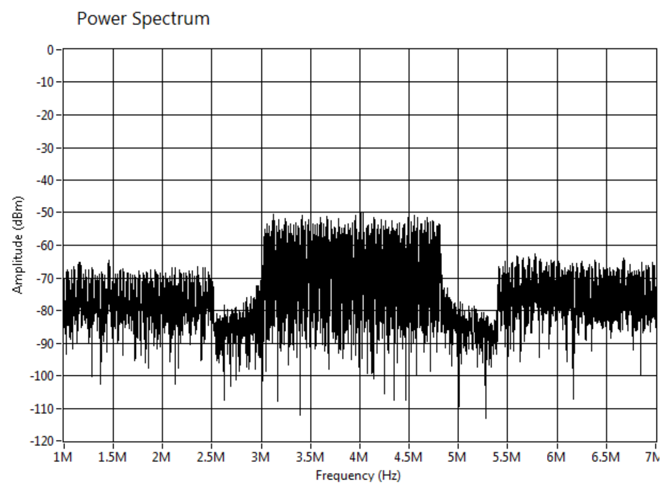


(b) Secondary Receiver Spectrum for guard band spacing of 2 RBs

Figure 4.8: Spectrum and constellation at the secondary receiver for a guard band of 2 RB



(a) Secondary Receiver Constellation for guard band spacing of 3 RBs



(b) Secondary Receiver Spectrum for guard band spacing of 3 RBs

Figure 4.9: Spectrum and constellation at the secondary receiver for a guard band spacing of 3 RB

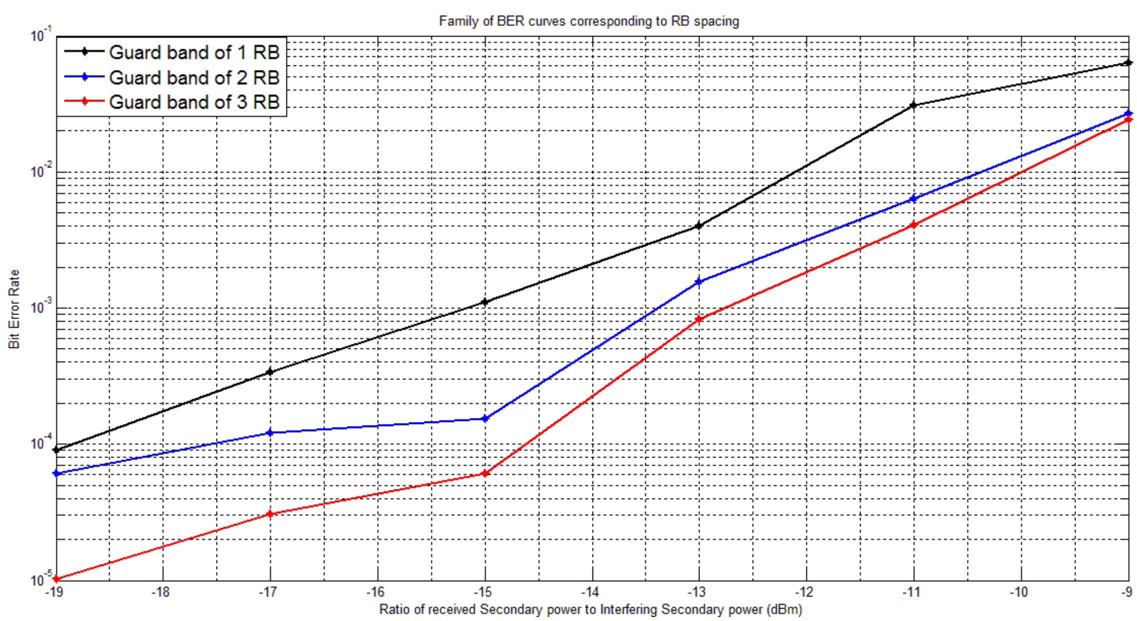


Figure 4.10: Bit Error Rate curves showing performance of secondary link against varying secondary interference transmit power for different guard band spacings in a wireless environment

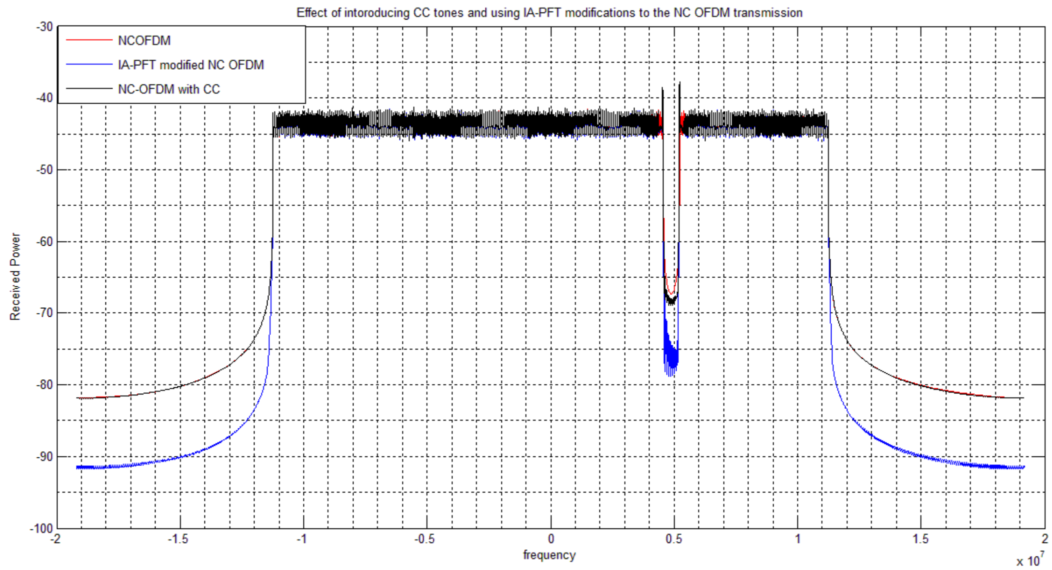


Figure 4.11: Spectrum of NC OFDM transmission, IA-PFT modified NC OFDM transmission, and NC OFDM transmission with CC tones added for a notch of bandwidth corresponding to 3 RB

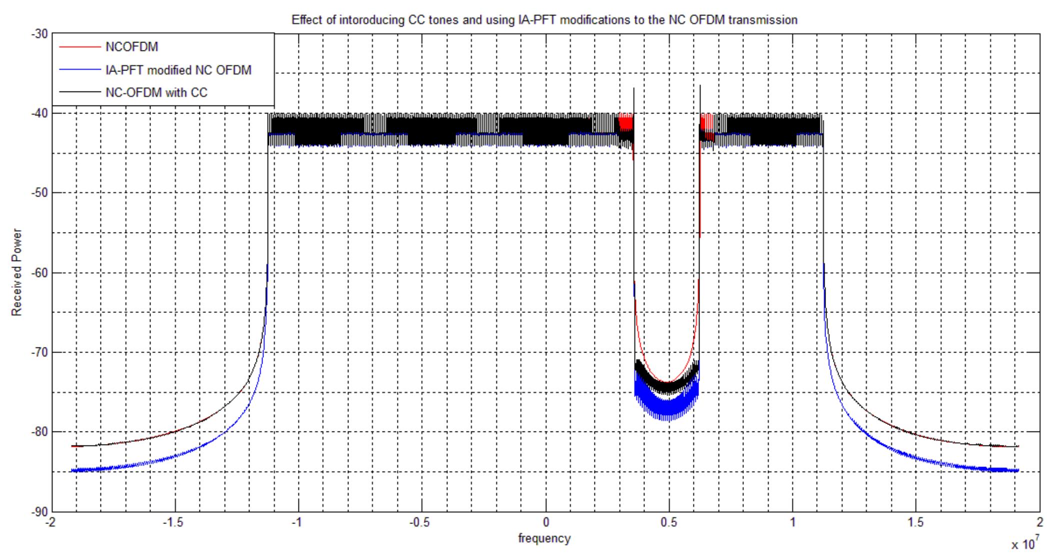


Figure 4.12: Spectrum of NC OFDM transmission, IA-PFT modified NC OFDM transmission, and NC OFDM transmission with CC tones added for a notch of bandwidth corresponding to 12 RB

Chapter 5

Conclusions and Future Work

5.1 Conclusions

This thesis focused on a real time implementation of a Secondary link and also discussed various parameters to be considered while evaluating coexistence of two or more secondary links. It has been assumed that the secondary nodes had been allocated their respective spectra for transmission. More Importance has been given to evaluation of DSA for two or more secondary links to coexist. The effect of interference of other secondary transmissions on a particular secondary link were studied and analyzed via BER analysis. It is possible to design a mathematical model based on these experiments to generalize the effect of secondary interference and thereby characterize secondary transceiver performance. This mathematical model would be beneficial in the design of future secondary devices. The guard band spacing has been observed to influence the effect of interfering secondary transmissions on the performance of a particular secondary link. Smaller guard band spacing increases the spectrum utilization efficiency but also affects the performance of coexisting heterogenous secondary links. The tradeoff between maximal spectral utilization and Secondary transceiver performance was better understood by the experiments performed. Implementation of advanced interference suppression techniques revealed that a suppression gain of 10-12 dB is clearly observed. Additionally, various hardware design related issues and concerns like timing considerations, resource block allocations, among others, were studied and a more efficient real time secondary transceiver design was implemented.

5.2 Future Work

The secondary transceiver setup that has been built that can serve as a testbed for further experiments. Since most of the design parameters used closely follow the LTE standards, the future experiments that will be performed using the testbed may yield results that adhere to industry specific standards. The IA-PFT module design built on the FPGA can be further improved to achieve more efficient resource allocation and meeting of the timing constraints. Wireless Experiments can be performed using IA-PFT modified NC OFDM transmission to observe gain in suppression. Further experiments can be performed to evaluate the coexistence of more than two coexisting secondary users.

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