FULL DUPLEX SELF INTERFERENCE CANCELLATION

A Project Report

submitted by

VIPUL JAIN

in partial fulfilment of the requirements
for the award of the degree of

MASTER OF TECHNOLOGY

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY MADRAS.

May 2014

THESIS CERTIFICATE

This is to certify that the thesis titled **FULL DUPLEX SELF INTERFERENCE CANCELLATION**, submitted by **Vipul Jain**, to the Indian Institute of Technology, Madras, for the award of the degree of **Master of Technology**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Dr. RadhaKrishna Ganti
Project Guide
Assistant Professor
Dept. of Electrical Engineering
IIT-Madras, 600 036

Place: Chennai

Date: 1 May 2014

ACKNOWLEDGEMENTS

First of all, I want to thank my guide **Dr.RadhaKrishna Ganti** for his immense support,coordination and a perfect guidance on any related issues.His enthusiasm, encouragement has always been a key factor behind the work and my learnings. I would also like to thank **Dr.S Aniruddhan** as for his thoughtful ideas and discussions with him has always been the driving force in this project.

I can't forget to thank Gaurav and Abhishek who has been a leading partners and main contributors not only on circuit development part of the project but has helped me also a lot.I would like to thank Ankit also for his insights into the work.Earlier in the project , i was not having any idea about the hardware, linux, USRP which could have made life difficult but Arjun, Praveen, Sourav, Reshma made it a lot easier with their help.

Life at IITM has been a wonderful time of my life. The pleasent atmosphere has always been a charm. I would take this opportunity to thanks all the professors who taught us not only the subject but the real concepts behind it and also thank my friend circle comprising of classmates including Mahesh ,Shailendra ,Praneeth ,Pavan ,Sriram and all the friends in networks lab and VLSI lab who have been an integral part of my life at IIT ranging from studies to meaningless gossips.I was also lucky to have Gourav, Malay, Pradeep at IIT who made looked this stay comfortable enough that I never felt bored or alone thanks to them. I take this opportunity to thank all the persons over the internet who have asked different questions also to who answered them , to thousands of people who have contributed in years over the internet since it has always been a great learning guide and helped me tackled a lot of problems.

I can't thank enough my parents and brother who have always supported me in all my endeavours and sacrificed their needs for my betterment ensuring that I am always ready to face any challenge in my life.

ABSTRACT

KEYWORDS: Full Duplex, Self Inteference, Analog RF Cancellation

In this thesis , an implementation of self interference cancellation for full duplex communication in analog RF domain is presented.In Full Duplex, for effective communication it is desirable to have self interference cancellation of transmitted signal to noise floor which for an OFDM Signal of peak power 30 dBm and noise floor -90dBm would be 120 dB. Achieving this cancellation becomes challenging with the effects from problems of group delay, phase noise, quantization noise , I-Q imbalance ,non-linear effects etc which are all part of self interference .These problems are resolved using the analog cancellation in RF domain which provides sufficient analog cancellation to counter these effects. It is also shown that with the analog cancellation achieved the signal can now be explored for more self interference in base-band domain since the self interference signal ,received signal, and noise floor all will be within the dynamic range of ADC.Required analog cancellation is attained using self cancellation board developed at our institute which provides around 30 dB of isolation and the remaining cancellation is attained by feeding from dummy port the cancellation signal in analog generated by changing attenuation and phase through vector modulators and external attenuators which gives us a total of 60 dB of cancellation in analog domain .The point of best cancellation is obtained using the modified version of gradient descent method.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

ADC	**A**nalaog to **D**igital **C**onvertor
AIN	**A**nalaog **IN**put
BB	**B**ase-**B**and
BBB	**B**eagle-**B**one **B**lack
DAQ	**D**ata **Aq**uisition Device
eMMC	**e**mbedded **M**ulti**M**edia **C**ard
GPIO	**G**eneral **P**urpose **I**nput **O**utput
IITM	**I**ndian **I**nstitute of **T**echnology **M**adras
MIMO	**M**ultiple **I**nput **M**ultiple **O**utput
mV	**m**illi **V**olt
NI	**N**ational **I**nstruments
PCIe	**P**eripheral **C**omponent **I**nterconnect **E**xpress
RF	**R**adio **F**requency
RSSI	**R**eceived **S**ignal **S**trength **I**ndicator
SI	**S**elf **I**nterference
SPI	**S**erial **P**eripheral **I**nterface
USRP	**U**niversal **S**oftware **R**adio **P**eripheral
VM	**V**ector **M**odulator

CHAPTER 1

Introduction

1.1 Introduction

In today's world,wireless communication is a need of all but with the limited spectrum the difficulty arises in going beyond the bar to increase capacity which result is the limited data transfer speeds and/or limited number of users that could be supported at a time. Most of the methods to increase capacity are at their best and so do not incur much improvement .But thinking of transmitting and receiving at same frequency band at the same time gives the solution in the form of doubling of the capacity and throughput.Also it can solve the problem of media access control and multirate adaption (Jain *et al.*, 2012).Generally, in wireless communication and in particularly full duplex, the data is transmitted and received at the same time in the different frequency band. It is so because if the same band is used, there arises self interference signal(i.e. transmitted signal at the same node) at receiver chain which is significantly of higher power than desired signal to be received from other node. In this case the concept of full duplex is redefined and here Full Duplex refers to simultaneous transmission and reception of different signals in the same band.Firstly, model for the full duplex presented at universities as RICE , STANFORD , etc who showed some interesting results related to the self interference cancellation and achieved remarkable results.Although the concept implemented showed results which can readily be applied to large wireless systems but still lacks the part to be considered as effective solution for small mobile devices.

So in full duplex communication we try to cancel the self interference to noise floor having only the desired signal left at the receiving part of the node which actually is also transmitting to other node from transmitter side at same frequency.The main concept is to cancel its own self interference through the various analog and digital cancellation techniques(Sahai *et al.*, 2012).Various methods have been applied to cancel the self interference, which began from using three antennas(Choi *et al.*, 2010) down to two antennas and now at single antenna.The different models for full duplex have been analyzed in depth for analytic results(Sahai *et al.*, 2012) which tells the limitation for the different techniques.Thereafter the recent technique is reported to be achieve cancellation of around 110dB, which brings down the signal to the level of noise floor by modeling the interference at analog and digital levels.The basic idea could be represented through the following figure :

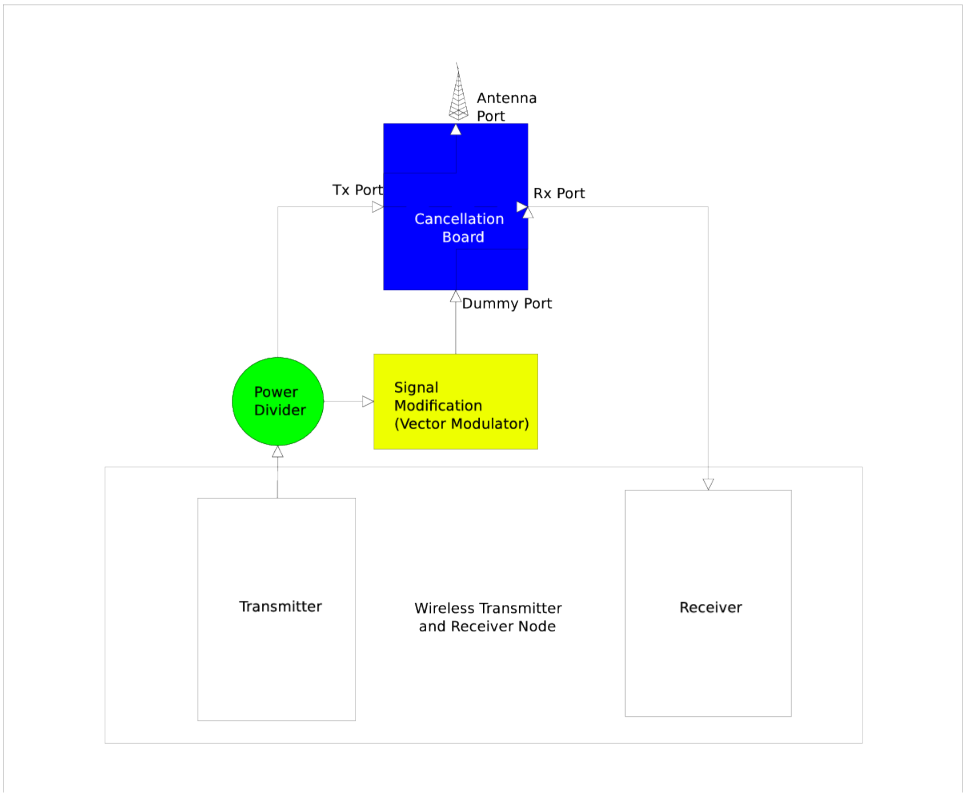

Figure 1.1: Basic Idea

Cancellation board has been explained in Chapter 3.It takes input from Tx port and transmits it from antenna through Antenna port.Received signal from antenna goes to Receiver port.Also cancellation signal is given through Dummy port. Here if the SI is canceled in analog domain through modeling the cancellation in digital domain, it is referred to as baseband analog cancellation and if the cancellation signal is extracted and varied in analog domain after transmission then it is referred to as RF analog cancellation.It is shown that due to various effects (non-linearities, phase noise of analog circuits like power amplifiers,oscillators) it is not possible to achieve required amount of cancellation for baseband analog cancellation.Therefore RF analog cancellation technique are used to cancel the signal in analog domain. Analog domain cancellation becomes important due to two main factors: 1)Limited Dynamic Range of ADC's : Due to limited dynamic range of ADC's, the required signal could get vanished in the quantization error so before ADC decent minimum cancellation is required in analog domain. 2)Due to random nature of noise in the RF domain which arises from high power components, it could to lead to complete distortion of received signal so should be tapped out and canceled in analog domain(Bharadia *et al.*, 2013). So for achieving full cancellation, RF cancellation technique is applied and it achieves around 60dB of cancellation for the main component path.But in the real wireless environment as we transmit through the antenna , antenna mismatch and multipath component also arises which also consists of significant power and must be canceled.For that we plan to increase the robustness of the technique to handle those path also giving sufficient amount of analog cancellation.

Next discussed in chapter 2 are the various challenges present in the implementation of full duplex followed by theory of analog techniques of cancellation which uses the board developed at our institute an it contains the basic mathematical model which is used to achieve the analog cancellation .Then the simulation for the cancellation using vector modulator is discussed. Thereafter follows the implementation details of it through various hardware devices used, which achieves the analog cancellation of around 60dB.

CHAPTER 2

Challenges in Full Duplex Communication

2.1 Challenges in Full Duplex Communication

As mentioned in the introduction there are numerous challenges faced in the implementation of full duplex which have to be taken into account while canceling SI signal.When we tried to cancel the SI through the base-band cancellation approach, we experienced these effects that heavily limits the cancellation in the analog domain. Some challenges faced were IQ Imbalance, ,effects of non-linearities, transmitter and receiver phase noise ,random group delays (which shifts the different frequency components by different amounts). In actual when signal is translated while transmitting from Base-band to RF, the signal in addition of getting frequency and amplitude translation also undergoes the addition of non-linear components, oscillator phase noise and random noise from high power components which must be canceled in the analog domain. Different components can be classified as(Bharadia *et al.*, 2013):

- **Linear Components** - Comprises of multipaths and delayed components leaking through the circuit.
- **Non-Linear Components** - They comprises of the non-linearities or harmonics generated by the analog components such as power amplifier ,mixers and other components.
- **Noise Components** - This is due to the high gain amplifiers and other high power components.

2.1.1 Phase Noise

Phase noise or jitter is a key element in many RF and radio communication systems as it significantly affect the performance of systems. While it is possible in an ideal world to look at perfect signals with no phase noise, that are a single frequency, this is not generally the case. Instead, all signals have some phase noise or phase jitter in them.

In many cases this may not have a significant effect, but for others it is particularly important and needs to be considered.

For radio receivers, phase noise on the local oscillators within the system can affect specifications such as reciprocal mixing and the noise floor. For transmitters it can affect the wideband noise levels that are transmitted. Additionally it can affect the bit error rate on systems using phase modulation as the phase jitter may just cause individual bits of data represented by the phase at the time to be misread.

Phase noise is also important for many other systems including RF signal generators, where very clean signals are required to enable the generator to be used as a reference source.It largely effects the error vector magnitude and spread the signal.The phase noise effect depends on oscillator and is generally modeled in frequency domain using lorentzian function. The effect is quantified in terms of dBc per hertz at the frequency close to the carrier frequencies and sometimes also related with jitter. The mean square value of jitter can be found by integrating the phase noise profile over the frequency range. The phase noise profile is typically specified in decibels, decibels below carrier per hertz or dBc/Hz at a frequency away from the carrier frequency .

In full duplex communication also , phase noise has been studied as a major limitation and models have been suggested for phase noise modelling and removal from SI(Sahai *et al.*, 2012).It can be understood as $x(t) = Asin(\omega_c t + \phi)$, where $\phi(t)$ is generally modeled as a cyclo-stationary random process and is mainly contribute by the oscillators.For getting an idea of the effect of phase noise with increase in phase variation, the simulation(Sankar, 2012) figure as shown below can be helpful.

Since modelling of phase noise and its accuracy can be a concern it becomes an all together an independent problem to be modeled and study its aspects in case of full duplex. Although in one of the other papers(Bharadia *et al.*, 2013) phase noise is removed by its replication in RF and then canceled out in analog part since it was found to be considerably less than the actual signal power .This can be measured using Spectrum analyzer in our case since the accuracy/resolution of spectrum analyzer is much better than phase noise of DUT(device under test).

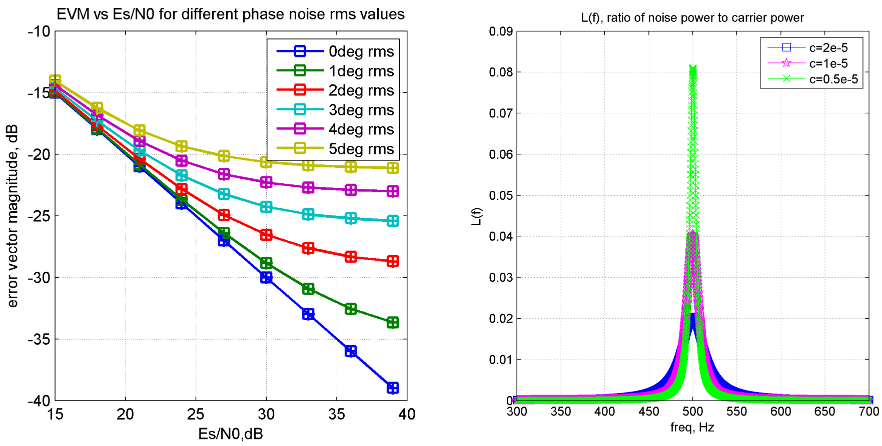

Figure 2.1: Effect of Phase Noise on EVM vs Es/No and Laplacian modelling of phase noise

2.1.2 IQ Imbalance

IQ Imbalance(Sankar, 2009) - There are three ways which can cause I-Q imbalance which are given as: **Amplitude Imbalance** - Since I and Q components take different paths both in transmitter and receiver to achieve I Q modulation and demodulation.IQ mixer introduces IQ imbalance due to its different branches. When the circuit introduces gain error between I and Q components, we get gain or amplitude imbalance as depicted in figure. **Phase Imbalance** - Also when the phase of I and Q signals are not matched then we get what is known as phase imbalance.

Also with variation in amplitude and phase imbalance of few degrees , the received spectrum in comparison with original becomes as follows:

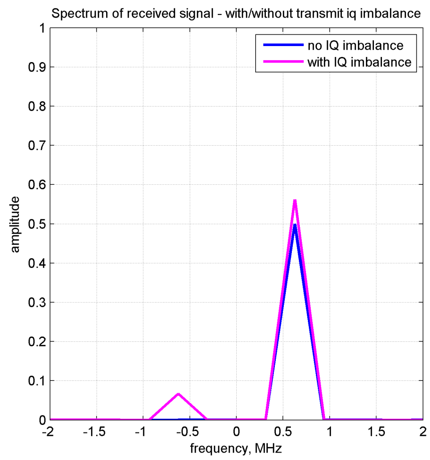

Figure 2.2: IQ imbalance

I and/or Q dc offset - It occurs due to difference between DC bias applied to I and

Q components.This results in carrier leakage at the output of the modulator. With an amplitude IQ imbalance compensation/correction

There are various methods available to compensate for these imbalances at the transmitter and receiver end. The most common are using known pattern/modulation type. Moreover IQ DC offset is compensated/corrected by adjusting DC bias applied to I and Q signals for better rejection of carrier at the output.generally By IQ compensation we can improve error vector magnitude of the modulated signal that helps in decoding the signal correctly and will decrease the Bit Error Rate (BER) of the system.

2.1.3 Non - Linearities

It mainly consists of odd harmonic components and inter-modulation products .Magnitude/Effect of 3rd harmonic component can be calculated by IIP3 which is the most high power non-linear component.Also the power of inter-modulation components depends on the device and frequency range used while transmitting the signal.These components can be effectively removed by filtering if they are in the different bands from the transmitted signal but have to be carefully dealt or compensated with if are in the same band since then they can distort the signal. In our experiment these are dealt directly as they are also replicated while using RF cancellation.

2.1.4 Multipaths

In wireless communication, multipaths are inevitable and always present in the form of reflections from the environment.They are generally modeled in the form of Rayleigh if they are due to scattered reflectors or in the form of ricean or nakagami in case of one main path component.Here in addition to the reflected path, self interference also consists of the leakage/direct component from the board since isolation inside the circuit is not perfect . Here we need to estimate the significant component arising due to multipath and cancel them appropriately in analog and digital domain cancellation.

2.1.5 Reflection Leakage

There also exists a major reflection component due to impedance mismatch of antenna with board's antenna port.This is of a significant power and canceled using vector modulator which generates a opposite signal at the dummy port to cancel it completely.

CHAPTER 3

Theory of Cancellation - Baseband and RF Cancellation

Our main aim is to achieve the analog cancellation of SI signal, which must be at least 60 dB and more for 20 dBm of transmit power.For achieving this cancellation a 4 port RF board has been designed. The board schematic is as shown .It consists of 4 ports labeled as Tx(Transmitter Port), Rx(Receiver Port),Ant(Antenna Port) and Dummy(Dummy Port).It consists of wave-guide of dimensions which provides us with the following response around 2.45 GHz.

Table 3.1: Board Parameters

Ports	Attenuation in dB	Delay in nanoseconds
Tx to Rx	30	1.057
Ant to Rx	4.134	0.642
Dummy to Rx	4.134	0.642

So it actually decreases(isolates) the main path power by atleast 30 dB in the desired range of frequencies and also the order of reflections are at the small but significant level due to mismatch occurring because of imperfect antenna impedance.There also occurs some multipath reflection from nearby reflectors through antenna which can be modeled by transmitting known symbols and estimating self interference channel generating them.Also the board is symmetric with respect to dummy and Ant ports.There comes other path from Ant to Rx port leakage and strong self multipaths as specified earlier which forms the secondary path. These two path consists of Self Interference which is to be canceled by using the opposite phase signal from dummy port.So as the opposite phase signal at dummy port adds with this signal, it leads to the cancellation of SI when properly matched.

The theory following this principle is quite simple and straightforward to understand.

3.1 BaseBand Analog Cancellation

In baseband analog cancellation, a sinusoid is transmitted from a USRP and the cancellation signal is generated in baseband from another USRP and fed to the dummy port.Now the amplitude and phase of the cancellation signal is adjusted such that it matches in amplitude and is of opposite phase.For any signal, addition of both SI signal and cancellation signal produces a null at receiver.In practice for single tone signals this method works quite well but for multi tone signals (or as bandwidth is increased), the cancellation achieved is decreased due to various effects of group delays, non-linearities, IQ imbalance, phase noise, etc.. All these effects limits the cancellation and therefore the required cancellation is not achieved.So to counter these effects and for achieving required cancellation, RF analog cancellation methods are explored.

3.1.1 Single Tone Cancellation

$$
\begin{aligned}
x_1(t) &= Ae^{j2\pi f_m t} \\
x_2(t) &= A'e^{j2\pi f_m t}e^{j\phi'} \\
x_{Tx}(t) &= Be^{j2\pi(f_c+f_m)t} \\
x_{Dummy}(t) &= B'e^{j2\pi(f_c+f_m)(t-\tau)e^{j\phi}e^{j\phi'}}
\end{aligned}
$$

where $x_1(t)$ represents transmitted signal and $x_2(t)$ represents dummy signal for which A' and ϕ' can be varied which leads to variation in B' and $\phi'.B$ and B' are the amplitude of the signal after getting amplified at the transmitter. When $B' = B$ and $\phi' = -[\phi + (f_c + f_m)(-\tau)]$, then required cancellation is achieved.

3.1.2 Multi Tone Cancellation (No. of tones = 2)

$$x_1(t) = A(e^{j2\pi f_{m1}t} + e^{j2\pi f_{m2}t})$$
$$x_2(t) = A'(e^{j2\pi f_{m1}t} + e^{j2\pi f_{m2}t})e^{j\phi'}$$
$$x_{Tx}(t) = B(e^{j2\pi (f_c+f_{m1})t} + e^{j2\pi (f_c+f_{m2})t})$$
$$x_{Dummy}(t) = B'(e^{j2\pi (f_c+f_{m1})(t-\tau)} + e^{j2\pi (f_c+f_{m2})(t-\tau)})e^{j\phi'}$$

A' and ϕ' can be varied which leads to variation in B' and ϕ' When $B' = B$ and $\phi' = -[\phi + (f_c + f_{m1})(-\tau)]$, then required cancellation is achieved for 1st tone and unless 2nd tone is close there is no significant cancellation at that tone.

3.2 RF Analog Cancellation

Here the cancellation signal is acquired as a tap from the transmitted signal and is then amplitude and phase shifted in the RF domain to match the self interference (consisting of transmitted signal leakage component from Tx to Rx port,antenna reflection and various multipaths).The cancellation methodology can be understood as follows:

$$x_{Tx}(t) = x(t)e^{j2\pi f_c t}$$
$$x_{SI}(t) = Ax(t-\tau)e^{j2\pi f_c(t-\tau)}e^{j\phi}$$
$$x_{Dummy}(t) = Bx(t-\tau_1)e^{j2\pi f_c(t-\tau_1)}e^{j\phi'}$$

Here τ_1(constant) and ϕ'(variable) compensates for delay and phase mismatch and B(variable) is used for the amplitude matching of the SI signal with dummy port signal.Extension of this for OFDM signal can be understood as: Consider a transmitted wave as $A * sin(\omega_c t)$ and let us receive a signal $b * sin(\omega t + \phi)$, where ϕ consists of phase change due to delays and other phase change(in any of the component) which is constant. Now we transmit a dummy signal $K * sin(\omega t + \theta)$, where K and θ are varied such that $K = b$ and $\theta = \phi + \pi$ so that they add up to produce null signal . This analysis also holds true for any narrow band signal also getting large values of cancellation. Here only Vector Modulator(Circuit changing the attenuation and phase) noise factors may limit the cancellation.

Now considering a transmitted OFDM symbol which is given as

$$x(t) = \sum_{k=0}^{N-1} X_k e^{j2\pi k \frac{t}{T}}, \quad 0 \le t < T \tag{3.1}$$

where $\{X_k\}$ are data symbols and T is the OFDM symbol time.Sub-carrier spacing of $\frac{1}{T}$ makes them orthogonal.With Cyclic Prefix also , signal becomes

$$x(t) = \sum_{k=0}^{N-1} X_k e^{\frac{j2(\pi)kt}{T}}, -T_g \le t < T \tag{3.2}$$

where T_g is the length of cyclic prefix. Now the real domain transmitted signal at carrier frequency of f_c is given by:

$$s(t) = \Re\left\{x(t)e^{j2\pi f_c t}\right\} \tag{3.3}$$

$$= \sum_{k=0}^{N-1} |X_k| \cos\left(2\pi[f_c + k/T]t + \arg[X_k]\right) \tag{3.4}$$

$$s(t-\tau) = \sum_{k=0}^{N-1} |X_k| \cos\left(2\pi[f_c + k/T](t-\tau) + \arg[X_k]\right) \tag{3.5}$$

$$= \sum_{k=0}^{N-1} |X_k| \cos\left(2\pi[f_c + k/T]t + \arg[X_k] - 2\pi[f_c + k/T]\tau\right) \tag{3.6}$$

For OFDM symbol time is $3.4\mu s$ and taking number of sub-carriers to be $N = 1024$, we get $\frac{K}{T} = \frac{1024}{3.4\mu s} = 280MHz << f_c$ which is around $5GHz$

So it can be seen that the OFDM wave can be assumed to be narrow band signal for Bandwidth of range used in 802.11ac and we can reasonably cancel the signal in analog domain by just matching the attenuation and phase of the signal.

3.3 Vector Modulator

It is used to change the gain and phase of the cancellation signal to match the SI signal.It works in the principle that the input signal to VM is divided into inphase and quadrature component and then they are attenuated by different amounts such that they combine to produce a required phase shift.Also an external attenuator can be installed which varies its attenuation such that the total attenuation of the circuit matches the required one.

3.4 Gradient Descent

To set the optimal value of attenuation and phase that achieves the maximum SI cancellation, searching over the entire space is not efficient.Therefore gradient descent method is applied which converges to the required point achieving decent amount of SI cancellation in few iterations depending upon the initial point and step size chosen.

3.5 Required amount of cancellation for full duplex

Based on above analysis and the results from different previous works(Bharadia *et al.*, 2013), (Sahai *et al.*, 2012) considering transmit power to be of 20dBm as of WiFi, the total amount of cancellation required comes out to be 110dB to set it to noise floor and out of that atleast 60dB must be achieved in analog domain and rest to be done in digital domain.Since the various effects caused by analog circuits which are random or complex in nature (therefore can't be modeled analytically)have the power owing to excess of around 60dB above noise floor so they must be canceled in analog domain.Also considering dynamic range of ADC to be 72dB(12 bits), it turns out that if 60dB in analog is achieved then received signal is totally prevented from distortion due to quantization error.

CHAPTER 4

Simulation Results with VM

This Chapter includes the details of the simulation done to find out the cancellation that can be achieved combinedly by cancellation board and Vector Modulator.Here a model for analog cancellation is made where For analog cancellation we use vector modulator to generate a copy of Tx signal and attenuate and phase shift it so that it matches the signal. The simulation is done to find out the amount of SI cancellation possible for a wideband OFDM signal with the help of a Vector modulator in real type of environment taking into account all the board parameters and multipath effects. We also extend this simulation to using 2 VM instead of one.

For this simulation, we consider the actual parameters of board and also did the following antenna measurements to find the power of reflected component from reflectors at different distances in real environment.

4.1 Antenna Measurements

Path Loss : Path loss (or path attenuation) is the reduction in power density (attenuation) of an electromagnetic wave as it propagates through space.Path loss normally includes propagation losses caused by the natural expansion of the radio wave front in free space (which usually takes the shape of an ever-increasing sphere), absorption losses (sometimes called penetration losses), when the signal passes through media not transparent to electromagnetic waves, diffraction losses when part of the radio-wave front is obstructed by an opaque obstacle, and losses caused by other phenomena. The signal radiated by a transmitter may also travel along many and different paths to a receiver simultaneously; this effect is called multipath. Multipath waves combine at the receiver antenna, resulting in a received signal that may vary widely, depending on the distribution of the intensity and relative propagation time of the waves and bandwidth of the transmitted signal. The total power of interfering waves in a Rayleigh fading scenario vary quickly as a function of space (which is known as small scale fading). Small-scale fading refers to the rapid changes in radio signal amplitude in a short period of time or travel distance.But for this case since antennas are close enough, the LOS path will be dominant.

Now,since we got the cancellation for the leakage component from Tx to Rx port(i.e. by terminating the antenna port), same cancellation was not achieved when antenna was fixed at the port.To get the power of reflection of the transmitted signal from outside reflectors back at the Tx antenna, characterization of antenna path loss at the nearby distances was done.In this experiment, known power was transmitted from one antenna and the other antenna was kept at a known distance and was tied to the power detector which was calibrated to measure the power received at the antenna in dBm. The difference in the power gave the path loss.

Same experiment was performed in two of the labs and the results for both are as shown:

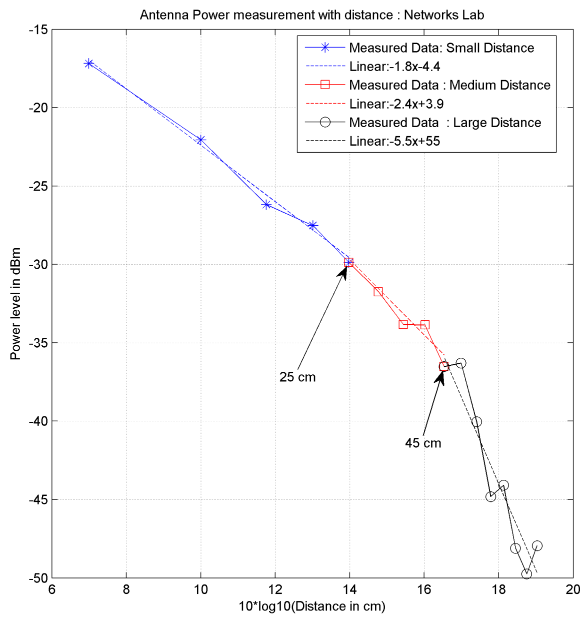

Figure 4.1: Path Loss as found in NSS lab

Results shows that as distance increases the path loss exponent also increases which is what we expected.Also the range of path loss exponent also matches the more general known path loss exponent for indoor environment of 4-6 which is what we got for distances over 50 cm.

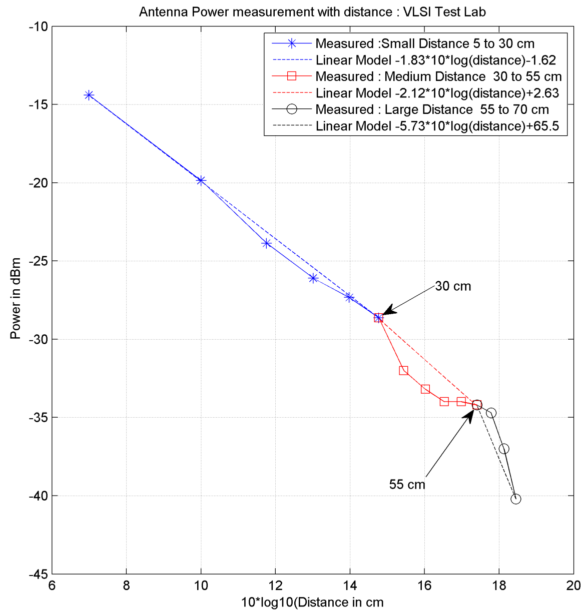

Figure 4.2: Path Loss as found in VLSI Testlab

4.2 Parameters Used in Simulation

Table 4.1: Simulaton Parameters

Parameters	Value/Comments
Bandwidth	10 MHz
Center Frequency	2.5 GHz
Interpolation factor	50-200 (for fine resolution of signal to replicate analog behavior)
Reflectors	Considered 3 at 15, 30 and 40 cm respectively (for fine resolution of signal to replicate analog behavior)
Vector Modulator Parametrs	
Attenuation Step	0.1 dB from 0 to 31 dB
Phase Step	0.1 degrees from 0 to 360 degrees
Constant attenuation	15 dB(so that optimal point lies in middle of search space w.r.t attenuation scale)

4.3 Simulation Results

Now the OFDM frames are taken and then up-converted to carrier frequency through quadrature modulation as follows :

$TX\ Signal = realpart(ofdm) * cos(\omega t) - imagpart(ofdm) * sin(\omega t)$

and converted to near analog signal by increasing resolution by interpolation factor. Here the path loss model as obtained from the readings at Vlsi test lab is use.Also the time propagation delay for each reflector is taken into account by calculating the delay and then reflected samples are generated by shifting the corresponding number of samples and attenuating by the value of path loss. For the isolation path since delay will be very small so it has been neglected and taken to be 0.Final samples for SI signal are calculated by adding the signal after isolation and all the reflected signals. Now the simple hill algorithm is implemented. In this algorithm an initial point (setting initial attenuation and phase value at VM) is chosen and the residual signal is found at that point and across its neighborhood. The next point is chosen from the neighborhood where the value achieves minimum. This process is recursively repeated until the local minimum is found. We perform this for two initial points , one beginning at 0 degrees and other at 360 degrees. Then out of the two points, the one with minimum value of residual signal is taken and this turns out to be the optimal point achieving the required analog cancellation of around 73 dB using 1 vector modulator and 73.5dB with 2 vector modulators. It tells us that there is no significant improvement by increasing the number of vector modulators from 1 to 2.

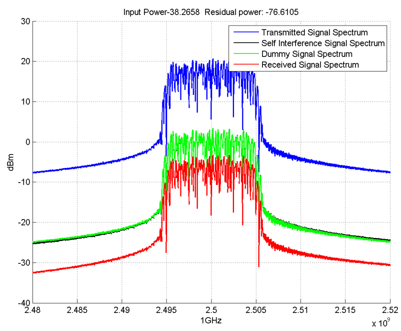

Figure 4.3: Residual Power using 1 VM

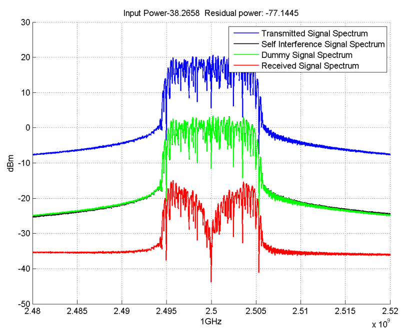

Figure 4.4: Residual Power using 2 VM's

CHAPTER 5

Implementation Details and Results

5.1 Method applied for Baseband Cancellation:

In base-band cancellation, a sinusoidal signal is transmitted from one USRP and the amplitude and phase shifted version is transmitted from another USRP which is MIMO synchronized with the first USRP. Now the amplitude of both signal are matched to the precision allowed and then phase is varied over the full range.It was found that when single tone is transmitted, this method works fine and cancellation close to noise floor was achieved(as seen on spectrum analyzer).But with the increase in number of tones, the cancellation was not uniform and random(not always same each time) over the tones.This may be due to various effects of group delay, narrowband assumption which gives rise to non uniform cancellation over different frequency bands and also many other artifacts of harmonics, phase noise as explained above which makes the cancellation limited. The residual value was measured with viperboard ADC and the RSSI chip available in IITM Full Duplex Board Rev 1 and the setup used is as shown below :

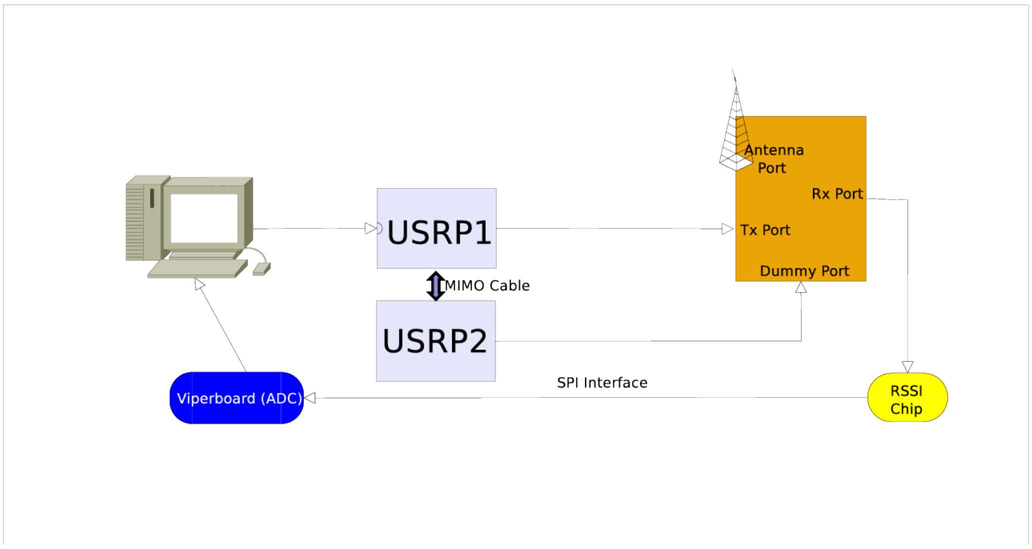

Figure 5.1: Base-band Cancellation

5.2 Method applied for RF cancellation (With Beagle Board and lumped Circuit Components):

With the limited scope of cancellation in BB method as explained, for getting required amount of cancellation in analog domain it was decided to explore the analog cancellation with practical signals by generation dummy/cancellation signal in RF domain itself by tapping a small amount of transmitted signal itself.So here a copy of known transmitted signal was generated and then used to cancel the self interference signal at the receiver.

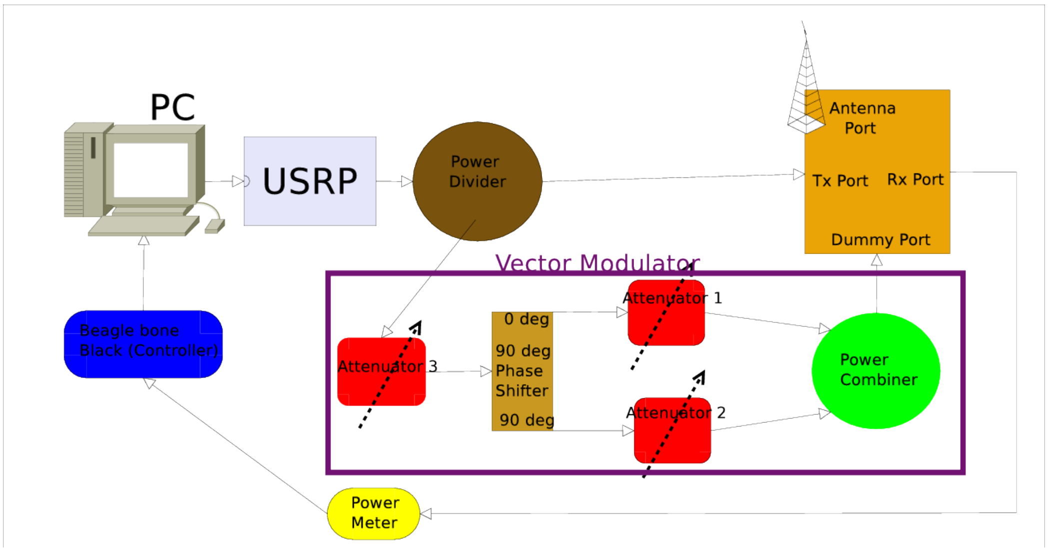

Figure 5.2: RF Cancellation

The concept is simple and yet powerful enough to provide with around 60 dB of analog cancellation. Firstly , the transmitted signal is divided into two equal (can be unequal also to save power) parts and main part is connected directly to the transmitter . On the supplementary/dummy path we set the required attenuation and opposite phase as incurred by the signal from transmitter to receiver and pass it to dummy port which leads to cancellation of the self interference to very low levels .Here we have three different attenuators which combines to provide the signal a range of different attenuation and any phase change.This signal is adjusted at an amplitude value(found with the help of spectrum analyzer once and for all and then the search path amplitude is adjusted to be around that) equal to main path and opposite phase which ultimately combines to give very low signal.

Range of attenuation value that can be achieved are from 0 to 31 dB and correspondingly phase change of 8 to 91 can be achieved.Now to cancel the delay of the supplementary path is adjusted with respect to main path such that opposite phase occurs at the setting of 45 degrees.Also the cancellation prevails over a high bandwidth upto 5 MHz .

Now there were many possible solution for achieving same attenuation and phase point but we chose the one according to following method which minimizes the error between the value of attenuation and angle required and the discrete value that can be achieved through the available search space since The values that could be taken by attenuators were limited for the requirement of any angle and attenuation .Suppose we want attenuation $X\ dB$ and angle θ so firstly, values of I and Q component are selected as

$$I = 20\log_{10}(Xcos(\theta)) \tag{5.1}$$

$$Q = 20\log_{10}(Xsin(\theta)) \tag{5.2}$$

After that external attenuator's ($A3$) value is chosen from the pool of values it can take. For each distinct value of A3, the corresponding values for remaining attenuator are calculated using :

$$A1 = I/A3 \tag{5.3}$$

$$A2 = Q/A3 \tag{5.4}$$

Now, among all these readings,one with minimum error in absolute sense with respect to closest allowed discrete value for $A1$ and $A2$ is chosen, i.e let $\tilde{A}1$ be the pool of distinct values allowed and $A1$ be actual values taken and same for A2,then one with minimum $|A1 - \tilde{A}1| + |A2 - \tilde{A}2|$ is selected.

Now the loop is swept over the range of various attenuation and angles possible and the cancellation through RSSI meter which reads the power in receiving signal is recorded.The plot between the attenuation , phase and dummy signal and $RSSI$ turns out to be having a deep valley as shown around a region which provides upto 60 dB cancellation points.

Here It can be noted that the RSSI meter provides the output value in volts from 0.6

to 2.1 V for various range of input power varying from 10dBm to -60dBm.Now for beaglebone black, maximum input for ADC is 1.8 V so a voltage divider is applied which truncates its maximum value to 1.8 V.Then with the help of signal generator, the RSSI meter is characterized with the help of signal generator to get the relationship shown between Output Voltage from RSSI meter and input power in dBm .Then a polynomial fit is applied as shown which is used to convert the values from RSSI meter in mV to dBm.

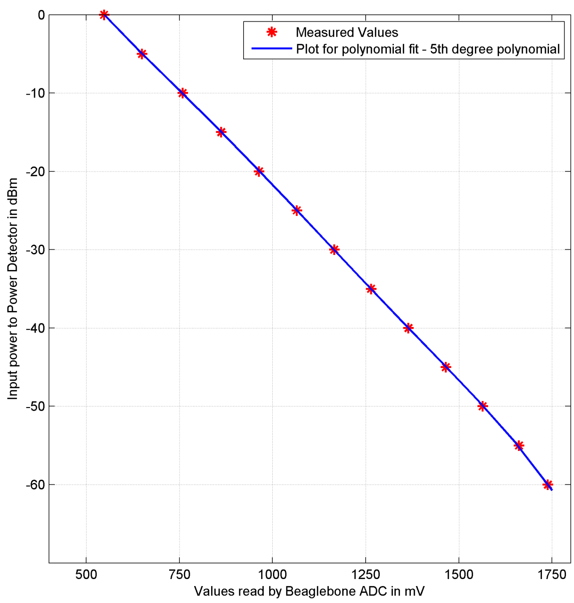

Figure 5.3: RSSI Mapping from mV to dBm

5.3 Phase Attenuators and Block Diagram

In this section ,the mathematical model behind the cancellation is presented. For simplicity if we assume a single carrier signal,this assumption is reasonably valid since carrier frequency is much higher than base-band frequency(also called narrowband assumption). Considering the transmitted signal reaching at receiver port be $x(t) = Acos(\omega t)$ and the signal from dummy port be $y(t) = Bcos(\omega(t - \tau) + \phi)$ where τ is some constant delay , B and ϕ can be changed to any desired value through some combination of values at attenuator's A1, A2 and A3 as explained above.Also the plot below shows the power level of signal when $A = 0.3$, B is varied from 0 to 1 and $(phi + \omega\tau)$,or say θ is varied all over from $0\deg$ to $360\deg$. The curve as shown has a valley of points which corresponds to the cancellation points.Although two-three points are there which in theory gives full cancellation , in practice it is found that the full cancellation is not possible to achieve due to random noise present and discrete range of values of θ and B achieved by the setup.

5.4 Modified Gradient Ascent Algorithm

Aim: To cancel self interference using attenuation and phase shift as mentioned in RF Cancellation part and To achieve the point of minimum cancellation or maximum mV reading from RSSI meter .
Algorithm Used(Modified Gradient Ascent): Since the exact function for the residual signal is not known apriori , but we know that over the search space the function is concave Hill Climbing Algorithm is being used here to find local maxima.

Step 1) Initial points are uniformly chosen from the search space to find the point of maximum cancellation.Here we chose 9 points distributed uniformly over attenuation and phase in 2D search space for a single vector modulator.(It was found that there is no need for uniform distribution over the attenuation dimension as point starting from same initial phase and different attenuation values converges to same optimal point.)So it can be reduced to 3 initial points.

Step 2) For each initial point the corresponding attenuation and phase value is set and resulting RSSI Value in mV is read through BBB-ADC. Also the RSSI value for its 3X3 neighborhood is calculated and the maximum among them is chosen.

Step 3) If the maximum value is found at the point other then initial point, the initial point is updated to be the same point and Step-2 is repeated.Otherwise the optimal point is declared if maximum is found at the initial point itself and from step-1 procedure is repeated for remaining initial points.

Step 4)Now local maximas found are compared among themselves to find the best possible maxima available.This is treated as the maximum cancellation point and the attenuation and phase value corresponding to this point are set.

The maximum cancellation point is found to be very close to actual global maximum.Also this point is found to have atleast $60\ dB$ of analog cancellation.

5.5 Specific Details

5.5.1 Beagle Bone Black Device Tree Overlays

Features: It consists of a 1GHz processor, 512 MB of RAM and 2GB eMMC on-board flash memory.On connector hardware side it has various options including SPI, I2C , GPIO(69 Max,3.3V I/O on all pins),4 AIN(1.8V Max) i.e 4 ADC pins ,etc.It comes with the angstrom OS installed which is a variant of linux and all its interfaces can be used by creating a device tree structure.Device tree structure is a new feature introduced in linux kernel which binds each device interface to a file structure which allows us to use the corresponding interface whether GPIO, ADC , SPI and so on.The device tree structures are compiled to form device tree overlays which is loaded onto system for using the pins through one-line command as given after next paragraph.

To begin with beagle board to program attenuators to set required attenuation values, GPIO pins were used and to read the RSSI values, the ADC pin was used.In beagle bone black available pins were allocated using device tree structure ,the required pins were allocated for specific use in the two different fragments, one for attenuators using GPIO pins and other for ADC pins used to read RSSI value.On loading the compiled overlay into /sys/devices/capemgr.9/slots in beagle board through the command

export SLOTS=/sys/devices/bone_capemgr.9/slots

echo FD-GPIO > $SLOTS

Here it can be checked that pin status for GPIO pins has been changed to mode 7 and also at path /sys/devices/ocp.3 folder namely **helper1.16** will be created consisting files AIN0-7 linked with ADC pins.Now these files are used in program to read RSSI values from the corresponding ADC pin. The file is set to read the value from the meter in mV and this value is then converted to dBm. The setup used is as shown below:

Following cancellation plot is achieved when sine wave at frequency of 2.45 GHz at 0 dBm is transmitted from signal generator.From the plot it is clear that about 60 dB analog cancellation is achieved at a range of points.

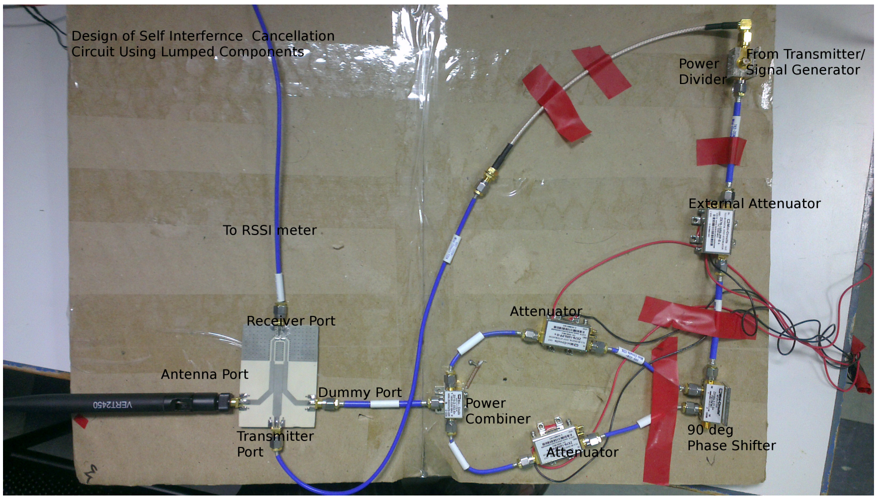

Figure 5.4: RF Cancellation Setup

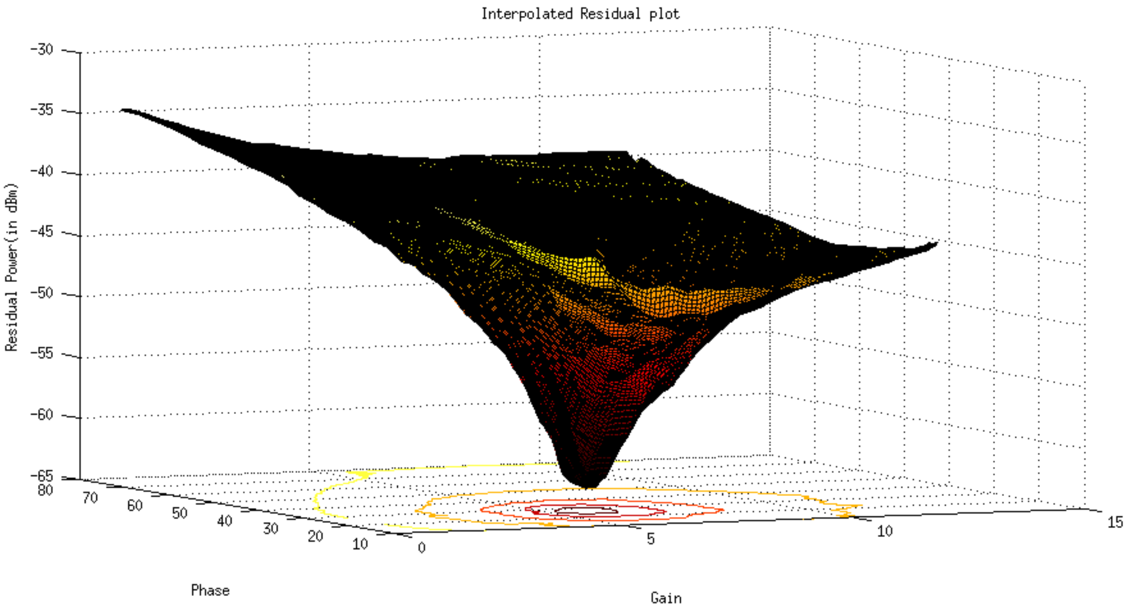

Figure 5.5: Cancellation Plot with Sinusoid

5.5.2 Important Notes

1. The pins which are already allotted cannot be allocated using the device tree and the device tree overlay although loads but doesn't provides the expected results.So unallocated pins as were found on Derek'sMolloy table were used.

2. Device tree overlays when loaded one after another , the second one doesn't load and just sits there.So whatever pins we want to set could be set using a single overlay.

5.6 Controlling Hittite Vector Modulator with NI DAQ (and Lab View)

Now to cope up with problems of limited angle range of 9 to 81 degrees, Hittie Vector Modulator(HMC631LP3) Corporation is used to have a full control over phase from 0 to 360 degrees.Now since this vector modulator work on the continuous control by varying I and Q control voltages from 0.5 to $2.5V$ to achieve a gain range of $40dB$ and angle range of 360 degrees, it necessitates the use of DAC to control voltage.So here NI-DAQ with PCIe NI interface is used which works with update rates of upto 2MSps which makes system very fast.Also to read RSSI value, its ADC interface is used. All interfaces were controlled using NI-Lab View software interface.The basic setup can be understood by the following figure:

Contrary to beaglebone ADC ,NI ADC can read voltage in a range -10 to +10 V. So here we use ADC in the range of 0 to 2.5 V in place of 0 to 1.8 V in beaglebone and it results in the following linear fit to convert voltage output of ADC to dBm.

In this system firstly, we first plot the residual power for all ranges of gain and theta available by varying gain and phase by changing I and Q which are calculated using given formula in the data sheet of Vector Modulator.

The system is developed using LabView NI-LabView which is a system-design platform and development environment for a visual programming language from National Instruments.LabView is commonly used for data acquisition, instrument control, and industrial automation.In our setup LabView is used to control the I and Q terminal of Hittite Vector Modulator through a fast speed NI-DAQ device NI PCIe-6363 using 2

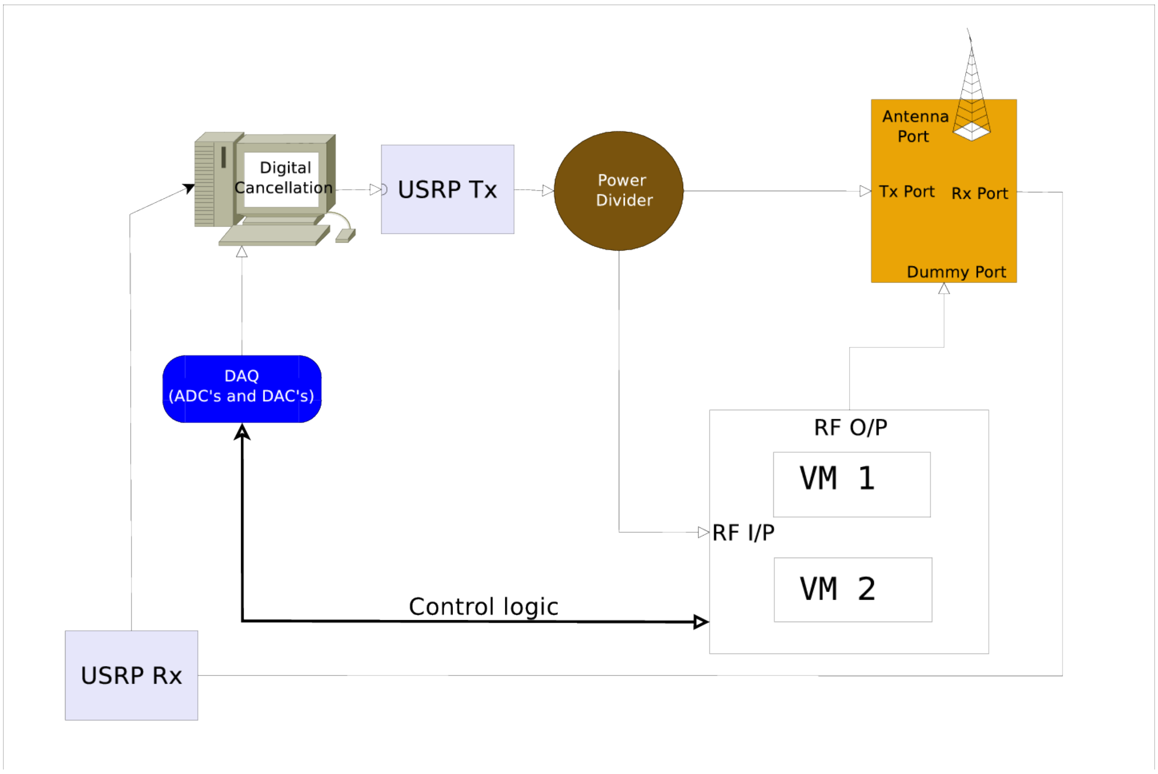

Figure 5.6: RF Cancellation

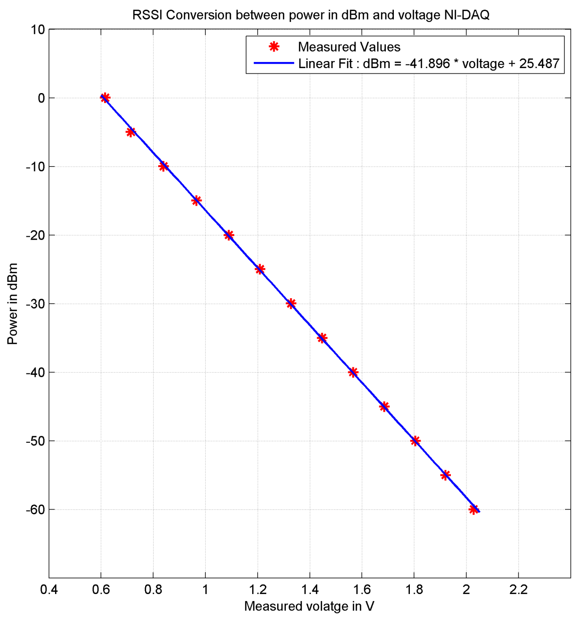

Figure 5.7: RSSI Mapping from mV to dBm

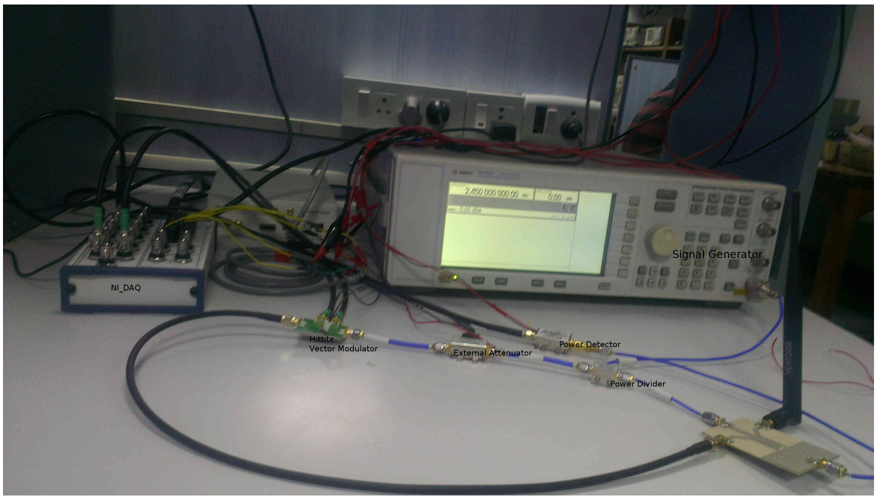

Figure 5.8: Cancelation Setup for Hittite VM

analog output pins which provides a 16 bit resolution over any given range between -10 to 10 V.In this case we have provided a range of 0.4 to 2.6 V so the resolution will be $(2.6 - 0.4)/(2^{16})$ which is $33.57\mu V$. Also an external attenuator is used to control the total attenuation in dummy path through available digital I/O pins. To read the residual output RSSI value, an ADC pin also of 16 bit resolution is used over the given range of $0 - 2.5V$.

5.6.1 Cancellation Results without antenna

Now we repeated the same experiment as in beagle board and lumped components.To summarize this setup, we experimented with the sine wave from signal generator at a frequency of 2.45 GHz as an input signal which is divided into 2 parts one of which is fed to the transmitter port of Full Duplex board and the other is connected to external attenuator and then to VM input. Output of VM is connected to dummy port.Again the Antenna port is terminated and the Receiver port is connected to RSSI meter input which outputs the corresponding signal power reading to ADC pin of NI-DAQ as mentioned above.Now through LaView programming, the attenaution value of Hittie VM is kept constant at 10dB attenaution.Along with this search space is varied over by varying external attenauation in outer loop and the phase value is swept over the full ranege of 0- 360 degrees from VM by changing its I and Q values accordingly at the DAC output of NI-DAQ.The cancellation plot in this case turns out to be as shown in Fig 4.8 where it can be clearly seen that there lies a point which achieves around 55-60dB of cancellation.

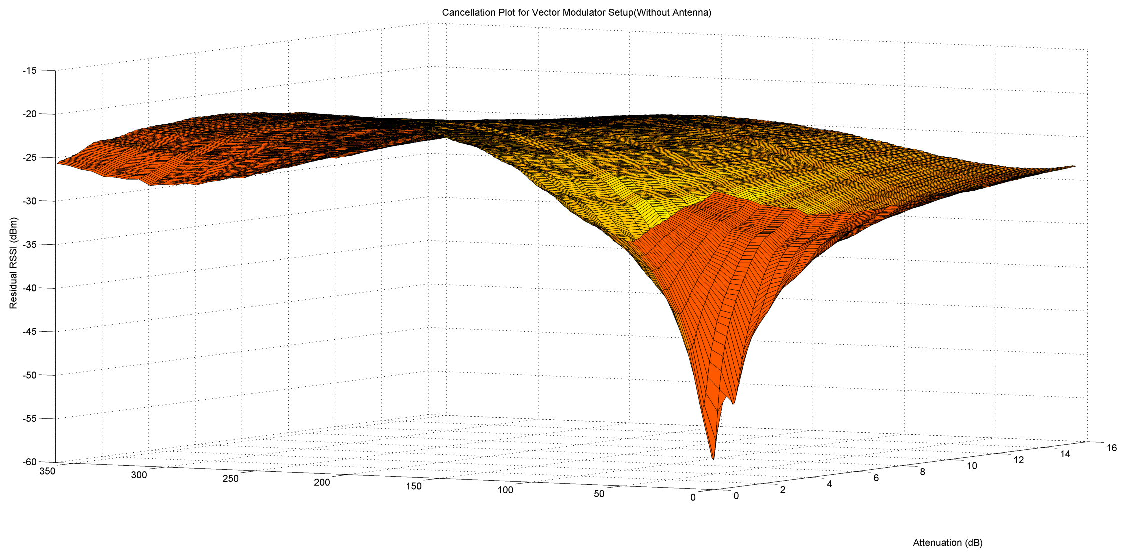

Figure 5.9: Cancellation Plot showing Residual RSSI in dBm

For getting the required I and Q values for desired phase and attenuation, we use the following formula as given in the data sheet Corporation of Hittite VM :

$$I(G, \theta) = V_{mi} + 1.0V \frac{G}{G_{max}} cos(\theta) \tag{5.5}$$

$$Q(G, \theta) = V_{mq} + 1.0V \frac{G}{G_{max}} sin(\theta) \tag{5.6}$$

where V_{mi} and V_{mq} are I and Q voltage setting corresponding to maximum isolation at room temperature and F=2GHz. Also $G = 10^x$ and $G_{max} = 10^y$ where $x = \frac{GainSettingindB}{20}$ and $y = \frac{MaxGainSettingindB}{20}$.Nominally $V_{mi} = V_{mq} = 1.5V$ and $G_{max} = 0.316$.

5.6.2 Cancellation Results with antenna

For measuring cancellation with antenna i.e multipath effects also will be considered, we found that cancellation plot comes out to be as shown below.Here the cancellation is achieved by having an extra 10 dB attenuation in transmit path which is inserted due to impedance mismatch at antenna port and dummy port since antenna impedance and Hittite Vector modulator impedance are not matched.So the total transmit power in this case is 10 dB less which makes total analog cancellation of this setup to be around 43 dB.According to the fact that the reflectors are far away from antenna and so the

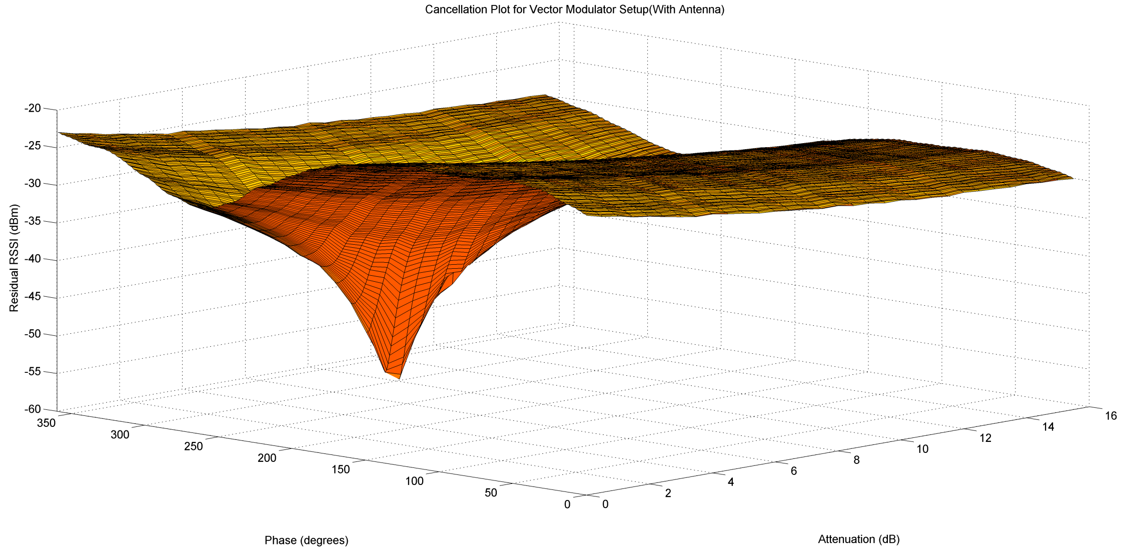

Figure 5.10: Cancellation Plot with antenna

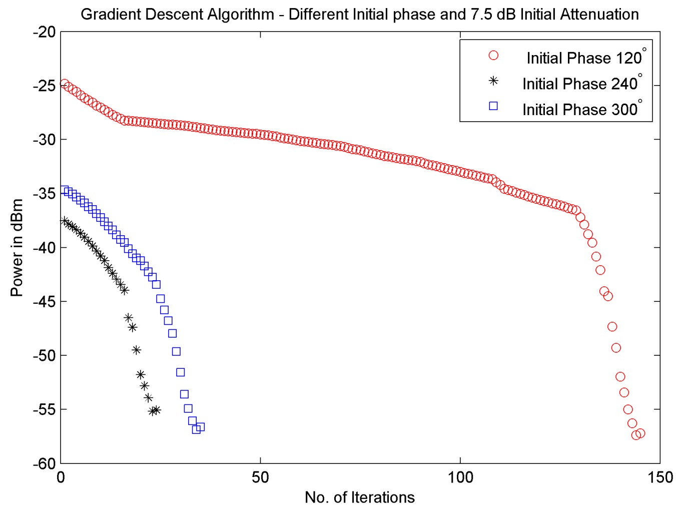

Figure 5.11: Gradient Descent Convergence

reflected power would be atleast 60 dB less than the transmitted power as found through antenna measurements. Therefore as shown in without antenna case, this cancellation can also be increased upto 55-60 dB with appropriate matching.

5.6.3 Gradient Descent Result

Gradient descent as explained earlier was applied and it was found to converge depending on the initial point chosen on which the number of iterations in which it converges also depends.The results for three different initial points chosen are as shown:

CHAPTER 6

Conclusions and Future Work

Full Duplex communication can have major advantages over present communication but to achieve that self interference is a major hurdle.Here we achieved the analog self interference cancellation of around 60 dB with the sine wave for the leakage component that is while there are no reflection path (antenna port terminated) and around 43 dB along with the reflections considered (with antenna installed) but this occurs primarily due to impedance mismatch between the antenna and the dummy port since the reflectors are present at large distance and will cause less reflected power.So a total of 60 dB is shown to be achievable through the setup used which certainly brings the desired received signal in the dynamic range of ADC so that it can be extracted through Digital baseband techniques.

REFERENCES

1. **Bharadia, D.**, **E. McMilin**, and **S. Katti** (2013). Full duplex radios.

2. **Choi, J. I.**, **M. Jain**, **K. Srinivasan**, **P. Levis**, and **S. Katti** (2010). Achieving single channel, full duplex wireless communication. URL `http://doi.acm.org/10.1145/1859995.1859997`.

3. **Corporation, H. M.** (). Hittite vector modulator. URL `http://www.hittite.com/content/documents/data_sheet/hmc631lp3.pdf`.

4. **Jain, M.**, **J. I. Choi**, **T. M. Kim**, **D. Bharadia**, **S. Seth**, **K. Srinivasan**, **P. Levis**, **S. Katti**, and **P. Sinha** (2012). Practical, real-time, full duplex wireless.

5. **Molloy, D.** (). Beaglebone: Gpio programming on arm embedded linux. URL `http://derekmolloy.ie/beaglebone/beaglebone-gpio-programming-on-arm-embedded-linux/`.

6. **NI** (). Ni-daq device. URL `http://sine.ni.com/nips/cds/view/p/lang/en/nid/207412`.

7. **NI-LabView** (). Lab view basics. URL `http://www.ni.com/academic/students/learn/`.

8. **Sahai, A.**, **G. Patel**, **C. Dick**, and **A. Sabharwal** (2012). On the impact of phase noise on active cancellation in wireless full-duplex. *CoRR*, **abs/1212.5462**. URL `http://arxiv.org/abs/1212.5462`.

9. **Sankar, K.** (2009). Iq imbalance in transmitter. URL `http://www.dsplog.com/2009/03/08/iq-imbalance-in-transmitter/`.

10. **Sankar, K.** (2012). Oscillator phase noise. URL `http://www.dsplog.com/2012/06/08/oscillator-phase-noise/`.