Extraction of RF Transceiver System Parameters and Impairments through Detailed Analytical Modeling combined with a Genetic Algorithm Approach

by

Aiswariya Sreenivassan

A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved October 2011 by the
Graduate Supervisory Committee:

Sule Ozev, Chair
Sayfe Kiaei
Bertan Bakkaloglu

ARIZONA STATE UNIVERSITY

December 2011

ABSTRACT

To meet stringent market demands, manufacturers must produce Radio Frequency (RF) transceivers that provide wireless communication between electronic components used in consumer products at extremely low cost. Semiconductor manufacturers are in a steady race to increase integration levels through advanced system-on-chip (SoC) technology. The testing costs of these devices tend to increase with higher integration levels. As the integration levels increase and the devices get faster, the need for high-calibre low cost test equipment become highly dominant. However testing the overall system becomes harder and more expensive. Traditionally, the transceiver system is tested in two steps utilizing high-calibre RF instrumentation and mixed-signal testers, with separate measurement setups for transmitter and receiver paths. Impairments in the RF front-end, such as the I/Q gain and phase imbalance and nonlinearity, severely affect the performance of the device. The transceiver needs to be characterized in terms of these impairments in order to guarantee good performance and specification requirements. The motivation factor for this thesis is to come up with a low cost and computationally simple extraction technique of these impairments. In the proposed extraction technique, the mapping between transmitter input signals and receiver output signals are used to extract the impairment and nonlinearity parameters. This is done with the help of detailed mathematical modeling of the transceiver. While the overall behavior is nonlinear, both linear and nonlinear models to be used under different test setups are developed. A two step extraction technique has been proposed in this work. The extraction of system parameters is performed by using the mathematical model developed along with a genetic algorithm implemented in MATLAB. The technique yields good extraction results with reasonable error. It uses simple mathematical operation which makes the extraction fast and computationally simple when compared to other existing techniques such as traditional two step dedicated approach, Nonlinear Solver (NLS) approach, etc. It employs frequency domain analysis of low frequency input and output signals, over cumbersome time domain computations. Thus a test method, including detailed behavioral modeling of the transceiver, appropriate test signal design along with a simple algorithm for extraction is presented.

ACKNOWLEDGEMENT

“A dream doesn't become reality through magic; it takes sweat, determination and hard work” - Colin Powell

Every individual has a dream but it takes more than just knowing your dream to achieve it. It gives me immense pleasure to extend my gratitude towards all those people who have stood by me, in realizing my dream, of completing my Master’s Degree from a highly acclaimed University.

This thesis is more than just a mere documentation. It stands witness to not just the hard work, determination and effort put in, but more importantly to the encouragement and support at every step of my research, from my Advisor, Dr. Sule Ozev. I would like to thank her for giving me the opportunity to perform research under her, for guiding me in every step and helping me to learn and grow through the 2 years of my Master’s Degree.

I would like to thank my professors for showing me by example and through challenging coursework how to mould myself for a great career ahead. I would like to thank my Professors, Dr. Sayfe Kiaei and Bertan Bakkaloglu in being instrumental in the journey of my Master’s.

I would also like to take this opportunity to specially thank Afsaneh Nassery, Arjun Jayaraman and Srinath Byregowda for their time and endless support in helping me overcome all the hiccups faced during the course of my research.

I want to thank those people who have stood by me in thick and thin and have always believed in my abilities, my closely knit group of friends. Be it in helping me out with technical expertise or be it with their encouraging words, they have been extremely important in helping me realize my dreams. They have been my family away from home.

Lastly, but most importantly, I would like to thank the most important people in my life. The ones who have believed in me, held my hand in every step, been supportive of all the decisions I have made in life. My beloved parents and the one who has always been my pillar of support. It was because of their motivation, I was able to dream big and successfully pursue my dream.

TABLE OF CONTENTS

Page

CHAPTER

CHAPTER Page

CHAPTER Page

LIST OF FIGURES

LIST OF TABLES

Table Page

NOMENCLATURE

BER	Bit Error Rate
BiST	Built in Self Test
CUT	Circuit Under Test
DC	Direct Current
FFT	Fast Fourier Transform
GA	Genetic Algorithm
I	In Phase
I/Q	In Phase and Quadrature Phase Component
IC	Integrated Circuit
IIP3	Third Order Intercept
LNA	Low Noise Amplifier
LO	Local Oscillator
NLS	Nonlinear Least Square
PA	Power Amplifier
Q	Quadrature Phase
RF	Radio Frequency

CHAPTER 1

INTRODUCTION AND REVIEW OF PRIOR WORK

Modern wireless devices utilize high level of circuit integration to meet market requirements of low power consumption and the demand for smaller devices. Continuous scaling of devices and demand for high data rate, have been made performance requirements and specifications more stringent. The emergence of advancements in system on chip technologies has lead to integration of different radio-frequency devices/modules, such as low noise amplifier (LNA), mixer and power amplifier (PA) onto a single die. Due to this increasing level of complexity of radio-frequency circuits, their testing becomes more challenging, -expensive, and time consuming.

Standard tests for present mixed signal integrated circuits, IC’s are complex and usually comprised of advanced measurement techniques. High performance test instruments are essential to accomplish these measurements. While prices for manufactures devices have been going down rapidly, the price for high calibre test equipment has not followed suit. This trend makes the test cost an increasing percentage of the overall cost. For the measurement of important parameters of Radio Frequency, RF Transceivers, traditional test approaches use a two step approach wherein the transmitter and receiver are tested individually. These traditional approaches also require high frequency test equipments. This approach requires long test time and several different test setups, both of which result in an increase in the overall test cost and time. Thus researchers, have been aiming at developing solutions to use available low cost test equipment to test and characterize the transceiver.

Complete characterization of an RF Transceiver, including transmitter and receiver, in terms of In phase and quadrature phase (I/Q) mismatch, time skew parameters, and non linearity is essential in order to ensure proper operation and quality of the transceiver. One step towards solving the transceiver test problem is to utilize on chip resources for test purposes [1], which is also known as built in test (BiST). In this approach the tester resources which are required for the particular test are implemented with available on chip functional blocks. Today's transceiver systems contain many on-chip functional blocks and hence this approach has been receiving much attention [2][3][4].

One strategy used to implement BiST involves separate testing of the individual building blocks of the RF front-end system. In this case each building block is considered as a separate circuit under test (CUT) and special test stimuli are used to test the blocks. Since this strategy calls for specialized BiST circuitry for each CUT, it increases the test overhead. Another disadvantage with this strategy is that variations in BiST circuitry could lead to large fluctuations in test results.

In order to reduce the dependency on expensive RF instrumentation, loop-back based testing has been very popular [4][5][6]. This technique involves testing the complete transceiver front end system as a whole. In this technique the output of the transmitter is looped back to the receiver input internally or on the test board, such that only baseband signals are used in the overall test.

Detailed characterization of the device under worst case scenarios such as in the presence of blockers, in presence of adjacent channel interferes, is extremely important in order to determine the quality of the device under test. A traditional approach to this has been through detailed characterization of performance parameters such as path gain, Third order intercept point- IIP3, 1-dB compression point, port impedances etc. However, measurement of all these parameters calls for the need for multiple test setups and long test times. Researchers have used the loop back setup for transceivers to measure various circuit characteristics [4][5][6].Also delayed, frequency shifted (offset mixer) or switched loop back paths were used for single channel direct frequency conversion transceiver circuits for measuring parameters such as path gain, , IIP3, and 1dB compression point.

One of the major challenges involved in loop back based BiST, is the decoupling of the transmitter and receiver parameters. A composite effect of impairments of the both the transmitter and receiver is what is observed as the receiver output. Some of the earlier loop back methods distinguish gain and nonlinearity parameters of the transmitter and receiver [5]. However decoupling of I/Q mismatch and time skew parameters is also extremely crucial. Another major difficulty associated with the loop back setup of the transceiver is the time delay introduced by the physical signal path connecting the transmitter and the receiver. This delay complicates measurements by adding another unknown parameter to the system. In prior work although an attempt was made to decouple I/Q mismatch, time skew and nonlinear characteristics through the use of nonlinear least square techniques (NLS)[6], this method is found to be computationally complex to implement on chip and time consuming. In [6] the transmitter and receiver nonlinearity characteristics are obtained through solving intermediate parameters extracted by NLS and by changing the loop back path attenuation. This increases the number of equations to extract the nonlinear behavior of the transmitter and receiver paths separately, thus increasing the complexity of the process of extraction.

In this work a loopback based testing along with mathematical modeling is employed similar to [6]. However in [6] the NLS is used for parameter extraction. In this work a genetic search algorithm is used to reduce the implementation overhead and memory requirements for on chip implementation. The method presented in this thesis analyzes low frequency receiver I/Q outputs, together with the test signals applied to the transmitter I/Q inputs. A detailed analytical model has been developed for the extraction of parameters. A two step process is employed. A linear model is first used to extract the IQ imbalance and time skew parameters. It is ensured that this linear model is valid by adjusting the signals such that all the signals are below the 1dB compression points of both paths. A nonlinear model is also developed for the system. Once the linear parameters such as path Gain, gain mismatch, phase mismatch, DC offsets and time skew are extracted. These parameters become as known for the second step of the proposed two step approach. A simplified non-linear model of the system is used to extract the nonlinear parameters.

CHAPTER 2

MATHEMATICAL MODELING OF THE TRANSCEIVER

Ideally, the transceiver should have all the desired properties such as a low bit error rate (BER) and high image rejection ratio. However, the transceiver encompassing analog circuitry is prone to parametric deviations, which can be a result of highly undesired process variations. The transceiver can thus be characterized in terms of impairments such as I/Q gain mismatch, I/Q phase mismatch, I/Q time skew, I/Q DC offset and transmitter/receiver nonlinearity.

Gain mismatch between the I and Q channels result in crosstalk between the I and Q signals which are uncorrelated. This crosstalk represents itself as noise and reduces the signal to noise ratio –SNR at the receiver output.

The I and Q arms are ideally 90° off phase which makes them orthogonal. The orthogonality of the carrier signals both on the transmitter and receiver side, have large impact on the efficient operation of the transceiver. The orthogonality of the I/Q arms is degraded by the phase mismatch between the I/Q arms. This phase mismatch is due to the errors in the phase shifter block as well as the time delay mismatches on the RF side of the system.

The time skew between the I and Q channels causes a shift in the received symbol time interval, which leads to error in calculation of the received symbols.

The nonlinearity is a result of the underlying nonlinear nature of semiconductor devices. While many blocks contained in the transceiver present with nonlinear behavior, the overall nonlinearity can be modeled in the LNA for the receive path and PA for the transmit path. For system level characterization focus is only on the nonlinearity of the whole path rather than the nonlinearity of the individual blocks. In the loopback mode receive path is cascaded with the transmit path. Nonlinear terms generated by the transmitter get further amplified by the receiver. Moreover the receiver generates additional nonlinear terms. The Figure 2-1 shows the basic block diagram of an I/Q modulating transceiver.

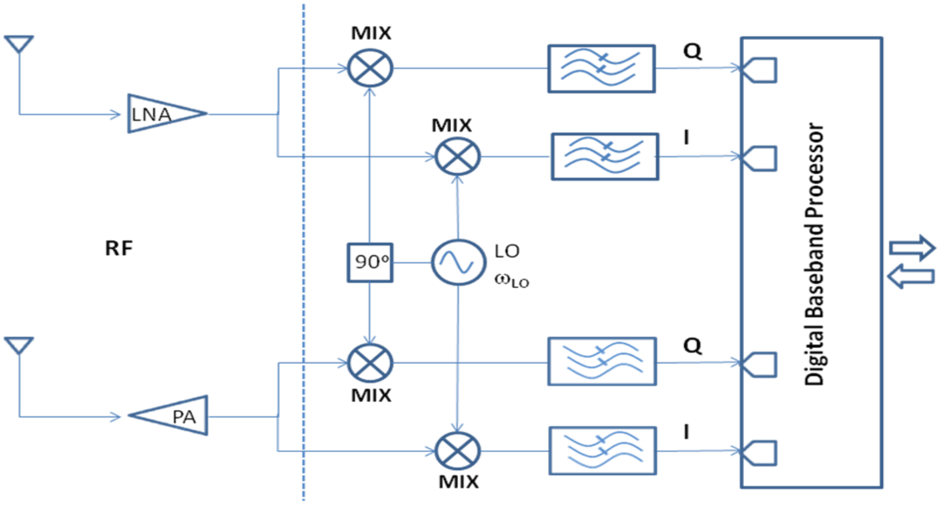


Figure 2-1 Block Diagram of RF Transceiver System

2.1 Linear Model:

In order to facilitate the extraction of parameters, a linear system model of the transceiver is derived. Using this model the goal is to extract the linear impairment parameters of the transceiver. The validity of this model is ensured by using low power signals for both paths which would minimize the effect of the nonlinear terms generated by either path. Starting with the transmitter base band signals, which can be waveforms modulated with any digital modulation technique. Using this approach the following section describes in detail how the linear system model of the transceiver is derived.

The transmitter I/Q signals are denoted by I(t) and Q(t). Transmitter delay is denoted by τtx , baseband time skew of the transmitter by τdtx, the gain mismatch by gtx, and DC components by DCitx and DCqtx. For phase definition the I arm is taken as reference. Signals at inputs of the up conversion mixers will be:

$$I^{'}(t)=I\left(t-\tau tx\right)+\ DC_{Itx} \tag{2.1}$$

$$Q^{'}(t)=(1+gtx).((Q(t-\tau tx-\tau dtx)+\ DC_{Qtx}) \tag{2.2}$$

As is seen from equation (2), I/Q gain mismatch is modeled on Q channel of the transmitter as an additional gain block with respect to the I channel. This gain block will amplify the Q signal by (1 + gtx), where gtx is the gain mismatch. Since the transmitter and receiver have separate gain mismatch two parameters are defined for I/Q gain mismatch, gtx and grx for transmitter and receiver respectively.

For up conversion, the above signals are multiplied by the modeled Local Oscillator (LO) signals which are as follows:

$$LOitx = \cos(\omega t) \tag{2.3}$$

$$LOqtx=\sin(\omega t + \phi tx) \tag{2.4}$$

While the phase mismatch ϕtx is caused by multiple factors, it can be modeled at the local oscillator LO since mathematically this will result in the same expression.

With the LO and baseband signals defined in (2.1), (2.2), (2.3) and (2.4), the transmitted signal can be expressed as:

$$r_{RF}(t) = Gtx.[I'(t).\cos(\omega t) - Q'(t).\sin(\omega t + \phi tx)] \qquad (2.5)$$

$$r_{RF}(t) = Gtx.[\left(I\left(t - \tau tx\right) + DC_{Itx}\right).\cos(\omega t) - ((1+gtx).(Q(t - \tau tx - \tau dtx) + DC_{Qtx})).\sin(\omega t + \phi tx)] \qquad (2.6)$$

Where Gtx is the gain of the transmit path.

This signal will be delayed by the loop back path before it reaches the receiver, where td represents the loop back path delay

$$r_{RF}(t-td) = Gtx.[(I(t - \tau tx) + DC_{Itx}).\cos(\omega(t - ((1+gtx).(Q(t - \tau tx - \tau dtx) + DC_{Qtx})).\sin(\omega(t - td) + \phi tx)] = rRF - RX(t) \qquad (2.7)$$

The above transmitted signal is then is then down converted. For down conversion, the LO signals for the receiver can be expressed as:

$$LOirx = \cos(\omega t + \varphi_d) \qquad (2.8)$$

$$LOqrx=\sin(\omega t + \phi rx+\varphi_d) \qquad (2.9)$$

RF time skew, delays on the RF side of the mixers will have different effects on the error of the phase shifter block for the transmitter and receiver sides. Thus in order to incorporate the time delays on the transmit and receive path we model the phase shift error as two separate variables ϕtx and ϕrx for the transmitter and receiver respectively.

Signal delayed by the loopback path represented by equation (2.7) is applied to the receiver input with an attenuator, having an attenuation factor, *k*. The received I/Q signals can be expressed as

$$Irx\ (t) = \frac{Grx}{k} . r_{RF-RX}(t). \cos(\omega t + \varphi_d) \qquad (2.10)$$

$$Qrx\ (t)=\frac{Grx}{k} .r_{RF\text{-}RX}(t).(1+grx).\sin(\omega t+\varphi_{RX}+\varphi_d) \qquad (2.11)$$

Where Grx is the gain of the receive path, φ_{RX} represents the receive path phase mismatch and φ_d represents the time delay termωtd.

During the down conversion of the I/Q signals, high frequency components are generated due the frequency mixing operation that takes place. These high frequency components are undesired and are removed using filtering. After filtering the I/Q signals can be represented as

$$I_{RX\text{-filtered}}(t)=DC_{Irx}+\frac{DC_{Itx}.Grx.Gtx.\cos(td\omega\text{-}\varphi_d)}{2\ k}$$

$$+\frac{DC_{Qtx}.Grx.Gtx(1+gtx).\sin\left(td\omega-\varphi_d-\varphi_{tx}\right)}{2\,k}$$

$$+\frac{Grx.Gtx.(1+gtx).\sin\left(td\omega-\varphi_d-\varphi_{tx}\right)Q(t-td-\tau dtx-\tau tx)}{2\,k}$$

$$-\frac{Grx.Gtx.\cos\left(td\omega-\varphi_d\right)I(t-td-\tau tx)}{2\,k}$$

(2.12)

$$Q_{RX\text{-}filtered}(t)=DC_{Qrx}+\frac{DC_{Qtx}.Grx.Gtx.(1+grx).(1+gtx).\cos\left(td\omega+\varphi_d+\varphi_{rx}-\varphi_{tx}\right)}{2\,k}$$

$$+\frac{DC_{Itx}.Grx.Gtx.(1+grx).\sin\left(td\omega+\varphi_d+\varphi_{rx}\right)}{2\,k}$$

$$+\frac{Grx.Gtx.(1+grx).(1+gtx).\cos\left(td\omega+\varphi_d+\varphi_{rx}-\varphi_{tx}\right)Q(t-td-\tau dtx-\tau tx)}{2\,k}$$

$$-\frac{Grx.Gtx.(1+grx).\sin\left(td\omega+\varphi_d+\varphi_{rx}\right)I(t-td-\tau tx)}{2\,k}$$

(2.13)

After the signal has been filtered, a baseband delay τrx is applied to Q arm of the receive path, DC components of the I and Q arms of the receive path are taken into account and the I/Q signals at the receiver output can be represented as:

$$
\begin{aligned}
&\mathrm{I}_{RX}(\mathrm{t}) \\
&= \mathrm{DC}_{\mathrm{Irx}} + \frac{\mathrm{DC}_{\mathrm{Itx}}.\,\mathrm{Grx}.\,\mathrm{Gtx}.\cos\left(\mathrm{td}\omega - \varphi_{\mathrm{d}}\right)}{2\,k} \\
&+ \frac{\mathrm{DC}_{\mathrm{Qtx}}.\,\mathrm{Grx}.\,\mathrm{Gtx}(1+\mathrm{gtx}).\sin\left(\mathrm{td}\omega - \varphi_{\mathrm{d}} - \varphi_{\mathrm{tx}}\right)}{2\,k} \\
&+ \frac{\mathrm{Grx}.\,\mathrm{Gtx}.\,(1+\mathrm{gtx}).\sin\left(\mathrm{td}\omega - \varphi_{\mathrm{d}} - \varphi_{\mathrm{tx}}\right)\mathrm{Q}(\mathrm{t}-\mathrm{td}-\tau\mathrm{rx}-\tau\mathrm{dtx}-\tau\mathrm{tx})}{2\,k} \\
&- \frac{\mathrm{Grx}.\,\mathrm{Gtx}.\cos\left(\mathrm{td}\omega - \varphi_{\mathrm{d}}\right)\mathrm{I}(\mathrm{t}-\mathrm{td}-\tau\mathrm{rx}-\tau\mathrm{tx})}{2\,k}
\end{aligned}
\tag{2.14}
$$

$$
\begin{aligned}
\mathrm{Q}_{RX}(\mathrm{t}) = \mathrm{DC}_{\mathrm{Qrx}} &+ \frac{\mathrm{DC}_{\mathrm{Qtx}}.\mathrm{Grx}.\mathrm{Gtx}.\,(1+\mathrm{grx}).(1+\mathrm{gtx}).\cos\left(\mathrm{td}\omega+\varphi_{\mathrm{d}}+\varphi_{\mathrm{rx}}-\varphi_{\mathrm{tx}}\right)}{2\ \mathrm{k}} \\
&+ \frac{\mathrm{DC}_{\mathrm{Itx}}.\mathrm{Grx}.\mathrm{Gtx}.\,(1+\mathrm{grx}).\sin\left(\mathrm{td}\omega+\varphi_{\mathrm{d}}+\varphi_{\mathrm{rx}}\right)}{2\ \mathrm{k}} \\
&+ \frac{\mathrm{Grx}.\mathrm{Gtx}.\,(1+\mathrm{grx}).(1+\mathrm{gtx}).\cos\left(\mathrm{td}\omega+\varphi_{\mathrm{d}}+\varphi_{\mathrm{rx}}-\varphi_{\mathrm{tx}}\right)\mathrm{Q}(\mathrm{t}\text{-}\mathrm{td}\text{-}\tau\mathrm{rx}\text{-}\tau\mathrm{dtx}\text{-}\tau\mathrm{tx})}{2\ \mathrm{k}} \\
&- \frac{\mathrm{Grx}.\mathrm{Gtx}.(1+\mathrm{grx}).\sin\left(\mathrm{td}\omega+\varphi_{\mathrm{d}}+\varphi_{\mathrm{rx}}\right)\mathrm{I}(\mathrm{t}\text{-}\mathrm{td}\text{-}\tau\mathrm{rx}\text{-}\tau\mathrm{tx})}{2\ \mathrm{k}}
\end{aligned}
\tag{2.15}
$$

It is seen from equations (2.14) and (2.15) that introducing time delay parameters shifts the transmitted signals as well as results in rotation of signal constellation diagram. Hence the loop back path delay and I/Q time skew parameters become significant impairments, that need to be extracted.

Hence the parameters included in the model are:

Gtx - Gain of the transmit path.

Grx - Gain of the Receive path.

DC_{Itx} - DC component of the I arm of the transmit path

DC_{Qtx} - DC component of the Q arm of the transmit path

DC_{Irx} - DC component of the I arm of the receive path

DC_{Qrx} - DC component of the Q arm of the receive path

gtx - Gain mismatch of the transmit path

grx - Gain mismatch of the receive path

td -Loop back path delay

ϕtx - I/Q phase mismatch for the transmit side

ϕrx - I/Q phase mismatch for the receive side

φ_d -Phase mismatch between the receive and transmit LO due to time lay. ωtd

tqrx - Time skew , delay mismatch between I and Q arm on receive side

2.2 Summary

This chapter explained the linear system modeling of transceiver. The detailed derivation for the expressions for the response of the system has been presented. This Chapter shows through mathematical expressions, the output of each stage of the transceiver when I/Q input signals are applied to the system. The next chapter will discuss in detail how these derived mathematical expressions are used in combination with a genetic algorithm to extract various system parameters and impairments.

CHAPTER 3

GENETIC ALGORITHM AND ITS APPLICATION

The expressions for the response of the transceiver model are derived as shown in the previous chapter. Using the expressions for the amplitude, the various parameters need to be decoupled and extracted. In previous work a solver like the NLS was used to solve the expressions .However the solver is computationally very complex and cumbersome to implement. So in this work a simpler Genetic Algorithm (GA) is used for this purpose. Genetic Algorithm is usually used for optimization problems; however in this work it is applied to solve the expressions derived to extract the parameters. This Chapter gives an overview and background information on genetic algorithms and its application

An algorithm is a series of steps that can be used to solve a problem. A genetic algorithm is one that uses genetics as its model for problem solving. It is a search technique to find solutions to an optimization or search problem. Genetic Algorithms are inspired by Darwin's theory of evolution – "Survival of the fittest". When one is trying to optimize a problem, one knows the forms of solutions corresponding to that particular problem. All these possible forms of solutions form the "search space." The main motivation in solving the problem lies in finding out the solution that fits the best. If it is possible to list out all possible solutions and be able to validate the same, then the problem seems simple. However if the search space is large, then this kind of enumeration becomes difficult, simply because it is more cumbersome and time consuming. It is in these situations that a specific technique is required to arrive at an optimal solution. Genetic algorithm (GA) is one such technique.

In a Genetic Algorithm the optimization problem takes the place of an environment and feasible solutions are considered as individuals living in that environment. Individuals are a set of symbols or numbers drawn from a finite set. For Genetic Algorithms to arrive at an optimum solution to the problem, it is necessary to perform certain operations over these individuals.

There are two distinct key elements that go into a genetic algorithm. They are individuals and population. An individual is a single solution while population represents a group of individuals involved in the search process. A population consists of a number of individuals being tested, certain parameters that define the individuals and some information about search space.

In a genetic algorithm, fitness of an individual is the value of an objective function. For calculating fitness, the chromosome is first decoded and the objective function is then evaluated. The fitness of the individual indicates how good the solution is, and also gives an indication of how close the chromosome or solution is to the optimal one.

Two important aspects related to the population are:

1. Generation of the initial population

2. Population size

It is desired that the first population chosen have a gene pool as large as possible in order to be able to explore the whole search space. All the different possible forms of solutions should be present in the population. In order to generate such an initial population, in most of the cases, a random sample is chosen. However a heuristic can be used to select the initial population. This increases the fitness of the solution and it may help the genetic algorithm to find good solutions faster. Large populations help explore the search space more thoroughly, while the convergence time of the genetic algorithm increases with population size, nlogn where n is the population size. Thus, how large a population is needed, is determined by factors such as type of heuristic used to choose the population, computational complexity and memory constraints.

The process termed as "breeding" is the most important aspect of the genetic algorithm. In this process new, members are created in two steps

a. Selecting the parents.

b. Crossing and mutation of the parents to create new offspring.

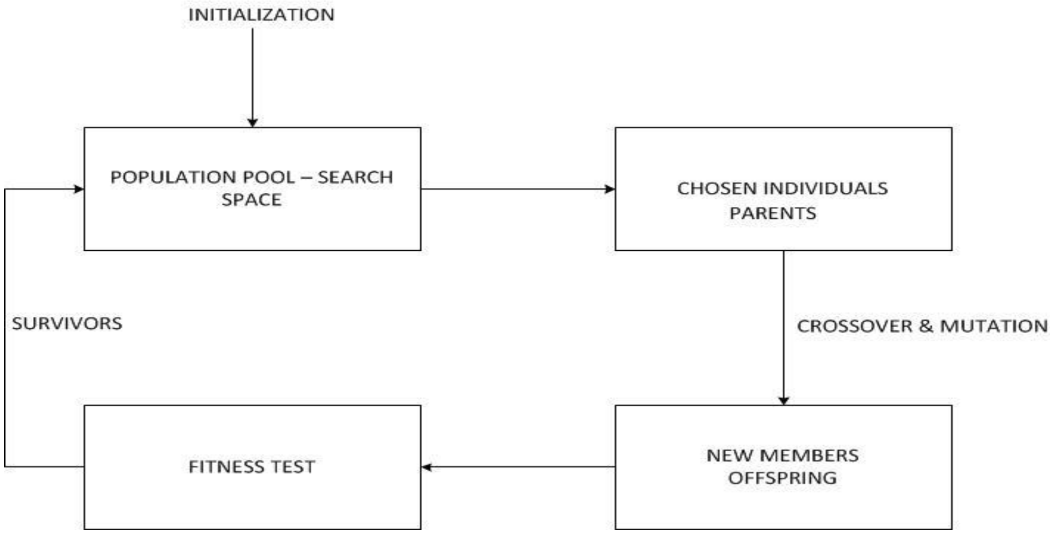


Figure 3-1 Evolution Cycle of the Genetic Algorithm

3.1 Key Steps in Implementing the Genetic Algorithm

3.1.1 Selection:

Selection is a method that randomly picks members out of the population according to their evaluation function. The higher the evaluated value of the fitness functions, the more chance that member is selected.

Selection Pressure is defined as the degree, to which better individuals are favored. Over successive generations, the selection pressure drives the algorithm to improve the population fitness. There are different types of selection techniques that can be used for selection of parents such as, rank selection, tournament selection, random selection, Roulette selection among others. For the test method proposed in this work, an intelligent random selection process is used to select the initial population. After the first cycle of crossover and mutation, “Rank Selection” is used.

For Rank selection, the fitness function is evaluated for each member of the search space which constitutes of initial members chosen and members produced from crossover and mutation. The members are then ranked based on the results obtained from the evaluation of the fitness function. In this application, the fitness function evaluated the mean square error between injected and extracted parameters. It is intended that this error is minimum. Hence from a huge pool of members, a new pool is chosen, fittest members from the ranked pool are chosen to form the new population for the next cycle. This way the search pool becomes stronger and stronger with each cycle and the algorithm eventually converges to the solution.

For Example if the initial population chosen has 100 members, and by crossing over and mutation another 200 members are added to the population. The cost function is evaluated for all 300 members. All 300 members are then ranked based on minimum error i.e. smallest error being the highest rank. The first 100 highest ranked members are chosen to be the new population. Eventually when an optimum solution is reached all 100 members will be the same, representing the best possible outcome for the solution. In this application, it will correspond to the extracted values of the impairments and parameters. The two basic operations for creating new members to be added to the initial population are discussed below.

3.1.2 Crossover:

Crossover is a genetic operator that combines, parents (two possible solutions from the chosen population) to produce a new offspring. The idea behind cross over is that the new offspring produced is fitter than the parents chosen if it takes the best characteristic from both of them, meaning that we move closer to obtaining an optimum solution. Cross over is done by defining a cross over probability and applying a crossover operator.

Crossover operators are of many types, one point crossover, two point crossover, uniform crossover, arithmetic crossover, heuristic crossover, etc. In this particular application of the GA to extract various transceiver impairments and system parameters, the arithmetic crossover operator has been used.

In this application, two members from the random initial population are chosen and the crossover operation is performed as shown below:

Member 1 = Rand Sample1 from Initial Population

Member 2 = Rand Sample2 from Initial Population

New member generated from crossover =(Member1 + Member2)/2

3.1.3 Mutation:

Mutation is an important part of genetic search as it helps in preventing the search algorithm from stagnating at local minima. It helps in maintaining genetic diversity of the chosen population. Mutation alters the members from the initial members, an creates new members which are added to the search space. The idea is that with this new pool of members, the GA might be able to arrive at a better, more optimum solution than that from the previous one.

Mutation is performed by defining a user defined mutation probability alpha, usually set to a fairly low value. In this application alpha is chosen to be 0.04 for the first cycle and is then made smaller for every following cycle. The member is mutated by adding a random multiple of the probability factor alpha to the member.

Member1 = member from initial population

New member = (Rand() *alpha + 1)*Member1

3.2 An Outline of The Genetic Algorithm:

1. Generate the initial random population of N members i.e. possible solutions to the problem.
2. Develop the Fitness function for the problem: for example in this application it is the sum of mean square error:

$$\text{Minimize } f(G, td, phid) = (I1C - I1)^2 + (I2C - I2)^2 + (I3C - I3)^2 \qquad (3.1)$$

Where

$$I1 = \frac{G}{(2k)}.\cos(\omega c1.td + phid) \qquad (3.2)$$

$$I2 = \frac{G}{(2k)}.\cos(\omega c2.td + phid) \qquad (3.3)$$

$$I3 = \frac{G}{(2k)}.\cos(\omega c3.td + phid) \qquad (3.4)$$

And I1C , I2C and I3C are evaluated for every member value for Gain G, propagation delay td and phase mismatch phid.

3. Repeat the following steps, until the new population is generated:

(a) Selection: Select two parent members from the initial population N. Better the fitness better the chances to be selected.

(b) Crossover: Using the defined crossover probability, apply the crossover operator on the selected members to form new members.

(c) Mutation: With a mutation probability, mutate members from initial population to form mew members.

(d) Combine all members into one search pool where:

Search pool = Initial members + New members due to crossover + New members due to Mutation.

4. Evaluate the fitness function for every member of the search pool.

5. Rank the members based on minimum error criteria.

6. Choose first N/2 highest ranked members and N/2 members from the initial population and form the new initial population of N members.

7. Using the new generated population, repeat the cycle from step 3 and iterate to obtain the most optimum solution, i.e. values of extracted parameters G, td and phid, that are comparable to the injected values of G, td phid. This enables the extraction of impairments and system parameters with high accuracy, by using a

simple intelligent search technique, involving very basic mathematical operations. Therefore this technique can be easily implemented.

3.3 Flow Chart of the Algorithm

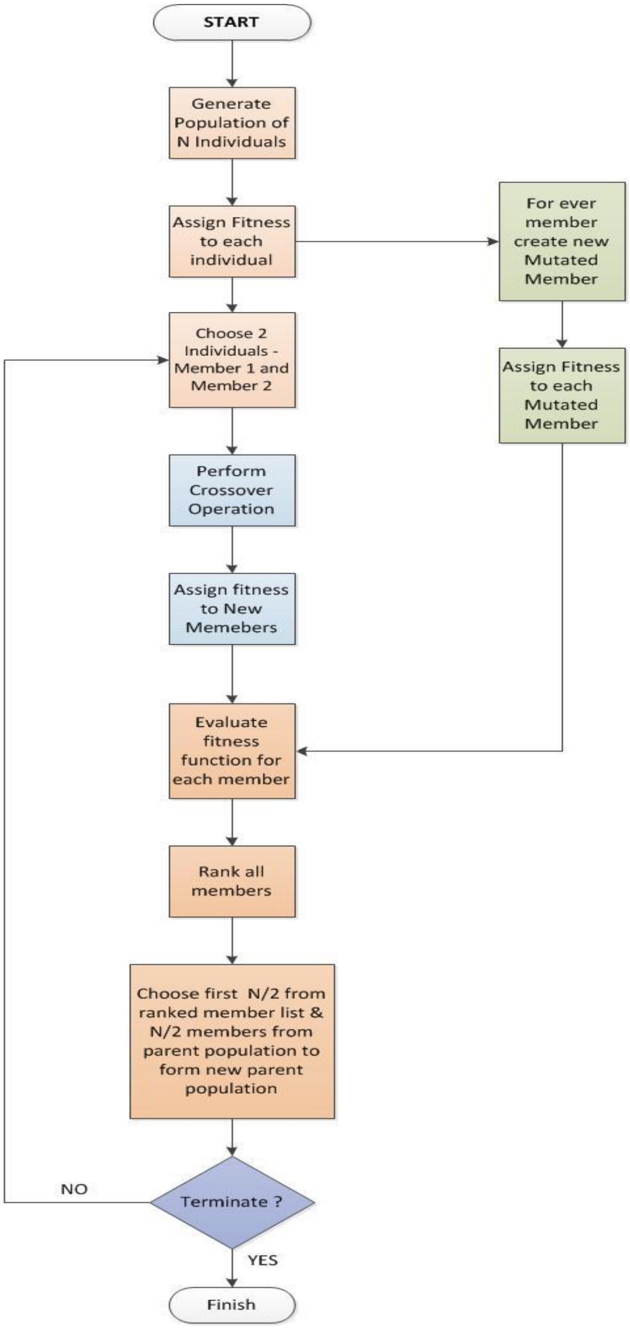


Figure 3-2 Flow chart describing the process involved in implementing the Genetic Algorithm

3.4 Summary

In this Chapter a detailed explanation of how genetic algorithm is chosen for the extraction of linear impairment parameters has been presented. The chapter explains in detail about genetic algorithm, the various steps such as selection, creation of new members and ranking. It also explains about the different factors that need to be taken into consideration while implementing the algorithm in order to obtain efficient results in the end. The chapter gives an outline of how the genetic algorithm can be applied for this particular problem of extraction of different system parameters. The next chapter presents and in depth analysis of combining the linear analytical model with the genetic algorithm for extraction.

CHAPTER 4

APPLICATION OF GENETIC ALGORITHM FOR EXTRACTION OF TRANSCEIVER SYSTEM IMPAIRMENTS & PARAMETERS

As described in Chapter 3, the transceiver parameters to be extracted are Gtx - Gain of the transmit path, Grx- Gain of the Receive path, gtx - Gain mismatch of the transmit path, grx - Gain mismatch of the receive path, td-Loop back path delay, ϕtx- I/Q phase mismatch for the transmit side, ϕrx - I/Q phase mismatch for the receive side, φ_d -Time delay ωtd. These parameters are extracted using the linear system model developed, by applying genetic search algorithm as described in the previous section.

4.1 STEP 1: Selection of Initial Population:

A random population of the parameters to be extracted is chosen. For example, in the first step the parameters extracted are: G, φ_d and td.

A set of 100 members (values) for each of the parameters are chosen within bounds defined for each.

G_initial = {G1, G2, G3 ……. G100}; G between 0.1 & 5

φd_initial = {φd 1, φd 2,φd 3……………………φd 100}; φ_d Between -10° & +10°

td_initial = {td1, td2, td 3………………………td100}; td between 10ps & 200ps

4.2 STEP 2: Formation of New Members:

Using the process of crossover and mutation described earlier, new members are created for { G, φ_d and td }.

4.2.1 Crossover:

From the set of 100 members, 2 random members are chosen for each parameter, and the crossover operator is applied to generate a new member.

$$G_{crossover} = \frac{(\,Gm1 + Gm2\,)}{2} \tag{4.1}$$

Where Gm1 and Gm2 can be any value from set { G1, G2,G3……G100}.

Similarly,

$$\varphi_{d_{crossover}} = \frac{\left(\,\varphi_d m1 + \varphi_d m2\,\right)}{2} \tag{4.2}$$

Where $\varphi_d m1$ *and* $\varphi_d m2$ can be any value from set,

$\{\varphi_d 1, \varphi_d 2, \varphi_d 3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \varphi_d 100\}$

And,

$$td\_crossover = \frac{(\,tdm1+tdm2\,)}{2}$$

Where tdm1 and tdm2 can be any value from set {td1, td2, td3………………………td100}.

1000 such crossover members are generated:

Gcrossovermem={Gcrossover1,Gcrossover2,……………………Gcrossover1000}

$\varphi_d$crossovermem={$\varphi_d$crossover1,$\varphi_d$crossover2,…………….$\varphi_d$crossover1000}

td_crossovermem={tdcrossover1,tdcrossover2,………………tdcrossover1000}

4.2.2 Mutation:

For every member of the initial set of 100 members chosen 5 mutated members are generated. This means a total of 500 mutated members are generated. The mutation coefficient alpha is chosen as 0.04 for the first iteration and then made smaller for iteration after. The mutated member is generated by applying the mutation coefficient as follows:

Mutation factor, Mutfact=(rand()*alpha+1), chooses a value of Mutfact between 1 and (alpha+1). This $Mutfact$ is used so that we can generate different mutated members of same Gm1 using different $Mutfact$ values.

G_muated=Mutfact*Gm1

So for every

{G1, G2, G3 …….G100},{φ_d1, φ_d2,φ_d3……………………φ_d100}and {td1, td2, td 3………………………td100}, 5 mutated members are generated :

$G\_mutatedmem = \{ G1mut1 \ldots G1mut5, \ldots. G100mut1, G100mut2, \ldots., G100mut5\}$

$\varphi_d$mutatedmem = { φ_d1mut1,.. G1mut5, ….φ_d100mut1,….,φ_d100mut5}

td_mutatedmem = { td1mut1,,….. td1mut5, …. td100mut1,…., td100mut5}

4.2.3 Building a total population – search space:

A total population for each parameter is built by combining the initial members, and the new members generated by performing crossover and mutation.

Gtotal={G_initial,G_crossovermem,G_mutatedmem}

Where, G_initial has 100 members, G_crossovermem has 1000 members and G_mutatedmem has 500 members. Hence the total search space, Gtotal has 1600 members.

4.3 STEP 3: Formation and Evaluation of cost function:

The system model for Irx and Qrx are used in order to form cost function or fitness function. The amplitude of the I component of the received signal Irx(t) from equation (14), is denoted with I

$$I=\frac{Grx.Gtx.\cos(td\omega-\varphi_d)}{2\ k} \tag{4.3}$$

$$I=\frac{G\,.\cos\left(td\omega\text{-}\varphi_d\right)}{2\ k}$$

(4.4)

Where G = Total Path Gain = Grx.Gtx can be extracted as a single parameter.

$\omega = 2\pi f$ where f is the frequency of the signal , 2.4Ghz to 2.5Ghz .

Consider $\omega 1 = 2\pi\,.\,(2.4e9)$

$\omega 2 = 2\pi\,.\,(2.45e9)$

$\omega 3 = 2\pi\,.\,(2.5e9)$

The different amplitudes are chosen so as to be able to independently decouple the parameters from the expressions derived. The frequency range chosen is the WIMAX frequency range. Hence this extraction technique has been developed for WIMAX applications.

Amplitudes corresponding to the frequencies can be written as:

$$I1=\frac{G\,.\cos\left(td\omega 1\text{-}\varphi_d\right)}{2\ k}$$

(4.5)

$$I2=\frac{G\,.\cos\left(td\omega 2\text{-}\varphi_d\right)}{2\ k}$$

(4.6)

$$I3=\frac{G\ .\cos\left(td\omega 3-\varphi_d\right)}{2\ k}$$

(4.7)

I1, I2 and I3 are first evaluated using the injected values of G, td and φ_d. For each set of parameters

{{G1, φ_d1 and td 1 }, { G2, φ_d2 and td 2 } …..{G1600, φ_d1600 and td1600}}, from the $Gtotal$ set, I1C, I2C and I3C are evaluated.

The cost function is defined as the summation of mean square error, is calculated for all 1600 sets of {G, φ_d and td}.

$$\text{Minimize } f\left(G,\ td\ ,\varphi_d\right)=\left(I1C-I1\right)^2+\left(I2C-I2\right)^2+\left(\ I3C\text{-}I3\right)^2 \qquad (4.8)$$

4.4 STEP 4: Ranking

Ideally the desired value of mean square error is zero. A mean square error of zero or approximately zero would result in a set of values for$(G, td\ , \varphi_d)$ which would correspond to accurately extracted parameters of the transceiver system. Hence Minimum mean square error is the terminating condition for the algorithm.

The evaluated f(G, td , φ_d) are arranged in ascending order. Smallest value of f(G, td , φ_d), corresponds to minimum mean square error and is given the highest rank. First 50 members from the ranked members are chosen and 50 random members from the initial population G_initial are chosen to be the new 100 members to be the G_initial set for the next iteration. The STEPS 2 through 4 are evaluated until the minimum mean square error criterion is met. Thus the fittest member survives. This set of {G, td , φ_d} will be the extracted system parameters.

After extraction of td ,φ_d , these extracted parameters are used to extract gtx and φ_{tx}. The same algorithm as described is followed, but the amplitude of the quadrature component of the received Irx , signal is used. A new cost function is used to extract { gtx, φ_{tx}} :

$$A1=\frac{G(1+gtx).\sin\left(td.\omega1+\varphi_d-\varphi_{tx}\right)}{2\ k}\tag{4.9}$$

$$A2=\frac{G(1+gtx).\sin\left(td.\omega2+\varphi_d-\varphi_{tx}\right)}{2\ k}\tag{4.10}$$

$$A3=\frac{G(1+gtx).\sin\left(td.\omega3+\varphi_d-\varphi_{tx}\right)}{2\ k}\tag{4.11}$$

A1, A2 and A3 are evaluated using the injected values and A1C, A2C, A3C are evaluated for every 1600 sets of { gtx, φ_{tx}} generated as described in the algorithm.

The Cost function is defined as:

Minimize $f\left(gtx, \varphi_{tx}\right)=(A1C-A1)^2+(A2C-A2)^2+(A3C-A3)^2$ (4.12)

The Ranking operation is performed, the algorithm is executed as described and the values for gtx and φ_{tx} are extracted.

Once G, td , φ_d ,gtx, φ_{tx} are extracted, these are used to extract grx, φ_{rx}. The amplitude of the received signal Qrx is used for the formation of the cost function

$$L1=\frac{G(1+gtx)(1+grx).\,Cos\left(td.\omega 1+\varphi_d-\varphi_{tx}+\varphi_{rx}\right)}{2\,k} \tag{4.13}$$

$$L2=\frac{G(1+gtx)(1+grx).\,Cos\left(td.\omega 2+\varphi_d-\varphi_{tx}+\varphi_{rx}\right)}{2\,k} \tag{4.14}$$

$$L3=\frac{G(1+gtx)(1+grx).\,Cos\left(td.\omega 3+\varphi_d-\varphi_{tx}+\varphi_{rx}\right)}{2\,k} \tag{4.15}$$

L1, L2 and L3 are evaluated using the injected values and L1C, L2C, L3C are evaluated for every 1600 sets of { grx, φ_{rx}} generated as described in the algorithm.

The Cost function is defined as:

Minimize $f(\, grx, \varphi_{rx}\,) = (L1C - L1)^2 + (L2C - L2)^2 + (\,L3C-L3)^2$ (4.16)

The Ranking operation is performed and the algorithm is executed as described and the values for grx and φ_{rx} are extracted.

The results for the extraction of system parameters using the proposed analytical method are as shown in Table 4-1. & Table 4-2.

Table 4-1 Measurement Results for proposed extraction technique over 5 iterations of the Genetic Algorithm.

Parameter	**Injected**	**Extracted**				
		Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**
G	2	1.9532	1.9102	1.9299	1.9787	1.9649
Td	50ps	52.3	54.7	53.3	50.9	51.7
Gtx	0.03	0.0300	0.0300	0.0300	0.0301	0.0300
Φtx	3°	3.0000	3.0000	3.0000	3.0034	3.0000
Grx	0.15	0.1500	0.1500	0.1456	0.1496	0.1493
Φrx	5°	5.0000	5.0000	4.7983	4.9780	4.9664

Table 4-2 Measurement RMS Error over 5 Iterations

Parameter	**Injected**	**Extracted**	
		Mean	**RMS Error**
G	2	1.947	0.130
td (ps)	50	52.55	6.42
Gtx	0.03	0.030013	0.000064
φtx(°)	3	3.0007	0.0034
Grx	0.15	0.1489	0.0045
φrx(°)	5	4.949	0.206

4.5 Summary

In this chapter an in depth analysis of application of genetic algorithm is presented. It is used in combination with the Linear analytical model developed to extract parameters and impairments such as overall Gain G, gain mismatch gtx, grx phase mismatch φtx , φrx and time delay td to determine the cost function. The last section of this chapter presents the results obtained for extraction by implementing the proposed technique. The results obtained for extraction are shown in Table 4-1 and Table 4-2. These results were compared with existing extraction techniques proposed in prior work such as in [6] and it has been seen that the RMS errors obtained for extraction using the technique presented in thesis are low. The RMS error for I/Q phase mismatch is found to be less than 0.1°, I/Q gain mismatch is found to be less than 0.0005 and time skew td around 6ps. The next chapter describes in detail the mathematical analytical nonlinear modeling of the transceiver.

CHAPTER 5

MATHEMATICAL MODELLING THE NON-LINEAR BEHAVIOUR OF THE TRANSCEIVER

Nonlinearity in analog circuits is mainly due to the nonlinear behavior of the system amplifiers and frequency conversion mixers. The signal transmitted through the antenna contains both the linearly and nonlinearly up-converted, amplified signal terms. Similarly due the down conversion mixer operation, in the receiver side, the signal captured by the antenna is amplified and down-converted. This adds more non linear terms. Since the transceiver circuit operates in a cascaded fashion the receiver sees a composite effect of linear and nonlinear terms both from the transmit and receive path.

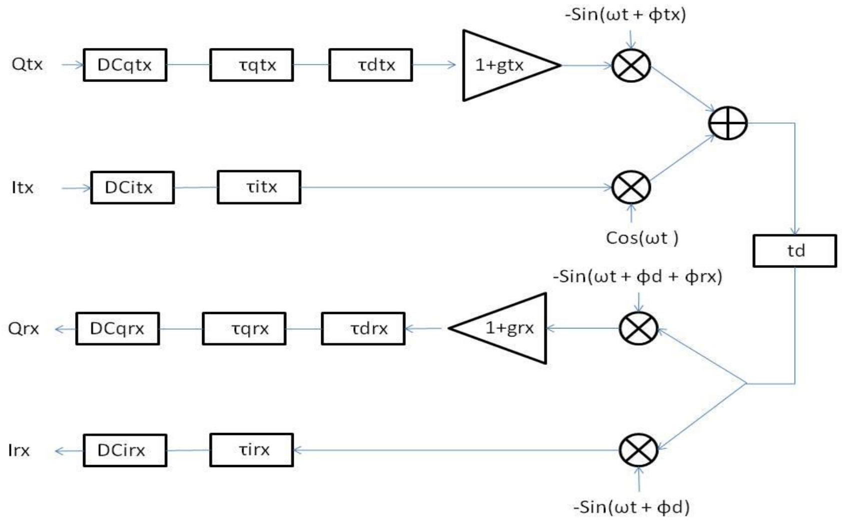


Figure 5-1 Transceiver Model with Impairments

5.1 Mathematical Nonlinear Modeling of the Transceivers

The nonlinearity of the transmit and receive paths can be modeled as third order polynomial gain functions. Third order gain functions for every analog circuit block on the transmit path and the receiver path, can be defined separately .However, this results in a large number of nonlinear gain function coefficients, that need to be extracted and the analytical modeling of the system becomes impossible due to the huge number of parameters and nonlinear signal terms involved. To simplify this process, nonlinearity of the transmitter path and the receiver path as a whole is measured rather than that of the individual components.

Thus the gain of the transmit path can be represented as:

$$G_{TX}= \alpha 1.x+ \alpha 2.x^2+\alpha 3.x^3 \tag{5.1}$$

And gain of the receive path can be expressed as:

$$G_{RX}= \beta 1.x+ \beta 2.x^2+\beta 3.x^3 \tag{5.2}$$

Equation (2.14) and (2.15) represent the complete linear response of the transceiver which includes all impairments and parameters except for the nonlinearities. Nonlinear response of the transceiver will include (2.14) and (2.15) as the linear term along with the nonlinear signal terms. The nonlinear model is developed by applying the gain functions defined in (5.1) and (5.2) to the transmitter and the receiver path. The nonlinearity of the whole transmitter or the receiver path can be approximated with the gain functions defined in (5.1) and (5.2). The linear gain coefficients $\alpha 1$ and $\beta 1$ of the transmitter and the receiver respectively can be used instead of Gtx and Grx in equations (2.14) and (2.15).

Gain functions of the transmitter and receiver are applied and the steps followed to derive the linear model are repeated as follows:

$$I^{'}(t)=I\left(t\text{-}\tau tx\right)+ DC_{Itx} \qquad (5.3)$$

$$Q^{'}(t)=(1+gtx).((Q(t\text{-}\tau tx - \tau dtx)+ DC_{Qtx}) \qquad (5.4)$$

The above signals are up converted by the modeled Local Oscillator (LO) signals which are as follows:

$$LOitx = \cos(\omega t) \qquad (5.5)$$

$$LOqtx=\sin(\omega t + \phi tx) \qquad (5.6)$$

The transmitted signal can be expressed as

$$r_{RF}\,(t)= I'(t).\cos(\omega t)\text{-}\ Q'(t).\sin(\omega t + \phi tx)$$

$$r_{RF}\,(t)=Gtx.[\ (I(t\text{-}\ \tau tx)+ DC_{Itx}).\cos(\omega t)$$

$$-\ \left((1+gtx).\left(Q\left(t - \tau tx - \tau dtx\right)+ DC_{Qtx}\right)\right).\sin(\omega t + \phi tx)]$$

$$(5.7)$$

This signal is delayed by the loop back path before it reaches the receiver,

$$r_{RF}(t\text{-}td) = [(I(t\text{-}\ \tau tx) + DC_{Itx}).\cos(\omega(t\text{-}td)) - ((1+gtx).(Q(t-\tau tx-\tau dtx) + DC_{Qtx})).\sin(\omega(t-td)+\phi tx)] = r_{RF-TX} \tag{5.8}$$

Applying the Gain function for the transmit path:

$$G_{TX}(x) = \alpha 1.x + \alpha 2.x^2 + \alpha 3.x^3$$

$$TX_{out} = G_{TX}(r_{RF}(t))$$

$$TX_{out}(t) = \alpha 1.\left[(I(t\text{-}\ \tau tx) + DC_{Itx}).\cos\big(\omega(t\text{-}td)\big)\right] - \Big((1+gtx).\big(Q(t-\tau tx-\tau dtx) + DC_{Qtx}\big)\Big).\sin(\omega(t-td)+\phi tx) + \alpha 2.\left[(I(t-\ \tau tx) + DC_{Itx}).\cos\big(\omega(t-td)\big) - \Big((1+gtx).\big(Q\big(t-\tau tx-\tau dtx\big) + DC_{Qtx}\big)\Big).\sin\big(\omega\big(t-td\big)+\phi tx\big)\right]^2 + \alpha 3.\left[(I(t-\ \tau tx) + DC_{Itx}).\cos\big(\omega(t-td)\big) - \Big((1+gtx).\big(Q\big(t-\tau tx-\tau dtx\big) + DC_{Qtx}\big)\Big).\sin\big(\omega\big(t-td\big)+\phi tx\big)\right]^3 \tag{5.9}$$

Where td represents the loop back path delay.

Signal $TX_{out}(t)$ delayed by the loopback path is applied to the receiver input with an attenuator, having an attenuation factor, *k*.

Applying the Gain function for the receive path to the above received signal:

$$G_{RX}(x)=\beta 1.x+\beta 2.x^2+\beta 3.x^3$$

$$RX_{out}=\frac{G_{RX}\ (RFrx(t))}{k}$$

(5.10)

The above signal is then is then down converted. Using the LO signals for the receiver:

$$LOqtx = \cos(\omega t+\varphi_d) \qquad (5.11)$$

$$LOqtx=\sin(\omega t + \phi rx+\varphi_d) \qquad (5.12)$$

The received I and Q signals are:

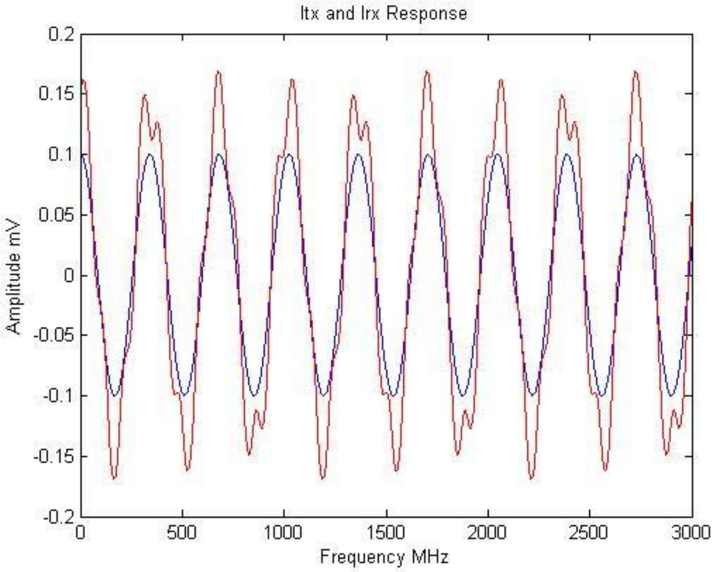
$$I_{RX}\ (t)=RX_{out}.\ \cos(\omega t+\varphi_d) \qquad (5.13)$$

$$Q_{RX}\ (t)=RX_{out}.(1+grx).\ \sin(\omega t + \phi rx+\varphi_d) \qquad (5.14)$$

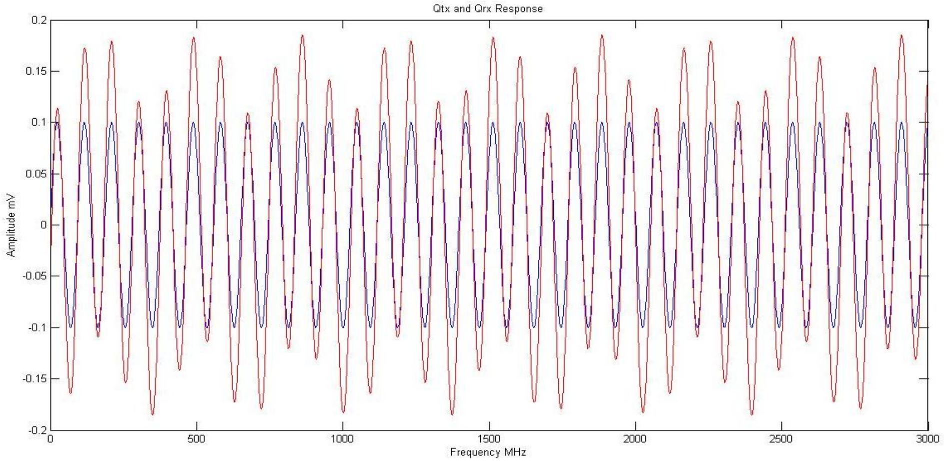
These received signals are filtered. The final equations expressing the nonlinear response of the transceiver containing up to 9th order nonlinear terms is thus derived analytically. The complete equation is highly complex and contains a large number of terms.

5.2 Validating the developed mathematical model of the Transceiver

A transceiver model as shown in Figure 5-1 is constructed in MATLAB including the nonlinear power Amplifier (PA), low noise amplifier (LNA) and frequency up – conversion and down –conversion mixers. Received signals are obtained and plotted by passing the transmitter I/Q signals through the nonlinear transceiver model. The waveforms shown in Figure 5-1 represent the actual I/Q response of the transceiver model developed in MATLAB.



5-2 (a)



5-2 (b) Figure 5-2 (a)I and (b)Q: Transceiver response of Simulated MATLAB Model.

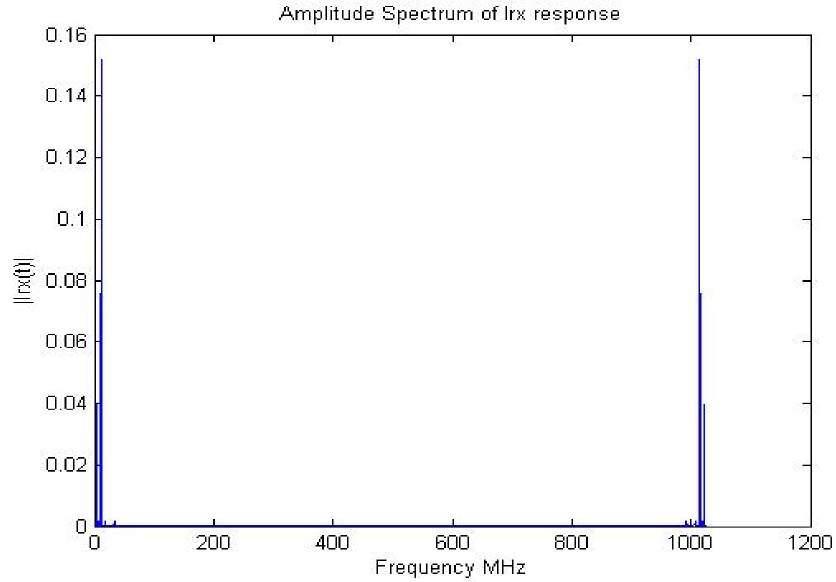


Figure 5-3 FFT of the Irx signal response of the MATLAB simulated transceiver model.

The actual and analytically calculated I/Q responses of a nonlinear transceiver model are compared. This comparison is done by first computing the FFT of the I/Q response waveforms generated in MATLAB. By computing the FFT the amplitude of the signal at different desired frequency locations is obtained. The FFT of the I component of the received transceiver response is shown in Figure 5-2.

From the analytical model, the amplitudes of the different frequency locations is computed by evaluating the derived equations, using a simple Mathematica code.

The amplitudes of the I/Q response, obtained from the FFT and Analytical computation are compared at corresponding frequency locations as shown in Table 5-1. From the results it can be seen that both the simulated amplitudes as well as computed amplitudes are comparable. The difference between the two responses is also shown in Table 5-1 and as an error plot in Figure 5-3. The maximum error is around 0.001158293 which is very low compared to the amplitude of the signal. This analysis validates the analytical nonlinear transceiver model developed and also justifies the sufficiency of the use of a simplified 7th order non linear analytical model. This analysis also indicates that although every block in the receiver and transmitter path may contain nonlinear terms, the overall nonlinearity can be modeled as overall path nonlinearity, which is more significant than the nonlinearity measurement of each individual component in the transceiver chain.

Table 5-1 Comparison of amplitude of Irx-Transceiver Response obtained from Mathematical Analytical Model Vs Simulated MATLAB Model.

Frequency Locations	**Amplitude From Analytical Model**	**Amplitude From FFT**	**Error**
w1	0.146933	0.146840407	9.25929E-05
3w1	0.00139432	0.001440799	4.64793E-05
5w1	7.35E-06	7.35E-06	1.69724E-09
7w1	1.64E-08	1.62E-08	2.09344E-10
w1+6w2	1.54E-08	1.51E-08	2.34327E-10
w1-6w2	1.54E-08	1.51E-08	2.34293E-10
w1-4w2	6.97E-06	7.01E-06	4.70563E-08
w1+4w2	6.97E-06	7.01E-06	4.70044E-08
w1+2w2	0.00133416	0.001404083	6.99232E-05
w1-2w2	0.00133416	0.001404084	6.99244E-05
4w1+w2	5.35E-07	5.20E-07	1.51188E-08
4w1-w2	5.35E-07	5.20E-07	1.51181E-08
6w1+w2	3.23E-09	3.13E-09	9.6289E-11
6w1-w2	3.23E-09	3.13E-09	9.62795E-11
5w1-2w2	4.89E-08	4.83E-08	5.89275E-10
5w1+2w2	4.89E-08	4.83E-08	5.89275E-10
3w1-4w2	4.78E-08	4.72E-08	6.18471E-10
3w1+4w2	4.78E-08	4.72E-08	6.18471E-10
w2	0.0137952	0.012636907	0.001158293
3w2	0.000247135	2.48E-04	5.04718E-07
5w2	1.32E-06	1.26E-06	6.67259E-08
7w2	2.78E-09	2.75E-09	2.48039E-11
4w1+3w2	3.58E-09	3.42E-09	1.61983E-10
4w1-3w2	3.58E-09	3.42E-09	1.61983E-10
2w1-3w2	9.03E-07	7.49E-07	1.53823E-07
2w1+3w2	9.03E-07	7.49E-07	1.53823E-07

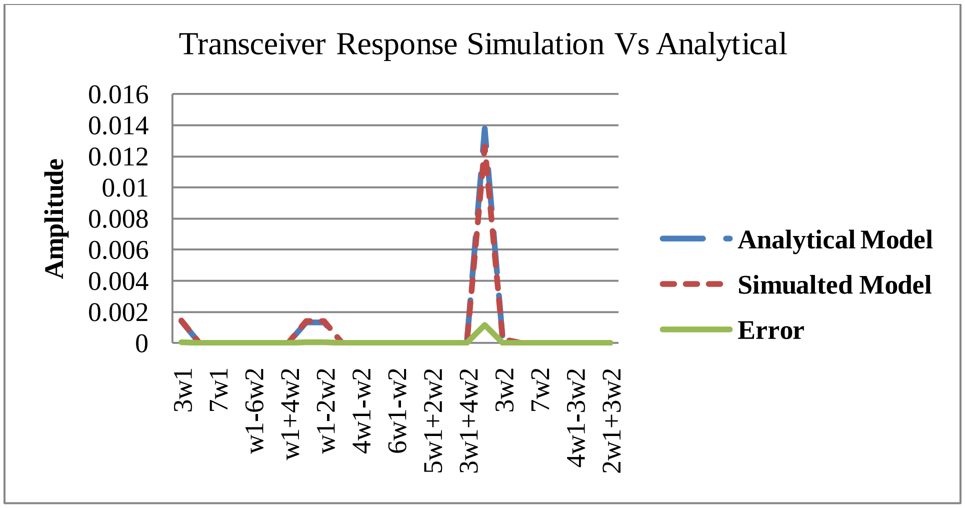


Figure 5-4 Transceiver response –Simulation Vs Analytical and the difference between the two responses.

5.3 Summary

In this chapter the detailed mathematical modeling of the nonlinear model of transceiver has been presented. Detailed expressions for the I/Q response at each stage of the transceiver, including the nonlinearity of the Analog/RF components such as LNA, Mixer and PA have been derived. The next half of the chapter describes the validation of the mathematical model developed. The transceiver model including all nonlinearities is simulated in MATLAB and the I/Q response of receiver is obtained and the FFT of the response is taken to get the amplitudes of the signal at different frequency locations. The amplitude from FFT is compared to the amplitude obtained from the mathematical expression for the I/Q response. The comparison results have been presented and the mathematical model developed has been validated.

CHAPTER 6

EXTRACTION OF PARAMETERS USING NON LINEAR RESPONSE OF TRANSCEIVER MODEL

The parameters to be extracted by using the nonlinear model developed are $\alpha1, \alpha2, \alpha3$ and $\beta1, \beta2, \beta3$. In this research a genetic algorithm is used for extraction of these parameters from the analytical model. The I/Q imbalance extracted from the linear model become known parameters. These known values are substituted for in the derived nonlinear system equations and the remaining nonlinear parameters becomes the unknown. A GA is used to solve for these unknown parameters. This technique use simple mathematical operations and hence is extremely fast and would be computationally simple to implement on chip, when compared to that used in the previous works [6] [14] [15]. Once the nonlinear parameters are extracted the extracted transmit IIP3, TxIIP3 and receive IIP3, RxIIP3 of the system can be calculated.

6.1 Application of genetic algorithm

From the expressions derived for the nonlinear model, for extraction of parameters, the expression corresponding to the I term of the output response of the transceiver model is used for extraction of $\alpha1, \alpha2, \alpha3$ and $\beta1, \beta2, \beta3$. The nonlinear model contains up to 9^{th} order nonlinear terms. Genetic algorithm is applied to extract $\alpha1,\ \alpha2,\ \alpha3$ and $\beta1,\ \beta2,\ \beta3$. The nonlinear expression derived, contains terms corresponding to various frequency locations such as $\omega1$,3 $\omega1$,5$\omega1$,7$\omega1$, $\omega2$,3 $\omega2$,5$\omega2$,7$\omega2$, $\omega1\pm4\omega2$, $\omega1\pm2\omega2$,3 $\omega1\pm4\omega2$, $3\omega1\pm2\omega2$, $9\omega2$, etc. From these the expressions corresponding to 6 different frequency locations are chosen. These expressions are used to formulate the cost function in the GA.

The sinusoidal test signals applied to the nonlinear system model denoted by,

$$I = A1'.\mathrm{Cos}(\omega 1.\ t) \tag{6.1}$$

$$Q = A2'.\mathrm{Sin}(\omega 2.\ t) \tag{6.2}$$

Where $A1'$ and $A2'$ are the input signal amplitudes.

These test signals are applied to both the mathematical analytical model and the MATLAB Model developed for the transceiver.

Consider the frequency locations $\omega 1$, $3\ \omega 1$, $9\ \omega 2$, $\omega 1 + 4\omega 2$, $3\omega 1 + 4\omega 2$. The amplitudes corresponding to these frequency locations are obtained by computing the FFT of the nonlinear response in the simulated MATLAB Model. These amplitudes are denoted by A1, A2, A3, A4, A5 and A6. The mathematical expressions corresponding to the amplitudes of these frequency locations are derived from the analytical non linear model. These are denoted by A1C, A2C, A3C, A4C, A5C and A6C. The expressions corresponding to the amplitudes are relatively complex and hence here a simplified form of the expressions has been shown. For simplification, the amplitude of the test signals are taken to me 0.1mV , and the extracted values for the linear system parameters as in Chapter 4 are substituted for in the mathematical expressions. Thus the only unknowns in expressions are $\alpha 1$, $\alpha 2$, $\alpha 3$ and $\beta 1$, $\beta 2$, $\beta 3$.

The process of extraction using the genetic algorithm is similar to the one described to extract the parameters using the linear response.

6.1.1 STEP 1: Selection of Initial Population

A random population of the parameters to be extracted, is chosen, and defined as

$$\alpha 1\_\text{initial} = \{\alpha 1_1 ,\alpha 1_2 \ldots\ldots \alpha 1_{100} \};\ \alpha 1 \text{ between } 1.5 \text{ and } 2.5$$

$$\alpha 2\_\text{initial} = \{\alpha 2_1 ,\alpha 2_2 \ldots\ldots \alpha 2_{100} \};\ \alpha 2 \text{ between } -0.00001 \text{and } +0.00001$$

And similarly for α3,β1,β2 and β3 as :

α3_initial, β1_initial, β2_initial and β3_initial.

6.1.2 STEP2: Formation of New Members

Using the process of crossover and mutation described earlier, new members are created for α1 α2, α3 and β1, β2, β3

Crossover:

From the set of 100 members, 2 random members are chosen for each parameter and the crossover operator is applied to generate a new member.

$$\alpha 1\_\text{crossover} = \frac{(\alpha 1_1 + \alpha 1_2)}{2}$$

Where$\alpha 1_1$ and $\alpha 1_2$ can be any value from the set $\{\alpha 1_1 ,\alpha 1_2 \ldots\ldots \alpha 1_{100} \}$

1000 such crossover members are generated for every parameter α2, α3 and β1, β2, β3 for eg.

$$\alpha1\_crossovermem=\{\alpha1crossover1,\alpha1crossover2,..............\alpha1crossover1000\}$$

Mutation:

For every member of the initial set of 100 members chosen 10 mutated members are generated. This means a total of 1000 mutated members are generated. The mutation coefficient alpha is chosen as 0.3 for the first iteration and then made smaller for iteration after. The mutated member is generated by applying the mutation coefficient as follows:

Mutation factor, $Mutfact=(rand()*alpha+1)$, chooses a value of Mutfact between 1 and $(alpha+1)$. This $Mutfact$ is used so that we can generate different mutated members of same Gm1 using different $Mutfact$ values.

$$\alpha1\_mutated=Mutfact*\alpha1$$

For example, for each element of the set $,\{\alpha1_1.......\alpha1_{100}\}$, 10 mutated members are generated:

$\alpha1\_mutatedmem = \{ \alpha1_1 mut1,,..... \alpha1_1 mut10, ... \alpha1_{100} mut1,...\alpha1_{100} mut10\}$

Similarly for each parameter $\alpha2, \alpha3, \beta1, \beta2$ and $\beta3$ 1000 such crossover members are generated.

The total population is built by combining the initial members, and the new members generated by performing crossover and mutation, for example

$$\alpha1total=\{\alpha1\_initial,\alpha1\_crossovermem,\alpha1\_mutatedmem\}$$

Where $\alpha1_{\text{initial}}$ has 100 members, $\alpha1_{\text{crossovermem}}$ has 1000 members and $\alpha1_{\text{mutatedmem}}$ has 1000 members. Hence the total search space for 1 , $\alpha1\text{total}$ has 2100 members. Similarly all the parameters α2, α3, β1, β2 and β3 have a search space containing 2100 members each.

6.1.3 STEP 3: Formation and Evaluation of Cost Function

The simplified expressions corresponding to the different frequency locations are expressed as:

$$\begin{aligned} A1C = {} & 0.0003232\,\alpha1^3\beta3 + 0.00001134*\alpha1^2\alpha3\,\beta3 \\ & + 0.00001134\,a1\,\alpha2^2\beta3 + 0.000725\,\alpha1\,\alpha2\,\beta2 + 1.507 \\ & * 10^{-7}\alpha1\,\alpha3^2\,\beta3 + 0.0434\alpha1\,\beta1 + 1.5072*10^{-7}\alpha2^2\alpha3\,\beta3 \\ & + 8.485*10^{-6}\alpha2\,\alpha3\,\beta2 + 6.89*10^{-10}\alpha3^3\beta3 + 0.000406\,\alpha3\,\beta1 \end{aligned}$$

$$\begin{aligned} A2C = {} & 0.00006467\,\alpha1^3\beta3 + 3.6483 * 10^{-6}\alpha1^2 a3\,\beta3 + 3.6483 \\ & * 10^{-6}\,\alpha1\,\alpha2^2\beta3 + 0.000145\,\alpha1\,\alpha2\,\beta2 + 6.1589 \\ & * 10^{-8}\,\alpha1\alpha3^2\beta3 + 6.15892398006327 * 10^{-8}\,\alpha2^2\alpha3\,\beta3 \\ & + 2.7289 * 10^{-6}\,a2\,a3\,b2 + 3.2741 * 10^{-10}\,\alpha3^3\beta3 \\ & + 0.0000814\,\alpha3\beta1 \end{aligned}$$

$$A3C = 1.2285 * 10^\wedge - 13\alpha3^3\beta3$$

$$\begin{aligned} A4C = {} & 4.0319 * 10^{-7}\alpha1^2\alpha3\,\beta3 + 4.0319 * 10^{-7}\alpha1\,\alpha2^2\beta3 + 1.3342 * \\ & 10^{-8}\alpha1\,\alpha3^2\beta3 + 1.3342 * 10^{-8}\alpha2^2\alpha3\,\beta3 + 3.0159 * \\ & 10^{-7}\alpha2\,\alpha3\,\beta2 + 1.01703 * 10^{-10}\alpha3^3\beta3 \end{aligned}$$

$$\begin{aligned} A5C = {} & 2.6868 * 10^{-9}\alpha1\alpha3^2\beta3 + 2.6868 * 10^{-9}\alpha2^2\alpha3\,\beta3 + 3.352 \\ & * 10^{-11}\alpha3^3\beta3 \end{aligned}$$

$$A6C = 0.0445625 * \alpha1 * \beta1$$

A1C, A2C, A3C, A4C, A5C and A6C are evaluated for all sets of α1, α2, α3 and β1, β2, β3 in the search pool. Using these evaluated amplitudes and the amplitude from the FFT of the response from the nonlinear model simulated in MATLAB the cost function for the GA is defined as follows:

Minimize

$$f(\alpha1,\alpha2,\alpha3,\beta1,\beta2,\beta3) = ((A1\text{-}A1C)^2+(A2\text{-}A2C)^2+(A3\text{-}A3C)^2 + (A4\text{-}A4C)^2+(A5\text{-}A5C)^2+(A6\text{-}A6C)^2 \qquad (6.)$$

$f(\alpha1,\alpha2,\alpha3,\beta1,\beta2,\beta3)$ is evaluated for all 2100 sets of $\alpha1,\alpha2,\alpha3,\beta1,\beta2,\beta3$ generated in the search space.

6.1.4 STEP 4: Ranking

The evaluated $f(\alpha1, \alpha2, \alpha3, \beta1, \beta2, \beta3)$ are arranged in ascending order. Smallest value of $f(\alpha1,\alpha2,\alpha3,\beta1,\beta2,\beta3)$ corresponds to Minimum Mean Square Error and is given the highest rank. First 50 members from the ranked and 50 random members from the initial population are chosen to be the new 100 members to be the $\alpha1$_initial set for the next iteration. The STEPS 2 through 4 are repeated until the minimum mean square error criterion is met. In this way the fittest values of $\alpha1, \alpha2, \alpha3, \beta1, \beta2, \beta3$ corresponds to the extracted values.

6.2 Results:

This process of extraction on nonlinear parameters using the GA and the analytical model was performed for the specified test input signals (6.1)(6.2) and the results were obtained as shown in the Table 6-1.

Table 6-1 Results for extraction of nonlinear parameters, using the Analytical Model and Genetic Algorithm

Parameter	Injected	Extracted Run 1	Run 2	Run 3	Run 4	Run 5	RMS Error
α1	1.9952	1.96156	1.96808	1.94904	1.99787	1.97236	0.06740
α2	0.0000	0.00000	0.00001	0.00000	0.00000	0.00001	0.00001
α3	-1.976	-1.99435	-2.00840	-2.09355	-1.96364	-2.00852	0.12691
β1	1.7782	1.78745	1.78191	1.79972	1.75368	1.77817	0.03409
β2	0.0000	0.00001	0.00000	0.00001	0.00001	0.00000	0.00001
β3	-2.376	-2.32289	-2.32096	-2.31825	-2.32043	-2.41226	0.11763

Using the extracted values of α1, α2, α3, β1, β2 and β3, the extracted values of TxIIP3 and RxIIP3 are calculated and compared to the injected values. It observed from Table 6-2 that the error in extraction of nonlinear parameters is very small and is around 0.04 dB.

Thus this extraction technique proposed in this thesis is not only cable of extracting the nonlinear parameters α1, α2, α3, β1, β2, and β3, but also provides important system parameter information, the extracted system TxIIP3 and RxIIP3.

Table 6-2 Results for extraction of nonlinear system parameters TxIIP3 and RxIIP3

Paramter	Injected (dBm)	Extracted (dBm)	Error (dB)
TxIIP3	14.3	14.33474	0.035
RxIIP3	13	13.0435	0.044

6.3 Summary

This chapter explains in depth the application of genetic algorithm in combination with the nonlinear model developed for the transceiver, to extract the nonlinear parameters of the system. The step by step extraction process to be followed has been explained in detail. The genetic algorithm was implemented in MATLAB and the results for extraction of the nonlinear parameters, along with system parameter, IIP3, has been presented.

CHAPTER 7

CONCLUSION AND FUTURE WORK

7.1 Conclusion

The first part of this thesis concentrated on developing a mathematical model of the transceiver, including the system parameters and impairments. A two extraction process has been presented for the extraction .First the linear system model was developed. The extraction of system parameters and impairments such as I/Q gain mismatch, phase mismatch and time delay was performed by using the expressions derived in the linear system model and the genetic algorithm approach. The second half of the thesis concentrates on mathematical modeling of the nonlinear system model for the transceiver. The transceiver model was also simulated in MATLAB. Test input I/Q signals were applied to this model and the output response was compared to the response obtained by applying the test signals to the mathematical model. This comparison was done by comparing the amplitudes of the response obtained from MATLAB Vs Mathematical Modeling. It was found that both the responses matched and the error was minimal. Thus the mathematical model developed was validated. This model was then used to extract the nonlinear parameters The extraction technique proposed in this work technique uses a GA in combination with the analytical model developed for the transceiver. The technique yields good extraction results. The extraction technique uses simple mathematical operations and a fairly simple genetic algorithm. The extraction is fast and computationally simple when compared to other existing techniques such as traditional two step dedicated approach, Nonlinear Solver (NLS) approach, etc. The NLS technique is computationally complex and runs the risk of non-convergence, which means higher extraction time, large memory requirement and cost. The aim of the thesis was to approach the issue of complex test extraction techniques and arrive at a computationally simple and cost effective solution.

7.2 Future Work

There is wide scope for potential future work and some of them are listed below.

- Hardware implementation of the linear model approach and nonlinear model approach for extraction of parameters.
- Time skew parameters were not extracted using this technique and this technique can be extended to extract these parameters as well.
- It is observed that the extraction results are sensitive to the input amplitude/power levels of the I/Q signals applied to the transceiver model. Analysis of this sensitivity and dependency of the system parameters on the amplitude can be investigated.
- The expressions derived for the nonlinear response model considers up to 9th order nonlinearity. It was found that the extraction results had a very high dependency on the order chosen. One way to simplify the computational complexity would be to reduce the order of the nonlinearity chosen.

But the sensitivity of the extraction results to that of the order chosen can be focused upon to achieve a simpler nonlinear mathematical model.

REFERENCES

[1] A. Valdes-Garcia, J. Silva-Martinez, and E. Sanchez-Sinencio, "On chip testing techniques for RF wireless transceivers," *IEEE Des. Test Comput.* vol. 23, no. 4, pp. 268–277, Apr. 2006.

[2] D. Lupea, U. Pursche, and H. Jentschel, "RF-BIST: Loopback spectral signature analysis," in *Proc. IEEE Des. Autom. Test Eur. Conf.*, Apr. 2003, pp. 478–483.

[3] J. Dabrowski, "BiST model for IC RF-transceiver front-end," in *Proc. IEEE Int. Symp. Defect Fault Tolerance VLSI Syst.*, Nov. 2003, pp.295–302.

[4] S. Bhattacharya and A. Chatterjee, "A built-in loopback test methodology for RF transceiver circuits using embedded sensor circuits," in *Proc. IEEE ATS,* Nov. 2004, pp. 68–73.

[5] A. Haider, S. Bhattacharya, G. Srinivasan, and A. Chatterjee, "A system-level alternate test approach for specification test of RF transceivers in loopback mode," in *Proc. IEEE Int. Conf. VLSI Des.*, Jan. 2005, pp. 289–294.

[6] Erdogan, E.S., Ozev, S., "Detailed Characterization of Transceiver Parameters Through Loop-Back-Based BiST", *Very Large Scale Integration (VLSI) Systems, IEEE Transactions* Volume: 18 Issue: 6, June 2011

[7] Duyvesteyn, K. ; Kaymak, U."Genetic Programming for Economic Modeling**",** *Evolutionary Computation, IEEE Congress,* pp: 1025 - 1031 Vol. 2 , 2005

[8] So, M.F., Wu, A., "Four-step genetic search for block motion estimation", *Acoustics, Speech and Signal Processing. Proceedings of the IEEE International Conference,* May1998, pp.1393 - 1396 vol.3

[9] "Genetic algorithms in search, optimization and machine learning", *by david e. Goldberg addision- wesley, 1989.*

[10] "Introduction to genetic algorithms", *by s. N. Sivanandam, s. N. Deepa, springer-verlag berlin heidelberg 2008.*

[11] "Practical genetic algorithms*", by randy l. Haupt & sue ellen haupt, second edition, john-wiley & sons inc. Publication,2004*

.

[12] "An introduction to genetic algorithms", *by melanie mitchell, mit press edition, 1998.*

[13] “Genetic algorithms: concepts and designs”, *By Kim F. Man, K. S. Tang, and S. Kwong, Springer-Verlag, 2001*

[14] Marquardt D W,”An algorithm for least-squares estimation of nonlinear parameters*” SIAM J. Soc. Indust. Appl. Math.* 11:431-41, 1963

[15] Erdem Serkan Erdogan, Sule Ozev, "Single-Measurement Diagnostic Test Method for Parametric Faults of I/Q Modulating RF Transceivers," *26th IEEE VLSI Test Symposium*, pp.209-214, 2008

[16] E. Acar and S. Ozev, "Low cost characterization of RF transceivers through IQ data analysis," ,*Proc. IEEE ITC*, Oct. 2007, pp. 1-10.

[17] G. Gil, Y. Song, and Y. Lee, “Non-data-aided I/Q mismatch estimation in low-IF receivers,” *Proc. IEEE Veh. Technol. Conf.*,May 2004, vol.3, pp. 1261–1264.

[18] I. Sohn, E. Jeong, and Y. Lee, “Data-aided approach to I/Q mismatch and DC offset compensation in communication receivers,” *IEEE Commun. Lett.*, vol. 6, no. 12, pp. 547–549, Dec. 2002

[19] Herrero, J.M; Blasco, X; Martínez, M; Ramos, C; Sanchis, J,” Non-linear robust identification using evolutionary algorithms” *Engineering Applications of Artificial Intelligence*, Vol. 21, Issue 8, Pages 1397-1408, Dec. 2008

[20]” An introduction to genetic algorithms”, *by Deb, Kalyanmoy Sadhana*, Vol. 24, Issue 4, pp. 293 - 315 ,Aug 2008

[21] Allende, Hector; Bravo, Daniela; Canessa, Enrique ,“Robust design in multivariate systems using genetic algorithms”, *Journal of Quality & Quantity*, Vol. 44, Issue 2, pp. 315 - 332 ,Feb. 2010

[22] Onabajo, M., Silva-Martinez, J., Fernandez, F., Sanchez-Sinencio, E., "An On-Chip Loopback Block for RF Transceiver Built-In Test", *Circuits and Systems II: Express Briefs, IEEE Transactions* , On page(s): 444 - 448, Volume: 56 Issue: 6, June 2009

[23] Erdogan, E.S., Ozev, S； A Multi-Site Test Solution for Quadrature Modulation RF Transceivers, *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, vol. 30, no. 9, Sep. 2011

[24] E. Erdogan and S. Ozev, “A packet based 2x-site test solution for GSM transceivers with limited tester resources,” *in Proc. IEEE VTS*, May 2009, pp. 303–308

[25] Acar, E.; Ozev, S.," Efficient Testing of RF MIMO Transceivers Used in WLAN Applications ", *International Conference on Computer Design*, 2006, Page(s): 432 - 437