SIMULINK BASED MODELING OF RF FRONT-END LOW NOISE AMPLIFIER (LNA)

SHERAZ SHAFIQUE

322-FET/MSEE/S13

SUPERVISOR

DR. AHSAN ULLAH KASHIF

CO-SUPERVISOR

DR. IHSAN-UL HAQ

DEPARTMENT OF ELECTRONIC ENGINEERING

FACULTY OF ENGINEERING AND TECHNOLOGY

INTERNATIONAL ISLAMIC UNIVERSITY ISLAMABAD (IIUI)

1. Amplifiers, Radio frequency
2. Broadband amplifiers

Thesis Entitled

SIMULINK BASED MODELING OF RF FRONT-END LOW NOISE AMPLIFIER (LNA)

Thesis Submitted in Partial Fulfillment of the Degree Requirements of MS in Electronic Engineering

BY

SHERAZ SHAFIQUE

322-FET/MSEE/S13

TO

THE DEPARTMENT OF ELECTRONIC ENGINEERING

FACULTY OF ENGINEERING AND TECHNOLOGY

INTERNATIONAL ISLAMIC UNIVERSITY, ISLAMABAD

(IIUI)

SESSION 2013-2015

Certificate of Approval

This Thesis Titled

SIMULINK BASED MODELING OF RF FRONT-END LOW NOISE AMPLIFIER (LNA)

By

SHERAZ SHAFIQUE [Reg.No: 322-FET/MSEE/S13]

Has been approved for the International Islamic University, Islamabad

External Examiner: (Dr. M. Usman)

Internal Examiner:
Dr. Suheel Abdullah Malik
Department of Electronics Engineering, IIU, Islamabad

Supervisor:
Dr. Ahsan Ullah Kashif
Department of Electronics Engineering, IIU, Islamabad

Co-Supervisor:
Dr. Ihsan-ul Haq
Department of Electronics Engineering, IIU, Islamabad

Chairman:
Dr. Muhammad Amir
Department of Electronic Engineering, IIU, Islamabad

Dean:
Dr. Aqdas Naveed Malik
Faculty of Engineering and Technology, IIU, Islamabad

DECLARATION

I, **SHERAZ SHAFIQUE s/o MUHAMMAD SHAFIQUE,** Reg. No: **322-FET/MSEE/S13,** student of MS Electronic Engineering, Session 2013-2015, hereby declare that the matter printed in the thesis titled **"SIMULINK BASED MODELING OF RF FRONT-END LOW NOISE AMPLIFIER (LNA)"** is my own work and has not been printed, published or submitted as research work, thesis or publication in any form in any University, Research Institution, etc. in Pakistan or abroad.

Sheraz Shafique

Dated: ____________

ACKNOWLEDGEMENTS

First of all, I would like to thank Almighty Allah for His immense blessing upon me and my family. Also, I would like to thank Muhammad (SallalahuAlayhiWaAllihiWasalam) for teaching the true path of Islam.

Next, I would like to thank Dr. Ahsan Ullah Kashif for bringing light to my track in the dark maze of research. Sometimes, he believed in me more than myself and motivated me like a father. I would like to thank him for all his solitaire and trust in me.

I would also like to thank Dr. Ihsan Ul Haq for being my Co-Supervisor and a special thanks to Sir Nauman Akhtar for not only his traces during my research but also treating me like a fellow and being a so beneficial travel partner. I would also like to thank my friends especially, Usama Farrukh, Khalid Ibrahim and Hayatullah for their moral support.

Furthermore, I would like to thank my family especially, my mother and my sisters for their daily prayers for me. A special thanks to my mother for calling me daily, encouraging me and giving daily tips about protecting myself from cold, hunger and more importantly reminding me nothing is more important than my health.

In this limited space, I would also want to mention my gratitude to HEC for its support during my MSEE. I would like to thank HEC for their fully funded scholarship for five years.

ABSTRACT

In this thesis, a novel approach is proposed regarding the behavioral modeling of LNA in SIMULINK environment. A hierarchical approach is adopted to design a comprehensive LNA model, that could provide sufficient understanding of the actual performance, as well as to predict the values of different design parameters of LNA i.e. stability, gain, noise and nonlinearity. In this regard, all the important design parameters of LNA are modeled separately with the help of their characteristic equations and by taking S-parameters, P_{1dB}, P_{ip3} and NF as input parameters. Whereas, the values of input parameters are taken from the datasheet/ADS circuit of LNA having device # ATF-34143 being simulated at $2.5e^{9}$Hz. In order to, develop a comprehensive LNA behavioral model, all the individual block models of different LNA design parameters are combined with the help of "Embedded MATLAB Function" block to observe the effect of gain, noise and nonlinearity altogether on the input signal. The approach under consideration ensures better accuracy, as well as less development and simulation time which enables the proposed behavioral model to be compatible with the latest RF front-end architectures. For the validation of design feasibility and for the performance optimization, the results of the proposed LNA model are compared with the results of LNA designed in ADS software.

TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

Chapter 1

INTRODUCTION

From the past few decades, there has been an exponential growth in the demand of communication systems which could provide resilient transmitting, as well as receiving performance. The development of new telecommunication standards and the limitation of frequency spectrum have led the communication industry to develop such systems which should be compatible with the new telecommunication standards and should keenly use the limited frequency spectrum with efficient frequency distribution and also provide higher data rates, faster communication, energy efficiency and longer life, etc. [1]

For this, multi-standard RF front-end receivers are in demand for new telecom systems as a common platform with optimized low noise amplifiers (LNAs), both in form of low power consumption and reduced noise effects (means low NF). Hence, it will enable the RF systems to reconfigure themselves in order to work in accordance with feasible communication standards, for instance, fourth generation (4G) of mobile telecommunications, satellite, as well as cellular communication, short-range and long range connectivity e.g. blue-tooth and WLAN etc. [2]-[3].

The limitations introduced in the electromagnetic spectrum, have pushed the RF design engineers to design efficient RF frontend receivers. In RF receivers, mixers are used to perform frequency conversion for an efficient use of frequency spectrum. But mixers, as well as all electronic circuits are a bit noisy and have non-linear behavior. Therefore, for RF receivers to be able to detect the weak and noisy information signal, an amplifier is needed to be placed before mixer which could not only amplify the weak input signals, but also add minimum noise for the desired information to be retrieved easily [4].

Hence in the receiver, LNA is considered as one of the major components, which is responsible for providing sufficient gain while adding as little noise as possible to the received weak and noisy signal. For small signals, LNA amplifies the received signal so that, its amplitude stays above the noise floor of the receiver whereas, for large signal values it provides amplification but does introduce some non-linearities. Although the linearity of the receiver is defined by the mixer but by defining a specific IIP_3, while designing an LNA can also help to control the linearity of the mixer. These concepts can be of great help in the designing of some RF front-end architectures [5].

Today the design complexities of RF systems have been increased due to the increasing demand of high data rates, efficient and portable devices that can operate on several communication bands. So, RF system design engineers are required to adopt new methodologies in order to meet the requirements of new telecom technology. The designers are needed to pay attention to design such devices which fulfill the commercial demand of multi-standard power efficient, low cost and portable RF devices. This issue of complex system design can be resolved by adopting accurate simulation tool which can not only help to simulate the system but also provide an environment for the designing of a whole system [6].

Computer Aided Design (CAD) tools have proved to be helpful in the designing of RF front-end architectures, by reducing the implementation cycle time in order to optimize a specific problem by providing proper design methodologies and system planning [7]. Although there has been an exponential growth in the numbers of commercial, as well as academic CAD tools for the design and development of RF front-end architectures but a lot of work needs to be done in this specific field [8].

1.1 Goal

The main goal of this research work is to provide a novel approach towards the modeling of LNA. A complete SIMULINK based system level model for an LNA has been designed that will provide sufficient understanding of the actual performance of an LNA. This approach is adopted because for the validation of higher level simulation of RF systems, a design being started from the scratch to high level ensures the feasibility of the whole system.

- The main interest lies in the designing of a SIMULINK based model for LNA in order to examine the mathematical, as well as behavioral models of different design parameters of LNA. In order to predict the values of design parameters adequately such as gain, noise, stability and non-linearity.
- In order to validate the results generated by SIMULINK LNA model, a typical LNA device having part # ATF-34143 is designed in Advanced Design System (ADS).
- Moreover, by using the proposed LNA model it is easy to investigate the different parameters of those LNAs which have no models in any CAD tools, but their measured data, such as S-parameters are available in their datasheets.

1.2 Problem Statement

The new standards in communication technology and its limited bandwidth has pushed the industry to undergo some major changes in order to develop such communication systems which should be compatible with the new standards while maintaining the features of better efficiency, higher data rates, compact size and longer life etc. These features play a vital role in the next generation of communication systems [9].

The next generation of communication systems will be capable of higher data rates and better sensitivity. Whereas, in order to improve the sensitivity of RF receiver, the major focus is to reduce the noise introduced in the received signal by using LNA as first amplifier/gain stage of RF front-end. Designing of LNA circuit still remains a challenging task in receivers because it must fulfill quite a few tough constraints such as, low noise figure (NF), optimal gain to minimize the non-linearity of mixer and input/output matching to get better reflection coefficient, etc. The key design considerations for an LNA are its gain, stability, noise factor and non-linearity and their mathematical expressions are as following [10]-[11]:

Power and Voltage Gain:

$$G_{pmax\_dB} = 10\log(G_{pmax}) \qquad 1.1$$

$$Gain\ (A_{v1}) = 10^{\frac{G_{pmax\_dB}}{20}} \qquad 1.2$$

Stability:

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2 * |S_{12}S_{21}|} \qquad 1.3$$

Noise Figure (NF), Noise Factor (F) and Noise Power:

$$\text{Noise\_Factor} = 10^{\frac{Noise\_Figure}{10}} \qquad 1.4$$

$$\text{Noise Figure (NF)} = 10\log(\text{Noise\_Factor}) \qquad 1.5$$

$$\text{Noise Power (Input Noise)} = \sqrt{4 * K * R * T * BW} \qquad 1.6$$

Where 'K' is the Boltzmann constant,R is the impedance, T is the noise temperature and BW is the bandwidth.

Non-linearity :

$$V_0 = V_{off} + \propto_1 * V_{in} + \propto_2 * V_{in}^2 + \propto_3 * V_{in}^3 \qquad 1.7$$

The nonlinear behavior of an LNA is characterized by equation (VII). Nonlinearity becomes a serious issue while designing an LNA. The main design complexity arises from the fact, that for signals with low amplitude, LNA shows linear response by amplifying the signals to keep their amplitudes above the noise floor, whereas, for signals with larger amplitudes, LNA behaves as a nonlinear device, it amplifies the signal but introduces some distortions as well. As a result, it becomes difficult to get maximum power, as well as better noise performance. So, nonlinearity plays a key role in performance analysis of an LNA [12].

It is evident that the sensitivity of RF front-end depends on the noise cancellation and gain provision of LNA which is the first active as well as a key component of RF front-end. So it would be of great interest to RF designers to test its performance at a system level which may consist of either a single block or a collection of blocks which may comprise of different LNA design parameters as input parameters. Although this approach would require careful observation but it can be used as a platform in order to test the gain, stability, noise figure and large signal parameters etc. [6].

Today an accurate simulation platform is highly in demand which can be used to tune the nonlinear behavior of LNAs. An RF systems simulation has also become a key issue in analyzing, optimizing and designing of front-end architectures. Typically, it is not an easy task to develop an efficient method, which should simultaneously fulfill the requirements of LNA design such as low NF, nonlinearity, stability and sufficient gain in order to amplify the weak and noisy signal [13].

These problems with LNA design can be solved by implementing a behavioral model of LNA in SIMULINK which should be extracted from circuit simulation software/measured data of active device, e.g. S-parameters. This will help to reduce the noise of LNA, and also provide sufficient gain and matching of input/output impedances of LNA for maximum output power transfer at desired radio frequencies. This will also lead to the design, modeling and implementation of RF front-end architectures with ease and in an efficient manner [14].

1.3 Research Approach

A hierarchical approach is implemented while designing an effective model for LNA in SIMULINK environment which could be used to predict the values of different design parameters of LNA. This approach would help the designers to create the behavioral model of a typical LNA without even dealing complex measurements such as length, spacing, area, etc. The following steps are taken in the designing of a behavioral model of an LNA in SIMULINK;

1) Select the design parameters of LNA according to the desired RF front end system demands e.g. gain 25dB, IIP3 -10 dBc, NF 2.5 dB, sensitivity, etc.
2) Select the RF device according to desired gain, frequency of operation, NF etc.
3) Create individual blocks of different LNA design parameters based on their mathematical expressions in SIMULINK e.g. stability, gain, noise performance and nonlinearity according to the desired demand.
4) Input the values of important LNA design parameters e.g. S-parameters, gain, OIP3, 1dBCP, NF, etc. into the SIMULNK model, from the LNA circuit being developed in another RF simulating software e.g. Advance Design System (ADS)/ or can be taken from the device datasheet, if applicable.
5) The comprehensive behavioral model of an LNA is developed by bringing together all the individual blocks of LNA design parameters with the help of

"Embedded MATLAB Function" by writing a MATLAB code to see the effect of gain, noise and nonlinearity on the input RF signal. The obtained results are shown on the display and scope blocks of SIMULINK.

6) The obtained results of the behavioral model are compared with the results obtained from the circuit designed in another high level simulation software, e.g. ADS or from the datasheet of the device under test (DUT), if applicable.
7) This approach is adopted so as to validate the design feasibility and for the performance optimization of DUT which can be possible in case of the behavioral model of that LNA in SIMULINK.
8) Moreover, by using the proposed LNA model, RF designers can optimized the LNA parameters e.g. stability, voltage and power gains, noise figure and nonlinear behaviors of those LNAs which have no models in any other CAD tools, but their measured parameters such as S-parameters and other information are available in datasheets as provided by the manufacturer.

1.4 Thesis Organization

The thesis is organized in the following manner; chapter 1 comprises of the introduction, goal, problem statement and the research approach. Chapter 2, comprises of literature review regarding different physical and behavioral models of LNA. In chapter 3, RF front-end systems, low noise amplifier and its important design parameters are described. In chapter 4, modeling of RF systems, as well as the proposed SIMULINK based behavioral model of an LNA is described systematically, by first developing individual design parameter blocks and then a comprehensive LNA model. Simulation and results are discussed in chapter 5. The conclusion and future advancements are discussed in chapter 6.

Chapter 2

LITERATURE REVIEW

Today the global market is experiencing an explosive increase in the demands of information communications. The development of compact sized RF front-end architectures is strongly required for the reliable communication, which ensures a quick and efficient way to transfer the data. For this purpose, LNA design which fulfill the needs of wider bandwidth is a quite stimulating task, which requires to keenly study different design parameters of an LNA such as noise, gain, stability and nonlinearity. This chapter comprises of literature review regarding technological advancements in the LNA design, as well as previous work done by other authors on different behavioral models of LNA.

2.1 Technological Advancements in LNA Design

Research activities for wireless communication in RF front-end receivers are especially, focused to LNAs and have greatly been increased. With the passage of time different LNA designs have been proposed and implemented, which involve LNA circuit design and simulations. Some previous work done in the field of LNA designing over the past few years is as follows;

In 2000, Dan An published his work regarding the designing and fabrication of a "microwave integrated circuit (MMIC) low-noise amplifier (LNA)" by using Q-matching in the 'Journal of the Korean Physical Society'. In the proposed work, a low Q matching method was used to design an impedance matching network, for achieving the wideband characteristics for MMIC LNA. The designed MMIC LNA was fabricated and then bonded to a test PCB (Print Circuit Board) for RF measurements. A good agreement was found between the results of simulated and fabricated models. The main focus of the work was on the gain (S_{21}), Noise Figure (NF), Maximum power output, IMD3 and IP_3 at the frequency of operation 1.5~2.5 GHz. The prposed work suggested that, feedback amplifiers can be used as the most distinctive wideband amplifiers in most wideband and high performance applications [15].

Martin Hansson, in 2003, designed three different types of low-noise amplifiers (LNAs) by adopting 0.25 μm SiGe BiCMOS process. First of all, a single stage amplifier with 11 dB gain and 3.7 dB NF at 8 GHz was designed. Then, a cascode two stage LNA having gain of 16 dB and NF of 3.8 dB at 8 GHz was described. At last, a cascade two stage LNA with gain greater than unity at 2~17 GHz and NF below 5 dB at 1.7~12 GHz was described. These proposed models of LNA's could be used in microwave receivers modules of sophisticated phased array antennas, leading towards cost-effective and compact sized modules in the future. All the proposed LNA designs have been employed with circuit layouts and their results have been validated through simulations using Cadence RF Spectre [4].

Hyung-Jin Lee, proposed an efficient technique to design CMOS LNAs for ultra-wideband (UWB) applications. He presented his work, in 2005, at IEEE International Symposium on Circuits and Systems, at 'Virginia Tech VLSI for Telecommunications (VTVT)' Lab. Lee proposed an efficient method to minimize the noise and to maximize the power efficiency of LNA models, while sustaining good input and output matching. The developed LNA, achieved power gain up to 14 dB, NF of 2 dB across the frequency range of 3~5 GHz and was implemented in TSMC 0.18 μm CMOS technology, is a single-stage architecture with very low power dissipation of 9 mW with a 0.9 V supply [16].

In 2006, Ahmad Saghafi and Abdolreza Nabavi, designed an ultra-wideband LNA and was simulated in CMOS technology across frequency range of 3-5 GHz. Shunt series feedback topology is used, for UWB operation. An inductive load is used to improve the noise performance of the LNA. Biasing point variation which occurs due to the resistive feedback is fixed by adding a capacitor in series with feedback. Thus, the desirable gain is achieved with lower power consumption. Simulations show a -3 dB gain bandwidth of

6 GHz between 2 GHz and 8 GHz, a minimum NF of 1.9 dB in the 3~5 GHz band, a power gain of 11.5 dB while consuming 13.9 mW [17].

Paul Westergaard, student Member of IEEE, published recent trends in LNA designing along with a comparison of two highest performance CMOS LNA architectures. In paul's work, a brief review of NF and linearity of LNA is presented along with a typical RF receiver architecture. Recent CMOS LNA performance comparisons are made and a representative LNA architecture is reviewed. The two highest performance CMOS LNAs to date (introduced at ISSCC 2001) in terms of noise figure and linearity are reviewed. Finally, a predicted low-voltage CMOS architecture based on an innovative bipolar architecture is presented [5].

S.-K. Wong and F. Kung, in 2009, proposed a single stage UWB CMOS LNA using inter-stage matching inductor on conventional cascode inductive source degeneration structure. The presented LNA is employed in 0.18 m CMOS technology for a 3~5 GHz UWB system. By careful optimization, an inter-stage inductor can increase the overall broadband gain, while maintaining a low NF. The fabricated prototype has a measured power gain of +12.7 dB, input return loss of 18 dB, output return loss of 3 dB, reverse isolation of 35 dB, NF of 4.5 dB at 4 GHz, while consuming 17 mW of DC dissipation at a 1.8 V supply voltage [10].

In 2012, Jian Ming WU, designed a 2.6 GHz RF frontend and implemented in a "hybrid microwave integrated circuit (HMIC)" for world-wide interoperability for microwave access (WiMAX) receivers. The heterodyne RF frontend comprises of an LNA for noise cancellation, an RF band-pass filter, a down-converter for linearization and an intermediate frequency BPF. The overall NF of the receiver is minimized to 0.9 dB, by reducing the thermal noise of LNA. The down-converter with diode linearizer give rise to gain compression, increasing the IIP_3 of RF frontend by 4.3 dB. The proposed method considerably increases the spurious-free dynamic range (SPDR) of the RF front end by 3.5 dB [18].

In 2012, Pankaj Jha at NIET, Greater Noida, India, designed and simulated a CMOS Ultra-wideband (UWB) LNA which consists of a resistive feedback amplifier with passive input/output impedance matching. Pankaj's proposed LNA design sustains a gain of 15dB over 3.1-10.2GHz with NF of 1.6-1.7dB [19].

Ms. Puri Zaveri, in 2013, used a bilateral approach while designing an LNA by using an RF transistor BFP 540 (product of Infineon Technology). The BFP 540 gives maximum gain with moderate NF by keeping VSWR in as constant whereas, plot of VSWR (input/output) variations are observed separately [12].

2.2 Technological Advancements in Behavioral Modeling of LNA

All the above research works are based on the circuit design and software simulations of RF front-end architectures. But there has been very little research work done in the behavioral modeling of RF front-end architectures, especially LNA designs which includes analyzing, optimizing and designing of wireless systems. For this, RF designers may design a mathematical model for an LNA to get the desired results.

In this regards, SIMULINK comes with so many specifications which can be used to test, analyze and optimize the behavioral modeling of RF front-end systems. In this thesis, we develop a behavioral model of LNA to test, analyze and optimize the characteristic parameters of LNA. The proposed model will be helpful to understand, the non-linear behavior of RF device and can be used to study the receiver bandwidth limitations etc. Some of the previous work done in the past by other authors, regarding SIMULINK based LNA models are as follows;

2.2.1 "SIMULINK Block Set for the High-Level Simulation of Multi-standard Radio Receivers"

In 2007, "Alonso Morgado" at "Instituto de Microelectrónica de Sevilla, SPAIN" proposed a SIMULINK based block modeling of RF receivers. He published his work with a title of "*A SIMULINK Block Set for the High-Level Simulation of Multi-standard Radio Receivers*". Alonso proposed the behavioral simulation all individual components of an RF receiver like amplifiers, mixers, filter, oscillators and switch etc. Alonso also proposed a method of modeling by emphasizing the nonlinear behavior of RF front-end components [20]. The proposed SIMULINK model of LNA by "Alonso"' is based on the nonlinear characteristic equation of LNA as follows;

$$V_0 = V_{off} + \alpha_1 * V_{in} + \alpha_2 * V_{in}^2 + \alpha_3 * V_{in}^3 \quad \textbf{2.1}$$

By rearranging the equation 2.20, the values of α_2 and α_3 comes out to be;

$$\alpha_2 = \frac{\alpha_1}{V_{ip2}{}^2}$$

$$\alpha_3 = \frac{4 * Gain\ (\alpha_1)}{3 * IIP_{3v}{}^2}$$

Hence, the nonlinear characteristic equation becomes,

$$V_0 = V_{off} + \alpha_1 V_{in}(1 + \frac{V_{in}}{|P_{i2}|} + \frac{4 * V_{in}^2}{3 * P_{i3}^2}) \quad \textbf{2.1a}$$

The proposed SIMULINK based behavioral model of LNA by "Alonso" is shown in figure 2.1 [20]. This model takes in the values of input signal (V_{in}), Voltage gain (α_1), Offset voltage (V_{off}), and second and third order intercept points P_{i2} and P_{i3} respectively.

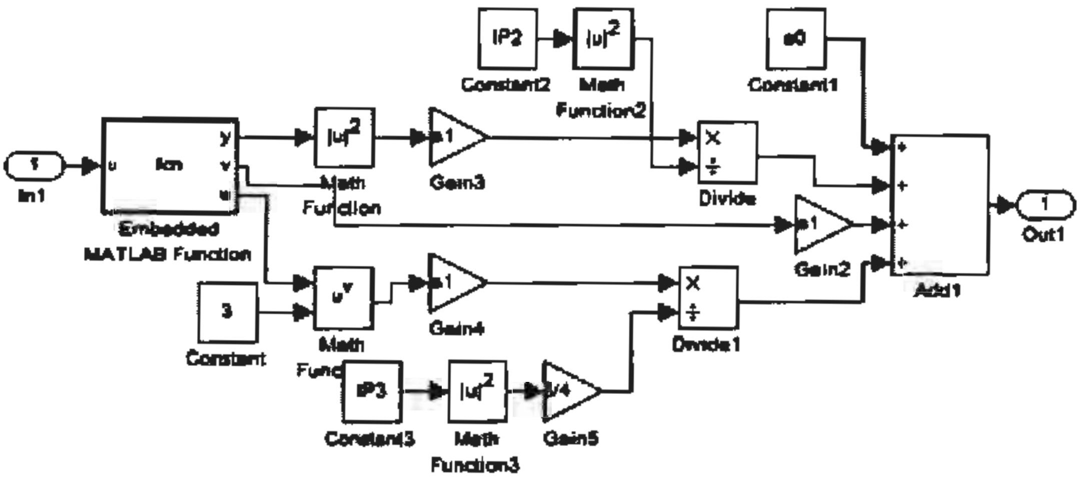


Figure 2. 1: Nonlinear LNA Model [20].

2.2.2 "System Oriented Design of LNA Modeling"

In 2007, "Benjamin Nicolle" at "Laboratoired 'Electronique Antennes & Télécommunications, France", adopted a top-down approach to develop a SIMULINK based LNA model, which would intake the values of Power Gain (G_p), IIP_3 and Noise Figure (NF) from a circuit simulation software to describe the linear voltage gain, first and third order coefficients of nonlinear characteristic equation of LNA, as well as the maximal input and output voltages of LNA along with the value of input noise voltage. The complete LNA model is shown in figure 2.2 [21]. The main block of the proposed model is **"LNA_CORE"** block. The individual stages of the above model were implemented and simulated in SIMULINK with the help of their mathematical expressions. The proposed model can be divided into two sub–portions; one describes the voltage gain, third order nonlinear coefficient and maximum input and output voltage, while the second part describes the input noise voltage. The model is based on the following mathematical expressions [21].

Voltage Gain (α_1):

$$Gain\,(\alpha_1) = 10^{\frac{Gpmax_{dB}}{20}} \frac{Z_o}{Z_i} \tag{2.2}$$

Third order Coefficient (α_3) of Non-Linear Characteristic Equation:

$$IIP_{3_{dBm}} = OIP_3 - G_{pmax_{dB}} \tag{2.3}$$

$$IIP_3 = 10^{\frac{IIP_{3_{dBm}}-30}{10}} \tag{2.4}$$

$$IIP_{3v} = \sqrt{2 * Z_i * IIP_3} \tag{2.5}$$

$$\alpha_3 = \frac{4 * Gain\,(\alpha_1)}{3 * {IIP_{3v}}^2} \tag{2.6}$$

Maximum Input and Output Voltages:

$$V_{in\_max} = \sqrt{\frac{Gain\,(\alpha_1)}{3 * \alpha_3}} \tag{2.7}$$

$$V_{out\_max} = \frac{2}{3} * \alpha_1 * V_{in\_max} \tag{2.8}$$

Input Noise Voltage:

The mathematical expressions for the noise model are described as follows;

$$\text{Noise Factor} = 10^{\frac{Noise\_Figure}{10}} \tag{2.9}$$

$$\text{Noise Figure (NF)} = 10\log\,(\text{Noise\_Factor}) \tag{2.10}$$

$$\text{Noise Voltage (Input Noise)} = \sqrt{4 * K * Z_i * T * (F - 1)} \tag{2.11}$$

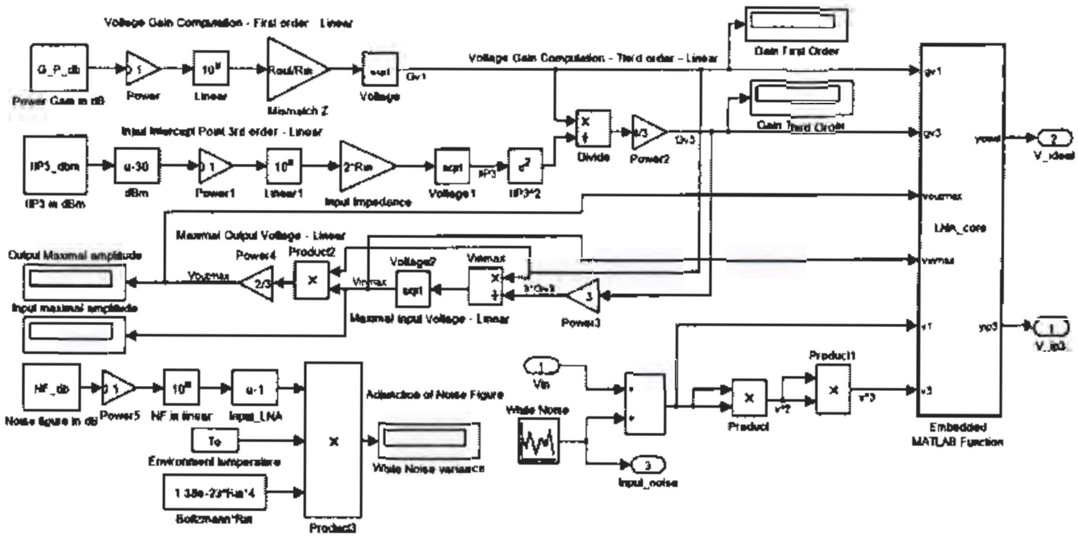


Figure 2. 2: LNA Model [21].

2.2.3 "Design and Performance Evaluation of BPSK UWB Receiver using SIMULINK"

In 2011, "Alpana P. Adsul" at "*SITS, IT Department, Maharashtra (India)*" proposed a SIMULINK model for LNA in order to predict noise performance and bit error rate for Ultra Wide Band (UWB) Receiver. In the proposed research paper, three different design techniques are adopted to design one wideband and two narrow band LNAs. The LNA circuits are designed in ADS while the SIMULINK model is used to verify the noise cancelation and bit error rate for better transmitter and receiver performance. The proposed LNA model is shown in figure 2.3 [22].

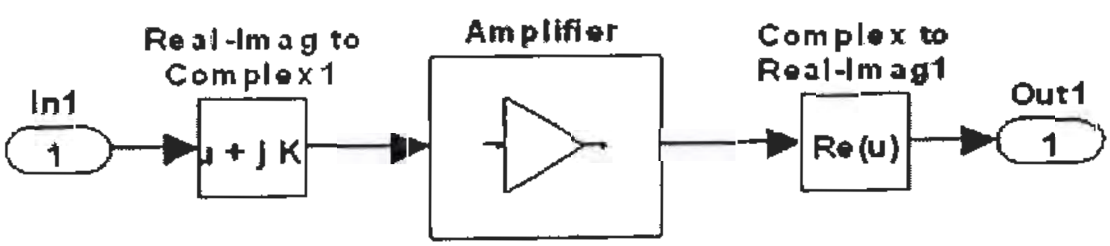


Figure 2. 3: SIMULINK Based LNA [22].

2.3 Problems with Previously Designed SIMULINK Models of LNA

Some of the problems with the previously designed SIMULINK models of LNA design are as follows;

- The model presented by "Alonso", only tells about the voltage gain and does not give complete information about the nonlinear behavior, noise performance and stability factor of LNA.
- "Benjamin Nicolle's LNA model does not give correct values of third order coefficient (α_3) of nonlinear characteristic equation, V_{in_max} and V_{out_max} as compared to the ADS results of device ATF-34143. Moreover, the proposed model does not give any information about the stability factor of LNA.
- The model presented by "Alpana P. Adsul", lacks the information about the stability factor, nonlinear effects and Noise performance, etc. as the model only provide mathematical values of bit error rate or noise.

So, a comprehensive LNA model is needed, which could provide all the required information about basic parameters of LNA e.g. stability factor, voltage and power gains, input and output voltages, NF and nonlinear effect. All these requirements are fulfilled by the proposed LNA model explained in chapter 4.

Chapter 3

LOW NOISE AMPLIFIER DESIGN ASPECTS

The main interest lies in building a behavioral block model in SIMULINK for low noise amplifier (LNA), a part of RF receivers. So, in this chapter the design aspects of an LNA and the factors affecting its performance are described. A brief introduction to RF front-end systems is also included to explain the basic functionality of an RF receiver.

3.1 RF Front-End

RF front-end refers to the analog front-end which comprise of communication operations being done on the receiver side of the wireless communication system. In RF communication systems, at the transmitter side the lone requirement is the desired signal. For this reason the designing of transmitter is easy as compared to the receiver side which requires better sensitivity, better noise performance and better efficiency to retrieve the desired signal properly [23].

In this regard, super heterodyne receiver is one of the most popular type among different RF receiver architectures being used most commonly in a multiple range of RF applications. A typical super heterodyne receiver block diagram is shown in figure 3.1.

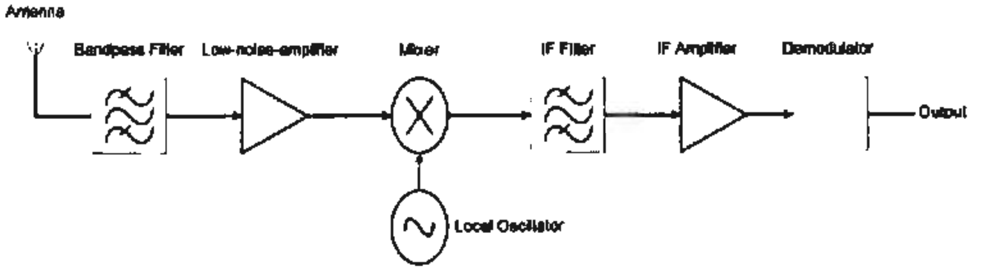


Figure 3. 1: Block Diagram of Super Heterodyne Receiver [1].

The most important function of a typical receiver is to recover the transmitted signal that after passing through the channel might have become noisy and weak. The first component of a receiver is antenna which receives the transmitted signal. The antenna captures a particular range of analog signals which also contain some other signals along with the desired signal. So a filter is required to pass a particular band while rejecting the frequencies outside of that band. After passing through a band pass filter, the received weak and noisy signal needs to be amplified to make it detectable for further next stages of the receiver. After amplification, the received signal is down converted and then converted again into digital data for further processing in a base band section. Processes done to the received weak and noisy analog signal in the RF front-end includes filtering, amplification and mixing. These processes are imperfect and add various impairments to the received signal as well. For example [17]-[18]:

a) At receive side filtering provides selectivity by passing the desired frequency signals and blocking the received signals with undesired frequencies. Moreover, filtering provides better efficiency as a filter being placed before LNA on receiver side would increase the performance of LNA.
b) On receiving end, the amplification and de-noising of the received weak and noisy signal is done with the help of LNA, which provides the sufficient gain and add a little noise as trade-off. The inherent noise of LNA is very small which plays a key role in the reduction of receiver's overall noise figure.
c) Down conversion or frequency conversion of the received RF signal is carried out by mixers, using the local oscillator (LO) signal which is generated by the frequency synthesizer/oscillator. But non-linearity is the main issue in mixers, which can effect on the performance of the receiver.

3.2 Low Noise Amplifier (LNA)

In RF front-end, the desired signal is usually very weak in terms of signal power and is surrounded by some interferer and noise. This is main reason that the receiver side of an RF communication systems needs to be more sensitive with better gain and noise cancellation performance. LNA is the first active component after receiving the signal through the antenna which is intended to provide sufficient gain to the weak received signal, sometimes its value goes below than -100dBm [23].

Hence, the purpose of LNA is to increase the signal strength according to the receiver's compatibility at the cost of little noise addition without producing any substantial distortion. As the received signal is noisy and the signal to noise ratio (SNR) at the input of LNA is small so by adding a little noise to the received signal may degrade the SNR and as a result the performance of the whole receiver will be affected [9]. Therefore, the noise of LNA is need to be kept very small so that the signal-to-noise ratio of the received signal remains above the minimum SNR value of the receiver [14].

3.2.1 LNA Design Parameters

As we know that LNA is one of the most important components of RF receivers and its two main functions involve provision of high gain and low noise. This is not as simple as it seems because LNA needs to provide noise figure (NF) as low as possible as the total NF of the overall receiver relies mainly on the NF of LNA. It needs to provide gain which is high enough to minimize the noise influence of the next stages of the receiver like mixer but LNA's gain should not be too high that it pushes the receiver towards nonlinearity [23]. So the main parameters to be considered while designing a LNA are Stability, Gain, NF and Nonlinearity as shown in the figure 3.2. These parameters are described as a design cycle by following;

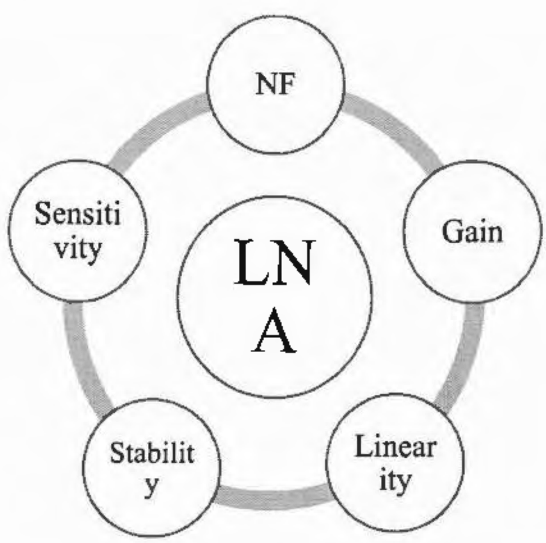


Figure 3. 2: Different Design Parameters of LNA.

3.2.1.1 S-Parameters

In general a two port network is basically an electrical circuit having four terminals through which it can be connected to other circuits. There are several methods to describe the performance of a two port network. At low frequencies networks theorems can be used to analyze a two port network while at high frequency these network theorems fail due to the generation of stray capacitances and inductances as well as the transmission line effects. This is a reason that S-parameters play a vital role to design RF systems. The RF designers use these parameter to define the input/output relations of the network [25]. A typical two port network is shown in the figure 3.3.

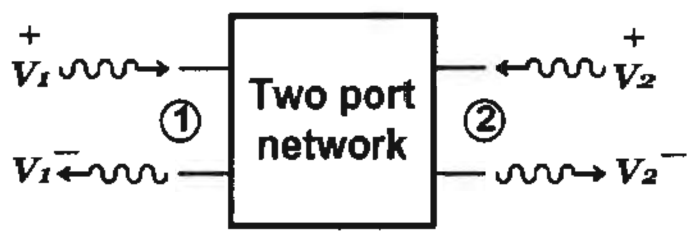


Figure 3. 3: A Typical Two Port Network [14].

"Scattering" or "S-parameters" are commonly used to define the response of a typical two-port network to voltage signals provided at each of its port. The concept of "S-parameters" arises when high frequency amplifiers are needed. The S-parameters comprises of four variables which describe the relation between input and output ports. As shown in the figure 3.3 V_1^+, V_2^+ and V_1^-, V_2^- are the incident and reflected waves of the two port network respectively [25]. The relation between these reflected and incident waves is explained in the set of equations 3.1 as follows [14]:

$$V_1^- = S_{11}V_1^+ + S_{12}V_2^+$$
$$V_2^- = S_{21}V_1^+ + S_{22}V_2^+ \qquad 3.1$$

By definition S_{11}= "Input Reflection Coefficient of the Network", S_{12}= "Reverse Gain of the Network, S_{21}= "Forward Amplifier Gain" and S_{22}= "Output Reflection Coefficient of the network". By knowing these definitions it can easily be predicted that a good LNA should have large value of $S_{21}$to have a high gain, whereas it should have smaller values of $S_{11}$and S_{22} to have good input/output matching and for stability as well as better reverse isolation an LNA should have small value of S_{12}. To design an LNA, the S-parameters values should be $(S_{11}, S_{22}) < -10dB$, $S_{21} > 10dB$ whereas, $S_{12} < -40dB$ [9].

$$S_{11} = \frac{V_1^-}{V_1^+}|_{V_2^+=0} \qquad \textbf{3.1a}$$

$$S_{12} = \frac{V_1^-}{V_2^+}|_{V_1^+=0} \qquad \textbf{3.1b}$$

$$S_{21} = \frac{V_2^-}{V_1^+}|_{V_2^+=0} \qquad \textbf{3.1c}$$

$$S_{22} = \frac{V_2^-}{V_2^+}|_{V_1^+=0} \qquad \textbf{3.1d}$$

3.2.1.2 Stability

In general amplifiers are designed to provide necessary gain for the particular range of frequency along with linearity and it is not desired that the amplifier starts to oscillate outside that desired frequency band. Oscillation means that the amplifier provides the same amount of gain for other frequency outside the band as well. This phenomenon leads to the concept of stability that is the indication of amplifier's tendency to oscillate outside the desired frequency band. So stability assurance is one of the most important design parameter of any type of amplifiers [26].

Therefore, LNA must be designed to provide stable operation by proving sufficient gain and linearity for particular frequencies. Device "S-parameters" proved to be helpful in finding the stability of the device. As the numerical method of finding the stability of LNA circuit consists of "Rollett Stability Factor (K)" which depends on the S-parameters as shown in the expression from chapter 1 below [12];

$$k = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2 * |S_{12}S_{21}|} > 1 \qquad \textbf{3.2}$$

$$\Delta = S_{11}S_{22} - S_{12}S_{21} < 1 \qquad \textbf{3.2a}$$

Usually stability is of two types [27]:

i) **Unconditional Stability** states that the amplifier will not oscillate no matter what type of load is connected to its output. For RF designers, the goal is to achieve unconditional stability. The operating conditions for unconditional stability are

- K >1
- Δ< 1

These conditions ensures the unconditional stability.

ii) **Conditional Stability** is the opposite to the unconditional stability as in this case the amplifier may be potentially stable and may oscillate with respect to the load connected across its output. For conditional stability the condition would be K<1.

3.2.1.3 Gain

Gain is one of the most important design parameters of any amplifier as it indicates the ability of an amplifier that how much it can amplify the amplitude of the input signal. Usually amplifiers are needed where there is a need to amplify the input signal which might be very weak to be detectable for the next stages like in RF receivers where the input signal is in mV or nV or below -100 dBm. In general, the amplification property of an amplifier is characterized by its gain [13].

Gain describes the relation between the input and output voltage or power it can also be defined as the ratio of output voltage or power to the input voltage or power. Mathematical expression for gain are as follows [14];

$$\text{Voltage} - \text{Gain}\ (G_v) = \frac{V_{out}}{V_{in}} \tag{3.3}$$

$$\text{Power} - \text{Gain}\ (G_p) = \frac{P_{out}}{P_{in}} \tag{3.4}$$

For LNA, the gain is needed to be sufficient enough to amplify the weak received signal so that it can be passed on to next stages of the receiver usually gain of an LNA should be above 10 **dB** [10]. In RF communication systems, the gain is expressed in decibels (dB) that is a logarithmic scale for the representation of very large or very small values. As the input signal to LNA is very weak like in nV, so one must represent the power gain in dB. The mathematical expression for power gain is as follows [23];

$$\text{Power} - \text{Gain} - \text{dB}\ (G_{p_{dB}}) = 10\log\left(\frac{P_{out}}{P_{in}}\right) \tag{3.5}$$

$$\text{Voltage Gain} - \text{dB}\ (G_{v_{dB}}) = 20\log\left(\frac{V_{out}}{V_{in}}\right) \tag{3.6}$$

Whereas dB is a simple ratio between the output and input voltage or power and it's a unit less quantity. In RF communication systems with the variation of frequency, the gain of the amplifier also varies hugely so it becomes more convenient to use logarithmic scale instead of simple ratio scale to express the gain. This approach makes the calculations to be performed more easily. This approach helps to express the large variation in specific value with a small value as shown in the table 3.1.

Table 3. 1: Comparison between Gain as Ratio and Gain in dB [28].

Gain as ratio	Gain as decibel (dB)
1000	30 dB
100	20 dB
10	10 dB
1	0 dB
0.1	- 10 dB
0.01	- 20 dB
0.001	- 30 dB
0.0001	- 40 dB

Also maximum power gain can be calculated with the help of stability factor and S_{21} which is the value of forward gain of LNA [12].

$$G_{pmax} = \frac{|S_{21}|}{|S_{12}|}\left(K - \sqrt{K^2 - 1}\right) \tag{3.7}$$

$$G_{pmax\_dB} = 10\log(G_{pmax}) \tag{3.8}$$

$$\text{Gain } (G_v) = 10^{\frac{G_{pmax\_dB}}{20}} \tag{3.9}$$

3.2.1.4 Noise

In RF systems, unwanted signal affects useful signal and is considered as a noise. The sensitivity of a typical RF front-end receiver is directly proportional to the noise performance of its different stages e.g. LNA, Mixer, Filters, etc. For better performance of an *RF* communication system, noise is the most important factor that is needed to be as low as possible w.r.t. the desired signal [9].

Noise is a severe issue especially for RF front-end systems, where very low power, weak and noisy signals are needed to be handled. Most important and effective way to reduce the noise effects is to use low noise amplifier with low noise figure (NF). As the noise is a main and important parameter of any type of LNA. In general, noise increases with the increase in the bandwidth of the signal. Today, current communication standards play with wideband signals so noise is also becoming very common as well as a very serious issue in a wireless communication [29].

Generally, every electronic device is a little bit noisy means it adds noise to the input signal such as transistors, etc. Noise can be generated naturally as well as by different man made sources. Whereas noise is present in almost all kind of RF and microwave wired and wireless communication systems. Moreover, the noise signal is amplified by the gain of the amplifier; this is the main reason that low noise amplifiers are used in RF receivers to minimize the impact of noisy signals. So, Noise is normally described as an unwanted unsystematic disruption added into the desired signal of a typical communication system. There are different types of noises present in electronic devices like "Thermal noise", "Shot noise", and "Flicker noise", etc. [30]. The brief descriptions are as following:

i. **"Thermal Noise"** is generated in electronic devices due to the thermal excitation of charge carriers. This type of noise is present in resistors. As the electrons are in arbitrary movement in a resistor and their movement is temperature sensitive, so with the increment in temperature these electrons start to move quickly generating fluctuations of current across the terminals of resistor as a result. In most LNAs the main focus is to reduce the effect of thermal noise. The thermal noise can be described with the help of following equation [24].

$$v = \sqrt{4KRTB} \qquad \textbf{3.10}$$

Where "K"is the "Boltzman constant ≈1.38 ×1023 J/k", "T"is the "absolute temperature in Kelvins", "R" is the "resistance" and "B" is the "bandwidth of the noise measured in Hz".

ii. **"Shot noise"** is generated in semiconductor devices such as diodes and is present due to the arbitrary motion of charge carriers across the PN-junction. As the electrons and holes penetrate through the PN-junction as a result generating small amount of leakage or noise current. It may be noted that shot noise dominates in low temperature and high frequency cases. The mathematical expression for shot noise is

$$i = \sqrt{2qIB} \quad \textbf{3.11}$$

Where "q= charge of an electron = 1.6 x 10^-19C", "I = diode current", and "B = bandwidth in Hertz" [24].

iii. **"Flicker noise"** also referred as "pink noise" is usually generated at low frequencies whereas at higher frequencies its effect is not so significant. So it has an inverse relation with the frequency as shown in figure 3.4. The source of this type of noise cannot be predicted as it is generated because of the improper connections between conductors and devices inside an electronic system. It can be represented by a mathematical expression as follows;

$$i = \sqrt{K\frac{IB}{f}} \quad \textbf{3.12}$$

Here "K" = "fudge factor" which have different values for different devices as well as different fabrication techniques. "I" = "current" and "B" = "bandwidth" [31].

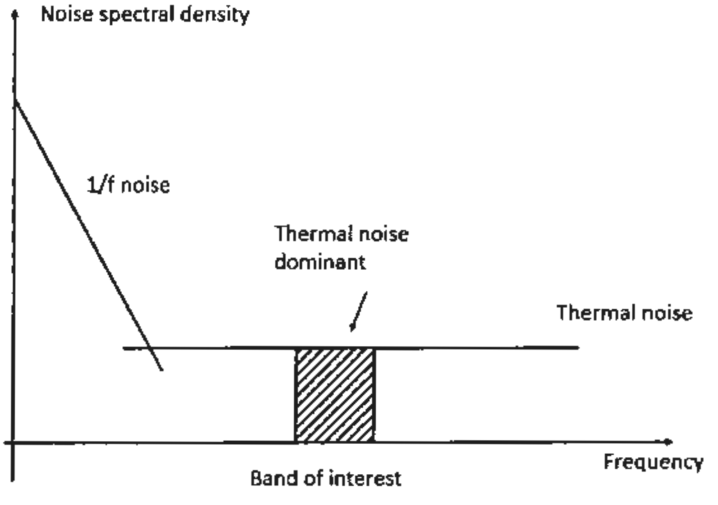


Figure 3. 4: Noise Approximation.

There are different factors which can be used to describe the noise performance of a typical amplifier like Signal-to-Noise Ratio (SNR), Noise Figure (NF) or Noise Factor (F), Sensitivity and Dynamic Range (DR). All these parameters are briefly described in as follows [1];

a) Signal To Noise Ratio (SNR)

SNR can be defined as the ratio between the powers of the wanted signal and the noise signal. In noisy networks the power of the input noise signal is less than the output noise signal this degrades the output Signal to Noise Ratio as at input the SNR will be high while at the output the SNR will be low due to the amplification of output noise signal. This degrades the whole system's performance. Whereas in noiseless networks like in Low noise amplifier (LNA), this is not the case the output SNR remains high enough to maintain the sensitivity of the system or device [1]. The mathematical expression for SNR is shown below; [11]

$$\mathrm{SNR} = \frac{P_{SIGNAL}}{P_{NOISE}} = \left(\frac{A_{SIGNAL}}{A_{NOISE}}\right)^2 \qquad \textbf{3.13}$$

Where '*P*' is the power and '*A*' is the amplitude of the corresponding signals, in dB the SNR can be expressed as follows

$$\mathrm{SNR_{dB}} = 10\log_{10}\left(\frac{P_{SIGNAL}}{P_{NOISE}}\right) = P_{SIGNAL,dB} - P_{NOISE,dB} \qquad \textbf{3.14}$$

The error in the received signal increases, if SNR of the received signal drops below the reference SNR value of the receiver as every receiver is set to have minimum possible SNR at its input.

b) Noise Figure (NF)

Noise figure (NF) is a important parameters to measure the noise performance of communication systems. It is a measurement of degradation of SNR between the input and output of a component in a receiver [1]. Whereas it is also another important factor which affects LNA performance and can be used to measure the overall noise of a receiver. The mathematical expression for calculating noise figure is as follows;

$$\mathrm{Noise-Factor\ (F)} = \frac{\mathrm{SNR_{IN}}}{\mathrm{SNR_{OUT}}} = 10^{\frac{Noise\_Figure}{10}} \qquad \textbf{3.15}$$

$$\mathrm{Noise-Figure\ (NF)} = 10\log_{10}(\mathrm{F}) \qquad \textbf{3.16}$$

Noise figure and noise factor are two interrelated factors one can be easily found out if another is known. NF of a single device as well as of a whole system can be calculated easily as the figure 3.5 shows the NF in case of cascaded stages. Where G_{LNA} is the gain of LNA while G_2 and G_3 are the gains of second and third devices respectively, and F_s are the noise factors of each devices [14].

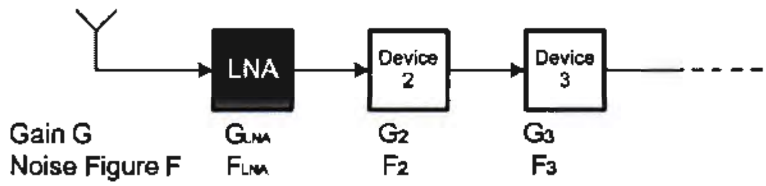


Figure 3. 5: NF in cascaded stages [14].

The mathematical expression of RF receiver noise performance or noise floor is as follows [14];

$$F_{tot} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots \qquad \textbf{3.17}$$

It is clear from the above expression that NF of the overall receiver network depends mainly on the NF of the first component with high gain (typically LNA). It means that a correct modeling of the noise which is added by LNA is essential for a good receiver model.

c) Sensitivity

In case of a typical receiver, Sensitivity (S) is a measure of minimal input signal level for which the receiver can deliver satisfactory output signal quality. It can also be defined as a minimal input signal for which the system can provide sufficient output signal with a significant SNR. Mathematically, it can be described as [32]

$$S = \left(\frac{S}{N}\right)_{min} kT_0B(NF) \qquad \textbf{3.18}$$

Here "$\left(\frac{S}{N}\right)_{min}$" = Minimal SNR required to detect a signal,

"NF = Noise Figure",

"k= Boltzmann's Constant = 1.38 x 10-23 Joule/EK", "To = Absolute temperature of the receiver input" and

"B = Receiver Bandwidth (Hz)".

Moreover, it is well known parameter that in case of a receivers the noise affects the sensitivity of the whole system. In this regard, LNA is an important component as by reducing the noise figure of LNA would result in the reduction of total noise figure of the receiver and this will lead the receiver to achieve better sensitivity. So sensitivity can also be described as [9];

$$\text{Sensitivity (dBm)} = \frac{-174\text{dBm}}{\text{Hz}} + 10\log(\text{BW}) + \text{NF}_{\text{tot}} + 10\log(\text{SNR}_{\text{out}}) \qquad \textbf{3.19}$$

Here "−174dBm/Hz" is the minimum noise level below which the receiver will not be able to detect any signal.

3.2.1.5 Non-Linearity

In RF communication systems, the linearity of a device refers to the ability of the device to process the input signal without introducing any distortion like in case of amplifiers the linearity would be that the amplifier amplifies the signal by providing constant gain. In other words, amplifier must provide linear gain. So linearity defines the maximum acceptable signal level on the input. Usually all electronic devices are nonlinear in nature. Distortion introduced in the input signal as a result of nonlinearity of the device which comes due to inherent capacitances or parasitic effects etc. [33].

At receiver side, the main purpose of the amplifiers is to provide a constant sufficient gain to the weak received signal. In general, the gain characteristics of an amplifier (Vout/Vin) are measured to be non-linear which leads to the truncated output signals, known as non-linear behavior. The non-linear behavior of an LNA can be characterized by the following non-linear equation [33]

$$V_0 = V_{off} + \propto_1 * V_{in} + \propto_2 * V_{in}^2 + \propto_3 * V_{in}^3 \qquad \textbf{3.20}$$

Non-linearity is normally measured by the 1-dB compression and 3^{rd} order intercept points also known as P_{1dB} and IP_3 respectively as shown in figure 3.6 [14].

a) 1-dB Compression Point (P_{1dB})

There are different factors due to which nonlinearity arises in amplifiers one of which is gain compression which refers to how much large signal an amplifier can accept at its input without introducing distortion. In other words, gain compression point tells about the maximum allowable input signal level. This can easily be determined by applying a frequency signal i.e. "A*sin(ωt)", where A is the amplitude and ω is the angular frequency [14].

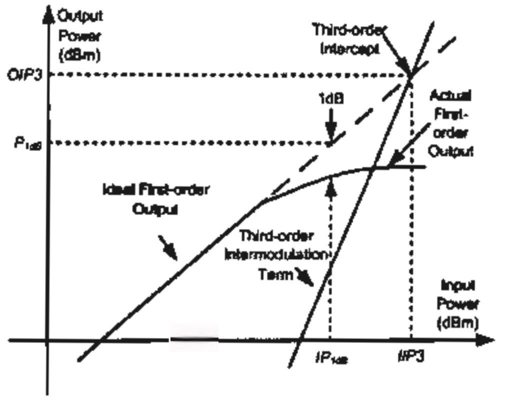


Figure 3. 6: Non-Linearity of LNA [14].

Due to nonlinearity at a specific point, the gain of an amplifier drops from its constant value also at that point the output power becomes constant while input power goes on increasing, that point is referred to as 1-dB compression point as shown in figure 3.7.

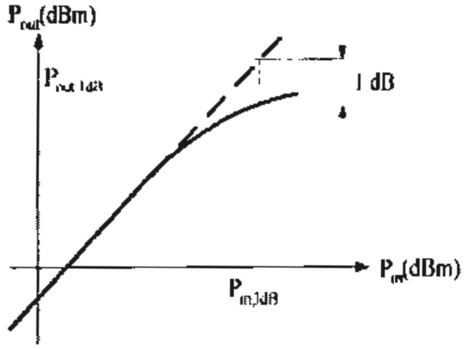


Figure 3. 7: 1-dB compression point [32].

1-dB compression point is a good measure of amplifier's linearity as it indicates a point which shows that at what value of the input power compression will begin and distortion will start. P_{1dB} the output power of an amplifier stays nearly constant whereas the input power goes on increasing. In nonlinear systems, when a sine wave is applied then the output shows different frequency components which are multiples of the fundamental frequency that of input signal. These frequency components are known as harmonics. As shown in the following calculations [18]; If input signal V= $(A * sinwt)$ then the nonlinear characteristic equation would be;

$$V_0 = a_1 * (A * sinwt) + a_2 * (A * sinwt)^2 + a_3 * (A * sinwt)^3 \quad \textbf{3.20a}$$

Simplifying,

$$V_0 = (a_1 A + \frac{3}{4} a_3 A^3) * sinwt + \left(\frac{1}{4} a_3 A^3\right) * sinwt^3 \quad \textbf{3.20b}$$

The first term in the above mathematical expression shows the gain compression point values as follows [11];

$$P_{1db} = P_{O(IDEAL)} - 1dB \quad \textbf{3.21}$$

$$V_{1dB} = \sqrt{0.145 \left| \frac{\alpha_1}{\alpha_3} \right|} \quad \textbf{3.22}$$

Here $P_{O(IDEAL)}$ is the output power of the amplifier. So, the gain compression indicates the bend in the curve of output power when the power gain is less than 1-dB from its ideal curve that point is indicated as 1-dB compression point as shown in the figure 3.6. This point shows that at this point the influence of other frequency components such as 3rd order harmonics on the fundamental signal starts which as a result affect the linear output power curve of the device and lead the device to saturation. So in RF communication systems it is of great interest to operate the devices below this P_{1dB}. [14]

b) 3rd order Intercept Point (IP3)

Another important nonlinearity measure is 3rd order intercept point. In wireless communication third order products cause serious distortion in the information signal also known as inter-modulation effects. IP3 is the point which shows that beyond this point the 3rd order products will become equal to the information signal. When two strong interferes with small difference in between are present with the input signal. Then the 3rd order inter-modulation (IM) products of those interferes lie within the band of interest and distorts the desired signal as shown in the figure. The 3rd order IM products also affect the output power as shown in the figure 3.8.

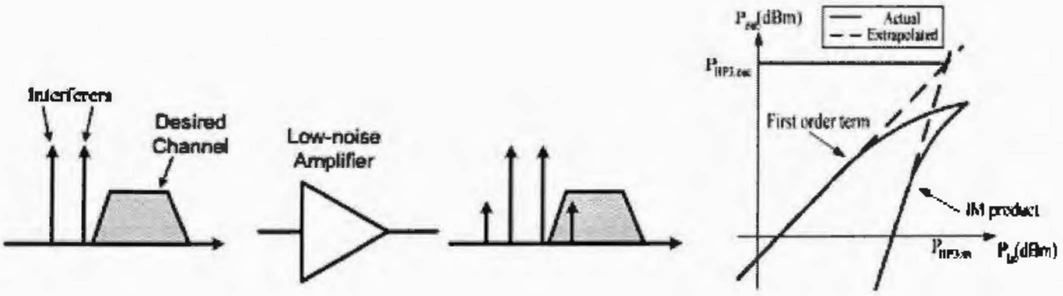


Figure 3. 8: Inter-modulation products and 3rd order intercept point [14].

If two different frequency signals are given at the input of a nonlinear systems then the output may show some frequency products other than the harmonics those products are known as inter-modulation (IM) products as shown below [13].

$$y(t) = \alpha_1(A_1 cos\omega_1 t + A_2 cos\omega_2 t) + \alpha_2(A_1 cos\omega_1 t + A_2 cos\omega_2 t)^2 + \alpha_3(A_1 cos\omega_1 t + A_2 cos\omega_2 t)^3 \quad 3.20c$$

The inter-modulation products are as follows

$$\omega = \omega_1 \pm \omega_2 : \alpha_1 A_1 A_2 \cos(\omega_1 + \omega_2)t + \alpha_2 A_1 A_2 \cos(\omega_1 - \omega_2)t$$

$$= 2\omega_1 \pm \omega_2 : \frac{3\alpha_3 A_1^2 A_2}{4} cos(2\omega_1 + \omega_2)t + \frac{3\alpha_3 A_1^2 A_2}{4} cos(2\omega_1 - \omega_2)t$$

$$= 2\omega_2 \pm \omega_1 : \frac{3\alpha_3 A_2^2 A_1}{4} cos(2\omega_2 + \omega_1)t + \frac{3\alpha_3 A_2^2 A_1}{4} cos(2\omega_2 - \omega_1)t \quad 3.20d$$

And the fundamental products are as follows;

$$\omega = \omega_1, \omega_2 : \left(\alpha_1 A_1 + \frac{3}{4}\alpha_3 A_1^3 + \frac{3}{2}\alpha_3 A_1^2 A_2\right) cos\omega_1 t + \left(\alpha_1 A_2 + \frac{3}{4}\alpha_3 A_2^3 + \frac{3}{2}\alpha_3 A_2^2 A_1\right) cos\omega_2 t \quad 3.20e$$

The 3rd order intercept point can be expressed mathematically as follows and also shown in figure 3.9; [11]

$$IIP_3 = OIP_3 - G \qquad 3.23$$

$$V_{ip3} = \sqrt{\frac{4}{3}\left|\frac{\alpha_1}{\alpha_3}\right|} \qquad 3.24$$

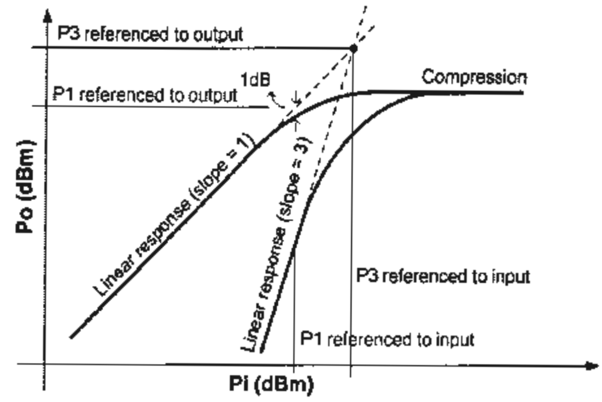


Figure 3. 9: 3rd order intercept point [14].

3.2.1.6 Dynamic Range

Typically in RF wireless communication systems, the receivers are somewhat at any distance from the base station and for the required signal to be received properly. The receiver must be able to detect the weak noisy information from the signal and add nonlinearities as low as possible. This could be possible in case of receivers which have good dynamic range. The term dynamic range (DR) can be defined as the ratio between two different levels one of maximal input which a circuit can accept without any nonlinearity introduced and second the minimal input for which a circuit can deliver satisfactory signal quality. In dynamic range calculation the maximal input level is described with the help of IP_3 or 1dB compression points while the minimal input level is described with the help of noise figure (NF). So, dynamic range (DR) refers to the receiver's capability to guarantee a good communication irrespective of the distance between the receiver and the base station [34].

For an LNA, which is the first active stage amplifier of any receiver and deals with both the noise and nonlinear issues of received information signal, good dynamic range means that the LNA needs to be able to remain linear while receiving weak noisy signal in the presence of robust interferers. For this reason, the lower limit of LNA's dynamic range (DR) can be NF and the upper limit can be the 1dB compression point for the retrieval of desired information signal. It would not be wrong to say that the dynamic range can describe the ability of an amplifier to demodulate the received signal also known as "spurious free dynamic range (SFDR)" [34]. So for an LNA the mathematical expression for "dynamic range" is

$$SFDR = \frac{2}{3}(OIP_3 - N_0)\ (dB) \qquad \textbf{3.25}$$

Where OIP_3 is the output 3rd order intercept point and "No is the noise power at output". Also "No" is the sum of "input noise (Ni)", "gain (G)" and "noise figure (NF)". So the above formula becomes

$$SFDR = \frac{2}{3}(OIP_3 - G - NF - 10 * \log(KTB/1mW))\ (dB) \qquad \textbf{3.25a}$$

Where,

$$N_i = 10 * \log(KTB/1mW)$$

Also,

$$IIP_3 = OIP_3 - G$$

So,

$$SFDR = \frac{2}{3}(IIP_3 - NF - 10 * \log(KTB/1mW))\ (dB) \qquad \textbf{3.25b}$$

The range of SFDR can be seen on the graph shown in figure 3.10 [23].

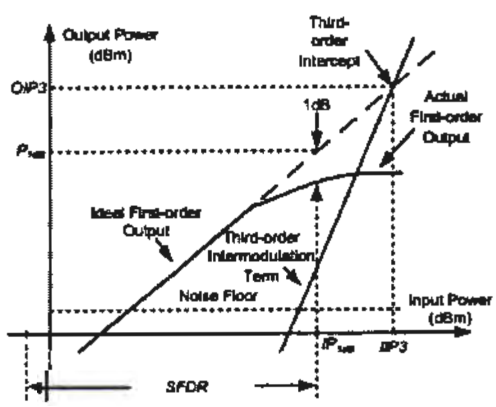


Figure 3. 10: Dynamic Range of an LNA [14].

Chapter 4

PROPOSED LNA MODEL

Latest advancements in the technology has pushed the RF designers/engineers to use such CAD tools, which have a range of features along with the provision of feasibility and better development and simulation time performances. In this regard, modern simulation CAD tools provide a platform to design and test the RF systems, whereas, simulation can be defined as the process of imitation, in which the behavioral results of different features of a typical system are duplicated in such a way, that the results are close enough to the real system. The main purpose of the simulation is to design a model of a typical system to perform specific experimentations to either understand the behavior under different operating conditions or to evaluate several approaches in order to test the performance of system under consideration [35].

As far as, the RF communication systems are concerned, it is the beauty of simulation software that the designers do not need to build any kind of hardware before designing a simulation model of a typical system. Rather, the simulation models help in designing the hardware of any RF communication systems. Whereas, for communication systems there is a need to imitate some specific features of the whole system, in order to ensure the feasibility of the design. Nowadays, the simulation of RF communication systems has become very complicated because the simulator needs to be very efficient as the systems are a combination of different subsystems. For this purpose, MATLAB SIMULINK is a good choice as it comes with a range of different system designing, as well as simulation features [22].

4.1 Proposed RF Block set in SIMULINK

SIMULNIK can come in handy while modeling systems as it comes with a variety of pre-defined simulation blocks. SIMULINK provides a platform for the behavioral representation of RF front-end architectures, which can be used in multi standard telecommunication systems. SIMULINK toolbox consists of a library, in which RF building blocks are present which can be used to employ RF front-end components such as LNAs, mixers, etc. SIMULINK usually provides behavioral modeling environment by constructing a design based on mathematical expressions [36].

It is the beauty of behavioral modeling that this approach specifies the performance, as well as the feasibility of a design by just dealing with certain specifications of the device under test (DUT). In case of LNA, SIMULINK would emphasize the NF, stability, gain and nonlinearity to specify the performance of that specific LNA [36]. These parameters are enough to provide specific knowledge about the performance of an LNA under certain conditions. A simple model consisting of a sine wave as input and its amplification with a factor of 10 as output is shown in figure 4.1.

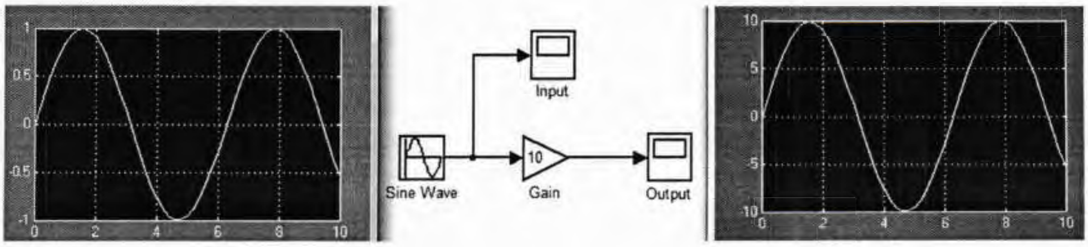


Figure 4. 1: A simple gain model in SIMULINK.

SIMULINK comes with a number of advantages as follows [36]:

- A well-known and friendly used behavioral simulation software; that is very much familiar to RF designers.
- Signal processing and data handling can be easily performed.
- Has the ability to design and develop new RF front-end architectures and even to incorporate in a singular block.
- Provides an environment to the designers to expand the block model library as well as to add new blocks into a model without any kind of programming.
- SIMULINK library consists of a wide range of RF block models which focus on the main RF circuit constraints.
- Complex RF system models can be developed by importing different building blocks from the SIMULINK library.

4.2 Types of Modeling

It is true that SIMULINK comes with a range of tools regarding system designing but it only deals with the behavioral or mathematical modeling of RF systems, whereas modeling is a way of describing a system with the help of mathematical relations. Modeling can be of two types [37]:

i. **"Physical modeling"** requires prior information about different features of a typical system which includes theoretical understanding, as well as the relation between those features. Usually, physical modeling is applicable in circuit simulation software. Physical modeling includes the technology features, i.e. device type, width, length and diameter, no. of turns, spacing, etc. In other words, physical modeling refers to a complete device level model of a specific device e.g. ADS circuit of an LNA. These models cannot be used for other devices as they would have their own features to be used as input [37].

ii. **"Behavioral modeling"** deals with the mathematical expressions of the specific features which are needed to be found. Behavioral or block modeling depends on the input and output relations, which could be electrical feature of a device e.g. in case of LNA, the NF, IP_3, voltage or power gain, etc. are important blocks. The factor which can affect the performance of behavioral modeling is the measuring technique, as well as the quantity to be measured; means there is a need to incorporate the measured parasitic effects as a part of modified equations which are used in behavioral modeling [37].

4.2.1 Top-Down and Bottom-Up Approach for Behavioral RF Models

Recently there has been a breakthrough in the technology regarding RF system design as the chip designing is moving towards the Nano-scale. So the behavioral, as well as physical modeling of RF devices has attracted the attention of system designers. With an increase in the applications of wireless ICs, as far as the physical modeling is concerned, it needs proper understanding of devices to be used in a system, whereas behavioral modeling can prove to be helpful in the designing of complicated systems. It deals with specific features of the whole system as shown in figure 4.2[38]. Two approaches can be used while designing the RF devices;

i. Top-Down Approach

ii. Bottom-Up Approach

The selection of design approach helps to use the model effectively. The design approach to be used depends on the needs of the system, as well as the tendency of a design to be reused. In order to save the development and simulation time top-down approach is mostly used.

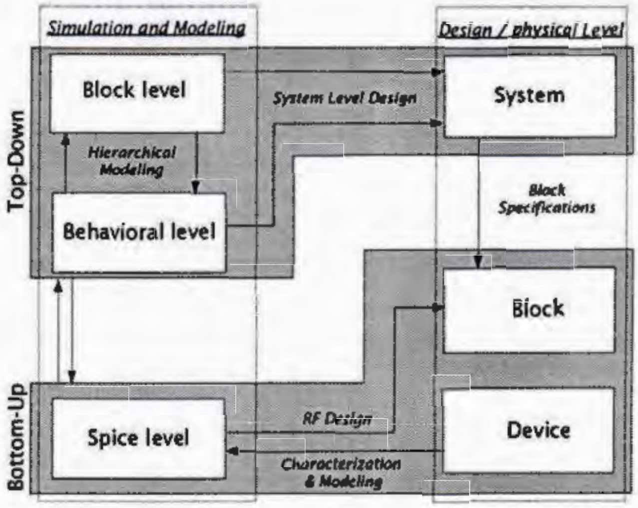


Figure 4. 2: Top-Down and Bottom-Up Approaches [39].

4.2.1.1 Top-Down Approach

In order to test the system performance, RF designers adopt top-down approach. Top-down approach usually refers to the behavioral modeling. In this approach, device parameters like electrical properties such as voltage or current gains, NF, IP_3 are used to develop blocks to understand and test the performance of the complete system as shown in figure 4.2. So, top-down approach can prove to be helpful to observe the behavior of an RF system under different conditions. The behavioral models describe how a system should respond under certain conditions, not how a system is being built up. In RF system, behavioral modeling is referred to as the effective modeling of RF components which provides better information about the whole system [39].

4.2.1.2 Bottom-Up Approach

This approach is a detail design flow of a system. It comprises of different steps, like circuit development, as well as simulation of a particular device, device prior knowledge, technology selection, development of device schematic and circuit or layout, etc as shown in figure 4.2. This approach shows resemblance with the physical modeling as this approach describes the development of a system of an existing device [39].

4.3 Behavioral Modeling of LNA in SIMULINK

SIMULINK provides an environment which can be used to design an efficient behavioral model for LNA, which can all together satisfy low NF, sufficient gain and modeling of nonlinearity. The basic idea of a block level model is, to take in an input signal perform some operations on it and provide it to the output port. For this purpose, a simple LNA block model which takes in the input RF signal, add its system impairments and send it to the output is shown in figure 4.3 [20].

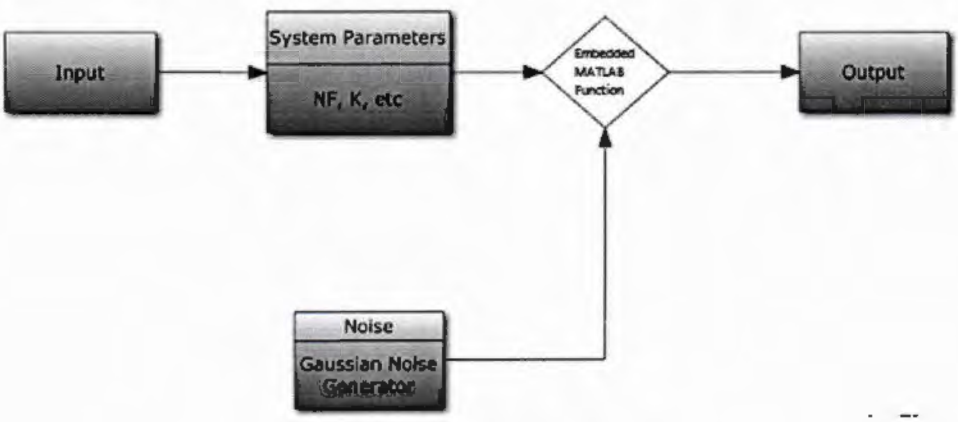


Figure 4. 3: A typical Block Model of LNA.

The model in figure 4.3 depicts the basic block model of an LNA. A brief explanation of the design is as follows [20];

- Input block refers to the input RF signal whose parameters, such as bandwidth, amplitude, etc. can be defined in the block parameters.
- System parameter block is the main block of LNA design, which includes the noise figure block, stability block, gain block and nonlinearity blocks. All these blocks are defined with the help of their characteristic equations.
- Gaussian noise generator is the block which is used to stabilize the Signal-to-noise-ratio (SNR).

4.4 SIMULINK Models of LNA Design Parameters

In SIMULINK RF front-end components can be easily modeled by using RF Block-set. In case of a typical LNA model in SIMULINK, S-parameters can be used to calculate different parameters like gain (G), stability factor (K), etc. of LNA. In order to, define different blocks of an LNA model, like Noise, Stability, gain and Nonlinearity blocks, first, there is a need to understand the mathematical expressions of these parameters and then these blocks would be inter-connected to develop a complete model. [20].

For the designing of a comprehensive LNA model in SIMULINK top-down approach has been adopted, which include the behavioral modeling of different LNA design parameters. In order to verify the design feasibility, each LNA parameter has been modeled separately based on its characteristic equation [20]. In order to verify the results of SIMULINK model, the values of input parameters have been taken from the circuit simulation software, like ADS and the results are to be compared with the ADS results to validate the proposed model. For this LNA's important design parameters, which provide enough information about system specification of an LNA are shown in table 4.1 [40].

Table 4. 1: Important LNA Design Parameters.

Design Parameter	Importance
Gain (G)	Minimum and maximum gain requirement by the application
Noise Figure (NF)	Thermal Noise usually described by the NF and the minimal detectable signal in the dynamic range of an amplifier
Stability Factor (K)	>1 for amplifier to provide unconditionally stable operation in the desired bandwidth
Intercept Point	Level of unwanted spurious signals
Compression Point	Level of power below which all design parameters of an amplifier are intact

It is understood, that designing of LNA is a compromise between different figure-of-merits. As, LNA is the first amplifying stage in a receiver, its main purpose is to provide adequate gain to overcome the noise added into the RF signal from subsequent stages. All the design parameters of LNA are integrated in the proposed SIMULINK model. The designing of RF front-end architectures in SIMULINK depends mainly on the transfer function or characteristic equations of that model, as SIMULINK deals with blocks defined with the help of transfer function equations. So, for the development of individual blocks of an LNA the mathematical expressions, as well as their SIMULINK models of important performance parameters are as follows;

4.4.1 Modeling of Stability Factor in SIMULINK

LNA must be designed to provide stable operation, by proving sufficient gain and linearity for particular frequencies. Device "S-parameters" proved to be helpful in finding the stability of the device. The numerical method of finding the stability of an LNA circuit consists of "Rollett Stability Factor (K)", which depends on the S-parameters as explained in the expression 3.2 from chapter 3 [10];

$$k = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2 * |S_{12}S_{21}|} > 1 \qquad \textbf{3.2}$$

$$\Delta = S_{11}S_{22} - S_{12}S_{21} < 1 \qquad \textbf{3.2a}$$

Usually, an LNA is designed to provide unconditional stable operation in the desired band of frequencies, which needs the stability factor K to be greater than 1 and delta to be less than 1 [27]. The SIMULINK model of stability factor based on its characteristic equation, is shown in figure 4.4. The values of S-parameters are taken from the ADS simulation circuit of device#ATF-34143 at the frequency of $2.5e^9$Hz [41].

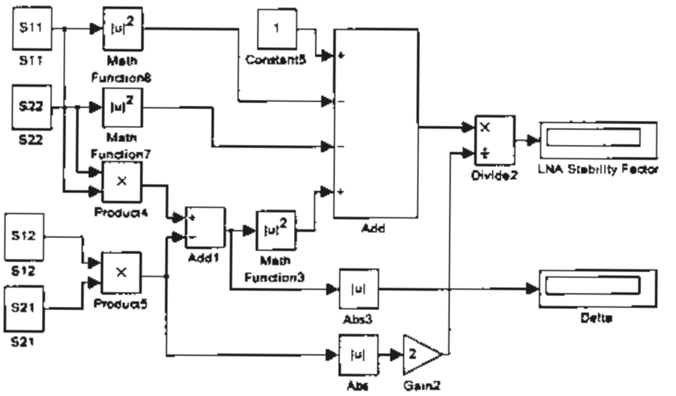


Figure 4. 4: Stability Model of LNA.

4.4.2 Modeling of Gain Block in SIMULINK

It is obvious that for LNA, gain is needed to be sufficient enough to amplify the weak received signal, so that it can be passed on to next stages of the receiver. Usually, gain of an LNA should be above 10dB [13]. In RF communication systems the gain is expressed in decibels (dB), that is a logarithmic scale for the representation of very large or very small values. As the input signal to the LNA is very weak like in nV, so one must represent the power gain in dBs. From chapter 3, the mathematical expression for power gain in dB is as follows [30];

$$\text{Power} - \text{Gain} - \text{dB}\left(G_{P_{dB}}\right) = 10\log\left(\frac{P_{out}}{P_{in}}\right) \tag{3.5}$$

$$\text{Voltage Gain} - \text{dB}\left(G_{V_{dB}}\right) = 20\log\left(\frac{V_{out}}{V_{in}}\right) \tag{3.6}$$

Also maximum power gain can be calculated with the help of stability factor and S_{21} which is the value of forward gain of LNA [12].

$$G_{pmax} = \frac{|S_{21}|}{|S_{12}|}\left(K - \sqrt{K^2 - 1}\right) \tag{3.7}$$

$$G_{pmax\_dB} = 10\log(G_{pmax}) \tag{3.8}$$

$$\text{Gain}\ (G_v) = 10^{\frac{G_{pmax\_dB}}{20}} \tag{3.9}$$

The SIMULINK model of gain block of an LNA is shown in figure 4.5.

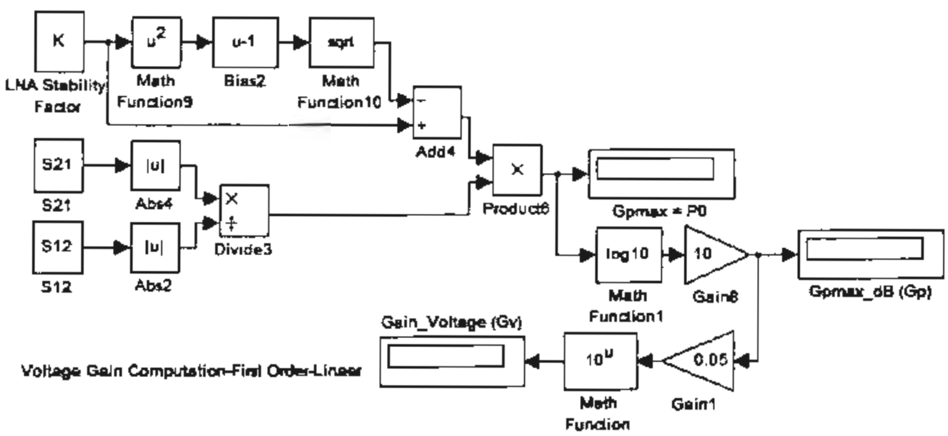


Figure 4. 5: Gain Model of LNA.

4.4.3 Modeling of Noise in SIMULINK

Noise is a severe issue, especially for RF front-end systems, where very low power, weak and noisy signals are needed to be handled. For better performance of an *RF* communication system, noise is an important factor that is needed to be, as low as possible with respect to the desired signal [9]. Noise performance, is one of the most important parameters of any type of LNA and an effective way to reduce the noise effects is to use low noise amplifier with low noise figure (NF) [29]. The simplest way to specify Noise-figure (NF) or Noise-factor (F), as well as Noise Temperature (T) of an LNA is to use following equations [14].

$$\text{Noise} - \text{Factor (F)} = 10^{\frac{Noise\_Figure}{10}} \tag{3.15}$$

$$\text{Noise} - \text{Figure (NF)} = 10\log_{10}(\text{F}) \tag{3.16}$$

$$\text{Noise Temperature (T)} = 290 * \left(\left(10^{\frac{Noise_{Figure}}{10}}\right) - 1\right)(K) \tag{4.1}$$

The SIMULINK model for the noise factor and noise temperature is shown in the figure 4.6 and the NF value has been taken from the ADS circuit of ATF-34143.

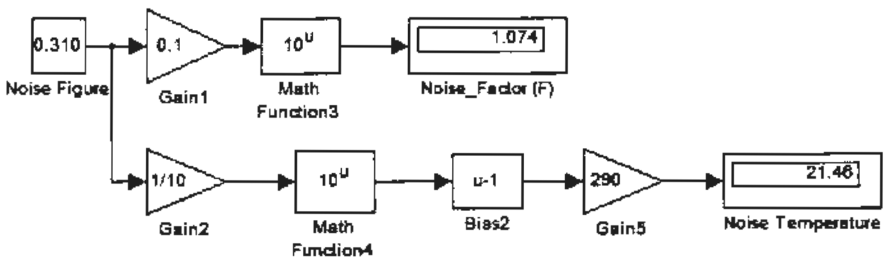


Figure 4. 6: Noise Factor (F) and Noise Temperature (T) model of LNA.

The main and important parameter worth knowing about the noise performance of any LNA is the thermal noise voltage, which results in the output noise performance. The mathematical expression for input-noise-voltage and its corresponding SIMULINK model is shown in figure 4.7, which takes in the bandwidth of 500MHz from the ADS circuit of ATF-34143 [14].

$$v = \sqrt{4KRTB} \tag{3.10}$$

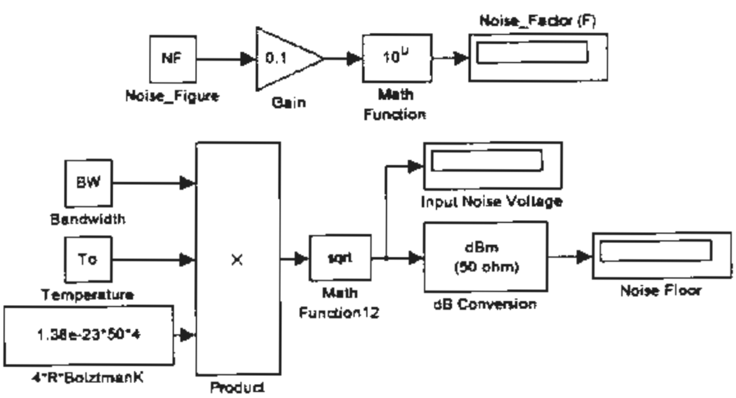


Figure 4. 7: Input-Noise-Voltage Model of LNA.

4.4.4 Modeling of Non-Linearity in SIMULINK

At receiver side, the main purpose of the low noise amplifiers is to provide a constant sufficient gain to the weak received signal. In general, the gain characteristic of an amplifier (Vout/Vin) is supposed to be linear which is [42];

$$V_o = \propto_1 * V_i \qquad \textbf{4.2}$$

But practically it is measured to be non-linear, which leads to the truncated output signals, known as non-linear behavior. The non-linear behavior of an LNA can be characterized by the following non-linear equation [42];

$$V_0 = V_{off} + \propto_1 * V_{in} + \propto_2 * V_{in}^2 + \propto_3 * V_{in}^3 \qquad \textbf{3.20}$$

Non-linearity is normally measured by the 1-dB compression and 3rd order intercept points, also known as P_{1dB} and IP_3. Input and output intercept points can be calculated if one quantity and the gain is known.

$$IIP_3 = OIP_3 - G \qquad \textbf{3.23}$$

If a sinusoidal signal is applied at the input of a nonlinear system, then the output comprises of harmonics, as well as the inter-modulation products and if the system has odd symmetry then the even harmonics disappear. So, the nonlinear characteristic equation becomes [42];

$$V_0 = \propto_1 * V_{in} + \propto_3 * V_{in}^3 \qquad \textbf{3.20b}$$

In order to, design nonlinearity model of LNA, the designer must calculate $\propto_1$and $\propto_3$ coefficients. For this purpose, power gain in dB (Gp) and output power at 1dB compression point can be used to find the coefficients as follows [42];

$$\text{Gain } (G_v) = \frac{V_o}{V_i} \qquad \textbf{3.3}$$

$$\text{Gain} - \text{dB } (G_{dB}) = 20 \log\left(\frac{V_o}{V_i}\right) \qquad \textbf{3.6}$$

From eq. 4.1,

$$V_o = \propto_1 * V_i$$

Hence,

$$\text{Gain} - \text{dB}\ (G_{dB}) = 20\log\left(\frac{\propto_1 * V_i}{V_i}\right)$$

$$\propto_1 = 10^{\frac{\text{Gain}-\text{dB}\ (G_{dB})}{20}} \quad 4.3$$

The third order coefficient $\propto_3$ can be calculated with the help of P1dB as follows;

$$P_{1db} = P_{O(IDEAL)} - 1dB \quad 3.21$$

Where,

$$P_{O(IDEAL)} = 20\log(V_o) = 20\log(\propto_1 * V_i) \quad 4.4$$

So,

$$20\log(\propto_1 * V_i) = P_{1db} + 1dB$$

$$V_i = \frac{10^{\frac{(P_{1dB}+1dB)}{20}}}{\propto_1} \quad 4.5$$

So, this is the input voltage at 1dB compression point. The output voltage can be calculated as follows [42];

$$V_o = 10^{\frac{(P_{1dB})}{20}} \quad 4.6$$

Putting the values of V_i and V_o in equation 3.20b provides the value of $\propto_3$ as follows;

$$\propto_3 = \left(\frac{V_o - \propto_1 * V_i}{V_i^3}\right) \quad 4.7$$

So, the above calculation proves to be helpful in designing a nonlinearity block for LNA as shown in the figure 4.8. It shows that for any values of P_{1dB} the nonlinear coefficients and the nonlinear behavior of LNA can be easily found. Also, the output voltages at 1dB compression, as well as third order intercept points can also be found with the help of following expressions [42].

$$V_{1dB} = \sqrt{0.145\left|\frac{\propto_1}{\propto_3}\right|} \quad 3.22$$

And,

$$V_{ip3} = \sqrt{\frac{4}{3}\left|\frac{\propto_1}{\propto_3}\right|} \quad 3.24$$

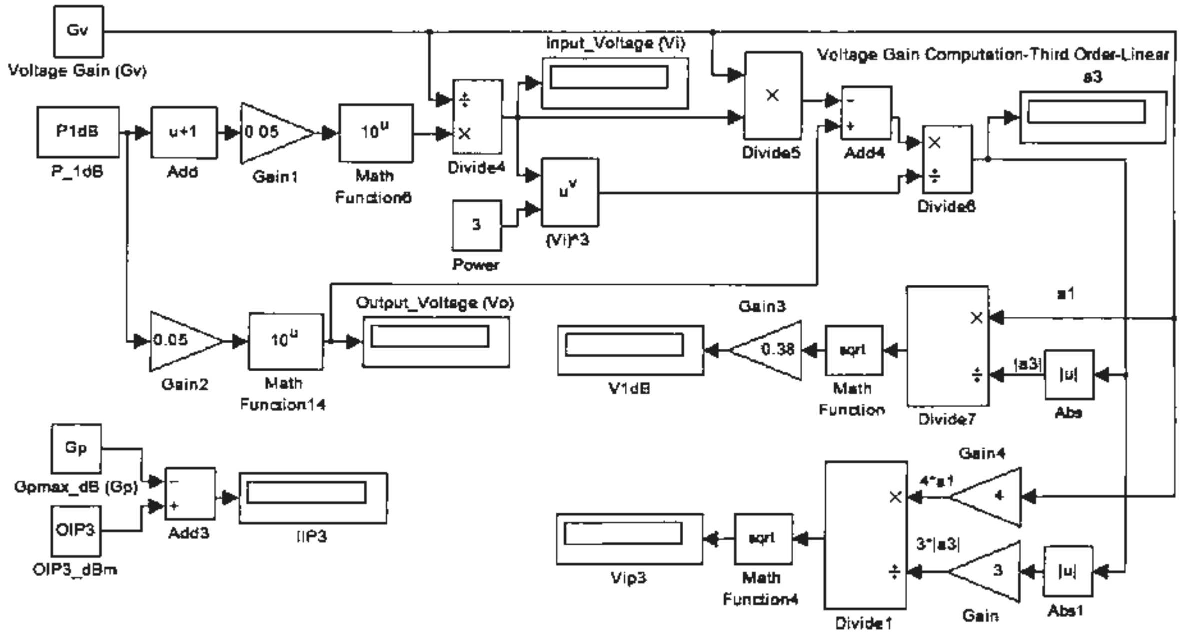


Figure 4. 8: Nonlinear Model of LNA.

4.5 Proposed SIMULINK LNA Model

The comprehensive SIMULINK LNA model is shown in figure 4.9. The main purpose of the comprehensive SIMULINK LNA model is, to see the effect of gain, noise and nonlinearity altogether on the input signal. In this regard, the design strategy of the complete LNA model is explained as follows;

4.5.1 Design Strategy

Modeling of a comprehensive SIMULINK LNA model requires a top-down modeling approach, which includes the individual behavioral modeling of different LNA design parameter blocks i.e. stability, gain, noise performance and nonlinearity, based on their mathematical expressions, as SIMULINK deals with blocks defined with the help of their transfer function equations. So, the proposed LNA model comprises of

i. All the individual SIMULINK block models of different LNA design parameters, i.e. stability, gain, noise performance and nonlinearity blocks.
ii. The values of the input parameters i.e. S-parameters, P_{1dB}, OIP_3 and NF for the individual blocks are taken from the datasheet/the ADS circuit of a typical LNA having device # ATF-34143.

iii. The individual SIMULINK models of different LNA design parameters are added up by using "Embedded MATLAB Function" block, which takes in the output values of the individual block models, perform operations on the input signal according to the LNA system impairments and generates output.

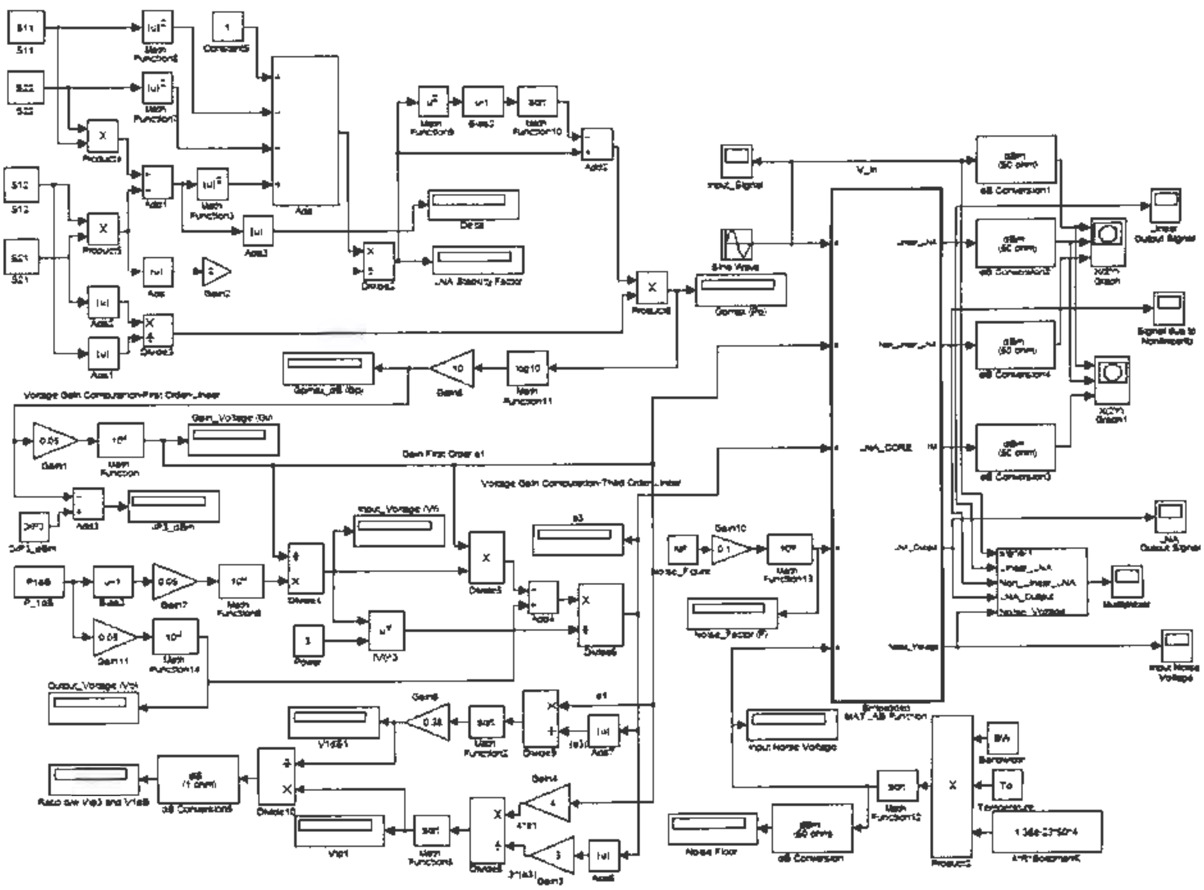


Figure 4. 9: Comprehensive SIMULINK Model of LNA.

Chapter 5

SIMULATION AND RESULTS

This chapter comprises of the results obtained from the LNA circuit designed in ADS, as well as the results obtained from the SIMULINK model and a comparison between the results of the two LNA models.

5.1 ADS Model

In order to, verify the design feasibility and results of SIMULINK LNA model, the values of input parameters for the individual design parameter blocks are taken from the datasheet/ ADS circuit of LNA having device # ATF-34143. The complete circuit diagram of such an LNA is shown in figure 5.1 [41].

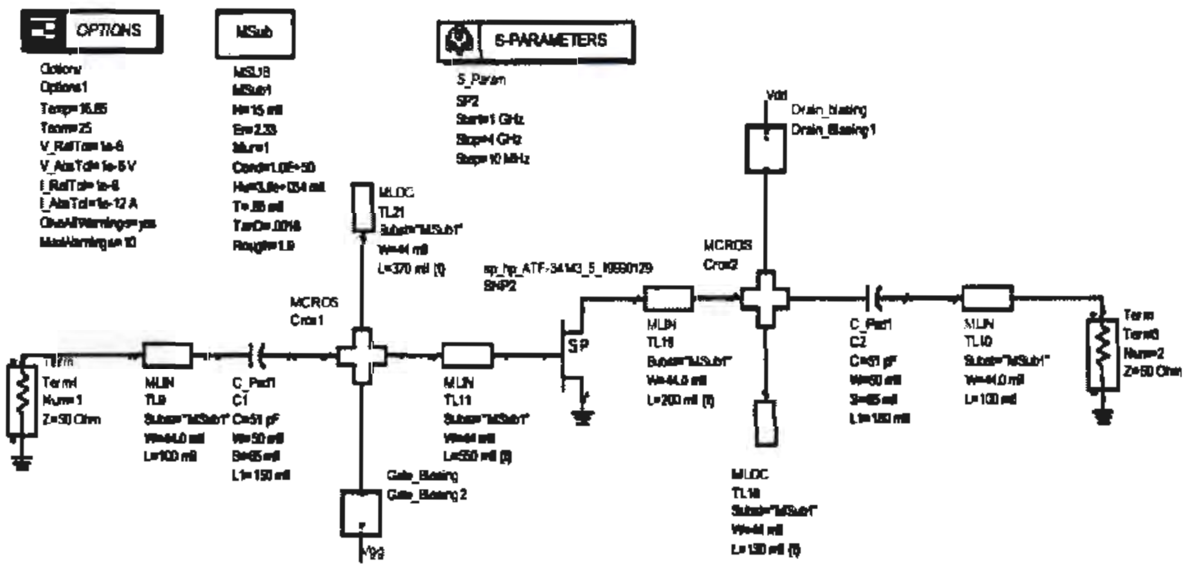
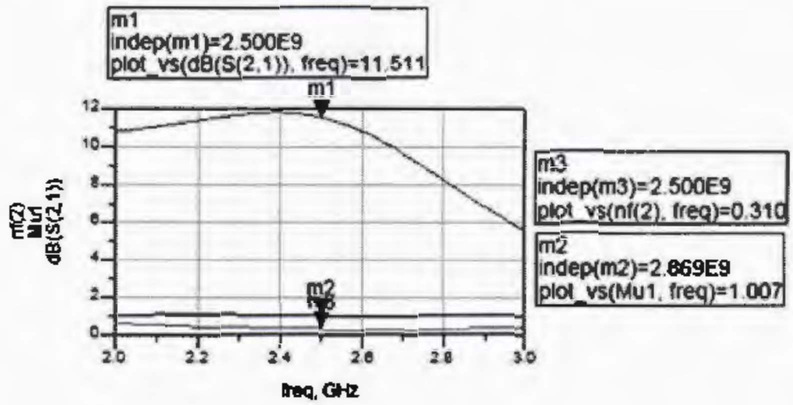
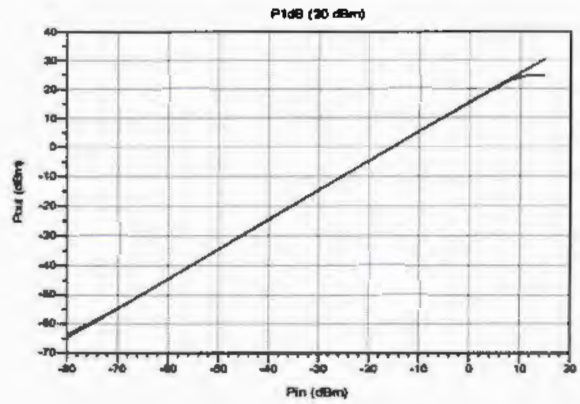


Figure 5. 1: ADS circuit of LNA device # ATF-34143.

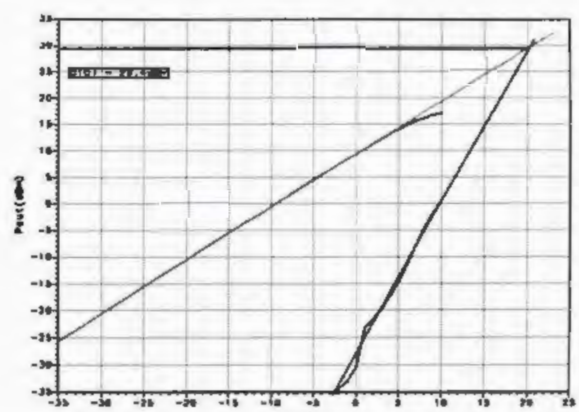
The circuit is simulated at $2.5e^9$ Hz to get the values of Power Gain (G_p), NF and Stability Factor (K), as shown in figure 5.2. Moreover, the S-parameters of the device are also extracted, to be used in SIMULINK model. Furthermore, the 1-dB compression and 3^{rd}-order intercept points are also shown in figure 5.2 [41].



(a)



(b)



(c)

Figure 5. 2: (a) Gp, NF and K (b) 1-dB compression point and (c) 3rd order intercept point obtained from ADS simulation.

5.2 SIMULINK LNA Model

The SIMULINK based LNA model comprises of five major parts named stability, gain, nonlinearity, noise and output blocks as shown in figure 5.3, with the help of red blocks.

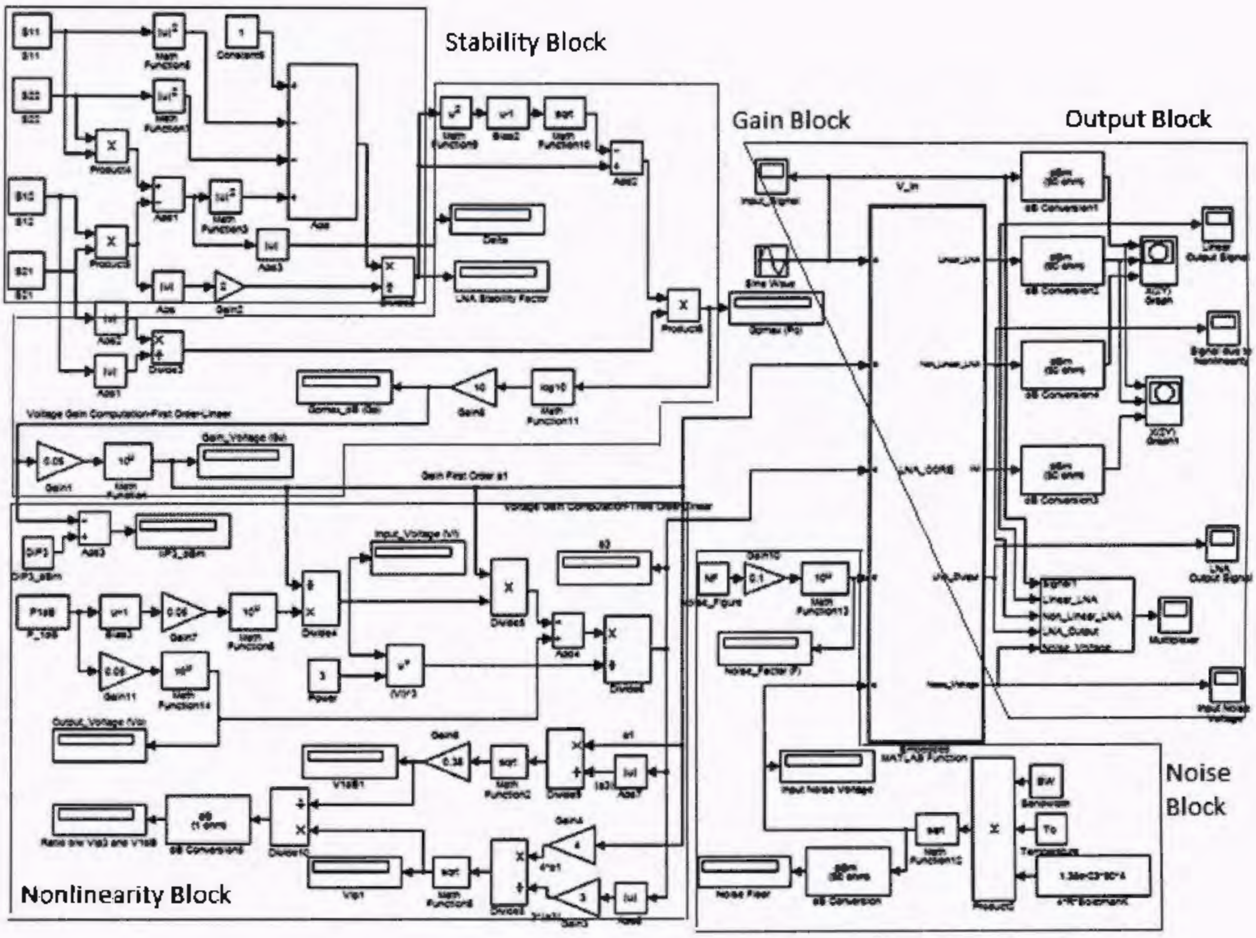


Figure 5. 3: Block wise SIMULINK Model of LNA.

The first four blocks are based on the mathematical expressions. Whereas, output parameters of the first four blocks include Stability Factor (K), Power (G_p), as well as Voltage gains (G_v), Noise Factor (F), Input Noise Voltage, Noise Floor, IIP_3, relation between input and output voltage levels, V_{ip3}, and V_{1dB}. Although, the output block works on the basis of a MATLAB code written for better LNA performance;

5.2.1 Stability Block

The mathematical expression for LNA stability factor is expressed in equation 3.2 and the input and output parameters of the stability block are listed in table 5.1.

$$k = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2 * |S_{12}S_{21}|} \qquad 3.2$$

Table 5. 1: Input and Output Parameters of Stability Block.

Input	
S_{11}	-0.067-0.025i
S_{12}	-0.205+0.038i
S_{21}	-3.645+0.936i
S_{22}	0.146-0.189i
Output	
Stability Factor (K)	1.007

5.2.2 Gain Block

The mathematical expressions for the calculation of power and voltage gains of an LNA are expressed in equation 3.7 through 3.9. The input and output parameters of the gain block are listed in table 5.2.

$$G_{pmax} = \frac{|S_{21}|}{|S_{12}|}\left(K - \sqrt{K^2 - 1}\right) \qquad \textbf{3.7}$$

$$G_{pmax\_dB} = 10\log(G_{pmax}) \qquad \textbf{3.8}$$

$$\text{Gain } (G_v) = 10^{\frac{G_{pmax\_dB}}{20}} \qquad \textbf{3.9}$$

Table 5. 2: Input and Output Parameters of Gain Block.

Input	
Stability Factor (K)	1.007
S_{12}	-0.205+0.038i
S_{21}	-3.645+0.936i
Output	
Power Gain (G_p)	12.05dB
Voltage Gain (G_v)	4.003V

5.2.3 Noise Block

The noise block is based on the calculation of noise factor, as well as input noise voltage. So, the mathematical expression, as well as the input and output parameters of the noise block are shown in equation 3.10 and table 5.3 respectively.

$$v = \sqrt{4KRTB} \quad (3.10)$$

Table 5. 3: Input and Output Parameters of Noise Block.

Input	
NF	0.310
Bandwidth	500MHz
Noise Temperature	290 (F)
R	50 ohm
Boltzmann Constant (k)	1.38×10^{23}J/k
Output	
Noise Factor (F)	1.074
Input Noise Voltage (V)	2.0 e^{-5}V
Noise Floor	-80.97dBm

5.2.4 Non-linearity Block

Non-linearity is the most complex parameter block of the proposed LNA model. The main purpose, is to find the first and third order coefficients of the nonlinear characteristic equation 3.20, which are $\propto_1$ and $\propto_3$ also known as first and third order voltage gains respectively. The values of V_i andV_o are also needed, which can be found with the help of equations 4.5 and 4.6. The input and output parameters of nonlinearity block are listed in table 5.4.

$$V_0 = V_{off} + \propto_1 * V_{in} + \propto_2 * V_{in}^2 + \propto_3 * V_{in}^3 \quad (3.20)$$

$$V_i = \frac{10^{\frac{(P_{1dB}+1dB)}{20}}}{\propto_1} \quad (4.5)$$

$$V_o = 10^{\frac{(P_{1dB})}{20}} \quad (4.6)$$

$$\propto_3 = \left(\frac{V_o - \propto_1 * V_i}{V_i^3}\right) \quad 4.7$$

Table 5. 4: Input and Output Parameters of Nonlinearity Block.

Input	
Power Gain (dB)	12.05
Voltage Gain (V)	4.003
OIP_3	29.4dBm
P_{1dB}	20dBm
Output	
IIP_3	17.35dBm
$\propto_1$	4.003
$\propto_3$	-0.05541
Relation Between Input and Output Voltage	If $V_i = 5.6V_{p-p}$ then V_o should be $22.4V_{p-p}$ but due to nonlinear effects $V_o = 20V_{p-p}$
V_{1dB}	3.23 V
V_{ip3}	9.815 V
Ratio of V_{ip3} to V_{1dB}	9.654 dB

5.2.5 Output Block

The output block of the proposed LNA model is based on the "Embedded MATLAB Function" block which works on the basis of a MATLAB code written for LNA.

- The code is written, so as to see the effect of gain, noise and nonlinearity altogether on the input signal by taking in the input RF signal (in our case sine wave) and the outputs of gain, noise and nonlinearity blocks i.e. G_v,$\propto_1$, $\propto_3$, Noise Factor (F) and Input Noise Voltage.
- The input noise voltage signal is shown in the figure 5.4, which depicts that the noise voltage is too small that it is considered as zero, also shown with the help of green line in figure 5.5.

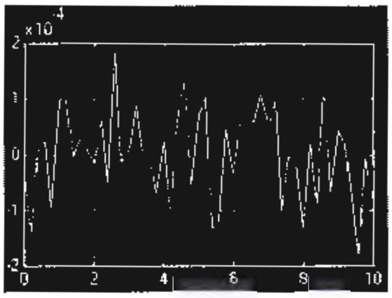


Figure 5. 4: Input Noise Voltage Signal of Proposed LNA Model.

- The voltage gain (G_v) of the LNA is 4.003V, at the given values of S-parameters and power gain (G_p).
- The model is capable of displaying the effects of noise and nonlinearity on the input signal along with the input, linear output, nonlinear output, 3rd order IM and noise signals in time domain. If the amplitude of the input signal is $5.6V_{p-p}$, then the output should be $22.4V_{p-p}$ but due to nonlinearity and noise effects the output voltage comes out to be $20V_{p-p}$ as shown in the graph in figure 5.5.

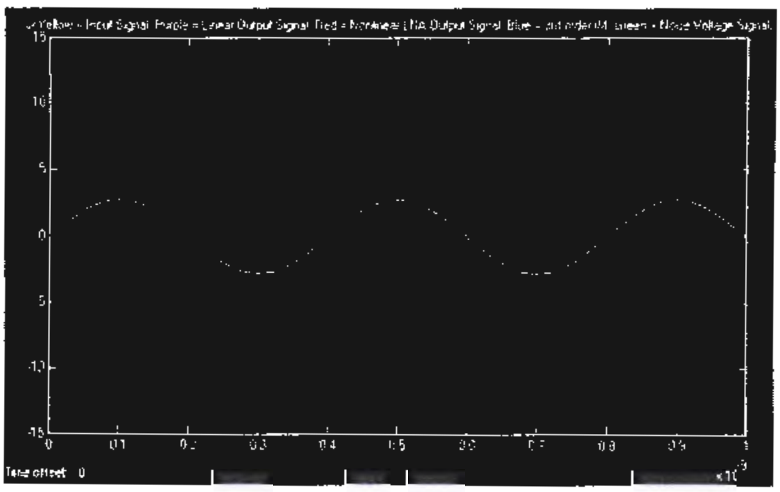


Figure 5. 5: Time domain waveform signalsYellow (Input), Purple (Linear Output), Red (Nonlinear Output), Blue (3rd Order IM) and Green (Noise voltage signal).

- The model can also predict the values of P_{1dB} and P_{ip3} as shown in the graphs of figure 5.6.

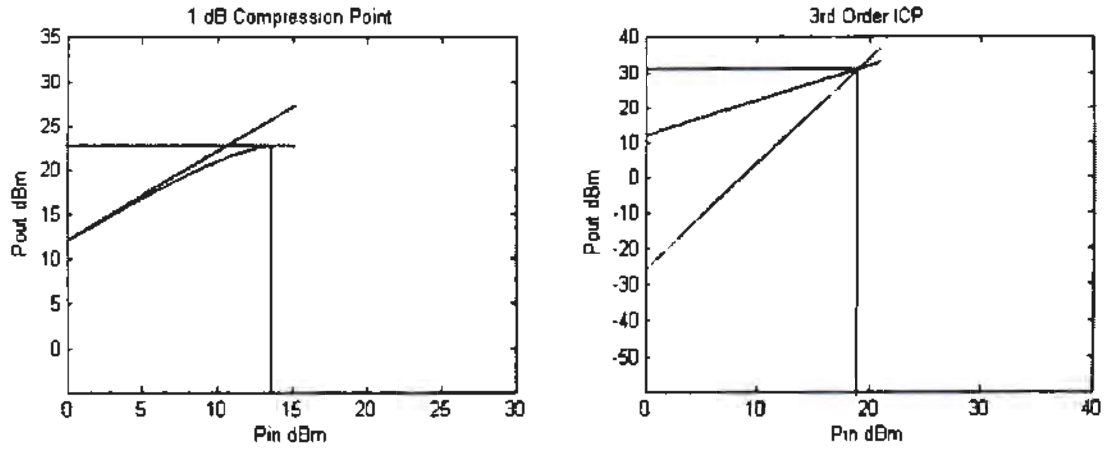


Figure 5. 6: Graphs of P_{1dB} (23dBm) and P_{ip3} (31dBm) of Proposed LNA Model.

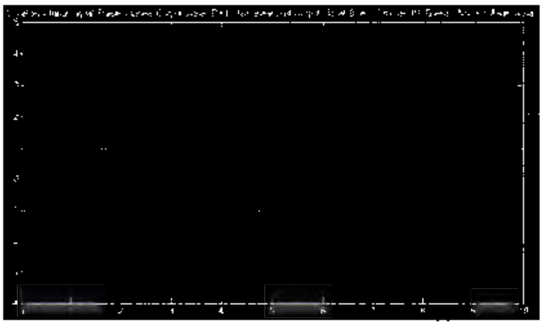
- Table 5.5 shows a comparison among the amplitudes of Input, Linear Output, Nonlinear Output, 3rdOrder IM and LNA Output Signals and their respective representation in figure 5.7.

Table 5. 5: Comparison among the amplitudes of Input, Linear Output, Nonlinear Output, 3rd Order IM and LNA Output Signals.

Amplitude of Input (V_{p-p})	Linear Signal (V_{p-p})	Nonlinear Signal (V_{p-p})	3rd order IM (V_{p-p})	LNA Output Signal (V_{p-p})	Figure 5.9
2	8.0	7.951	0.055	7.9	(a)
4	16.0	15.12	0.88	15.1	(b)
6	24.0	21.0	3.0	21.0	(c)
8	32.0	25.0	7.0	25.0	(d)
10	40.0	26.3	13.7	26.0	(e)

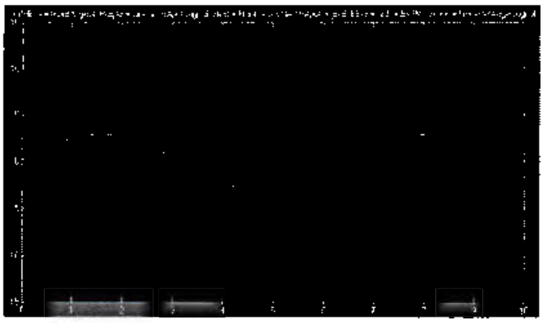
- On the other hand, the graphs in figure 5.7 show, the Input (Yellow), Linear Output (Purple), Nonlinear Output (Red), 3rd Order IM (Blue) and Noise voltage signal (Green) and the effect of nonlinearity and noise on the LNA Output Signal (RED), by increasing the amplitude of the input signal (Yellow).
- The graphs in figure 5.7 depict, that for smaller amplitudes of the input signal (Yellow), the effect of 3rd order inter-modulation products (Blue) and noise (Green) on the LNA output signal (Red) is low, but by increasing the amplitude of

the input signal (Yellow), the amplitude of the 3rd order inter-modulation products (Blue) also increase, as a result distorting the LNA Output Signal (Red).

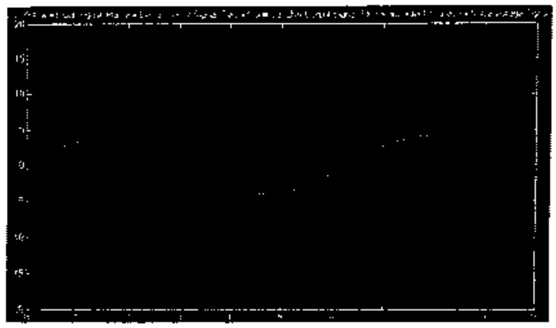


(a) (V_i= 2V_{p-p})

(b) (V_i= 4V_{p-p})



(c) (V_i= 6V_{p-p})



(d) (V_i = 8V_{p-p})

(e) (V_i= 10V_{p-p})

Figure 5. 7: Time domain waveform signals; Effects of 3rd order IM products (Blue) on the LNA Output Signal (Red) by varying amplitude of Input Signal (Yellow).

- Table 5.6 shows the comparison between the results, as well as the features of SIMULINK and ADS models of LNA. It depicts, that the proposed model can predict the relation between the amplitudes of input (V_i) and output (V_o) signals at the given P_{1dB}. Moreover, the model can demonstrate the effect of Gain, Noise and Nonlinearity on the input signal as well.

Table 5. 6: Comparison between the SIMULINK and ADS LNA Models.

Design Parameter	SIMULINK Model	ADS Model
Power Gain (G_p)	12.05 dB	11.51dB
Voltage Gain (G_v)	4.003V	4.0V
Stability Factor (K)	1.007	1.007
Input Noise Voltage	Yes	No
Relation Between Input and Output Voltage	Yes	No
Pout at 1-dB Compression Point	23dBm	20dBm
P_{out} at 3rd Order Intercept Point	31dBm	29.5dBm
V_{1dB}	3.23 V	No
V_{ip3}	9.815 V	No
Ratio of V_{ip3} to V_{1dB}	9.654 dB	No
Variation of Input Signal w.r.t Noise, Gain and Nonlinearity	Yes	No

Chapter 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

In this thesis, a unique and interactive MATLAB/SIMULINK based behavioral model for an LNA is proposed, to analyze the effect of all LNA design parameters i.e. gain, noise and nonlinearity on the input RF signal. In this regard, for the design feasibility regarding different applications, top-down behavioral modeling approach has been adopted to model each LNA design parameter separately based on its characteristic equation. All the individual parameter blocks of LNA are brought together with the help of MATLAB code, written for LNA in "Embedded MATLAB Function" block. S-parameters, P_{1dB}, P_{ip3} and NF are used as input parameters for the proposed model, whereas the values are taken from the datasheet/ADS circuit of LNA having device # ATF-34143.

This approach is adopted, so as to validate the design feasibility and for the performance optimization of the proposed SIMULINK model. Moreover, the results obtained from the proposed SIMULINK model are compared with the results of the ADS model. In this regard, table 5.6 shows a comparison between the results, as well as the features of SIMULINK and ADS models of LNA. It depicts, that the proposed model can provide the values of stability factor (K), power as well as voltage gain and can predict the relation between the amplitudes of input (V_i) and output (V_o) signals at the given P_{1dB}. Moreover, the model can demonstrate the effect of Gain, Noise and Nonlinearity on the input signal, as shown in figure 5.7. The graphs in the figure depict, that for smaller amplitudes of the input signal (Yellow), the effect of 3rd order inter-modulation products (Blue) on the LNA output signal (Red) is low, but by increasing the amplitude of the input signal (Yellow), the amplitudes of the 3rd order inter-modulation products (Blue) also increase, which as a result distort the LNA Output Signal (Red). So, the proposed

LNA model can be used to see the effect of gain, noise and nonlinearity altogether on the input RF signal.

6.2 Future Improvements

Some of the future improvements regarding the design, as well as the performance approximation of the proposed SIMULINK LNA model are as follows

- As far as, the design of the proposed LNA model is concerned, it can further extended by adding up the sensitivity, dynamic range and Fourier transform blocks, to analyze the spurious free dynamic range SFDR, as well as to analyze the output signal in frequency domain.
- The presented model can be further utilized by RF designers to optimize the LNA design parameters e.g. stability, voltage and power gains, noise factor and nonlinear behaviors of those LNAs which have no models in any other CAD tools, but their measured parameters, such as S-parameters and other information are available in datasheets as provided by manufacturer.
- Can be integrated in multi-standard receiver architectures operating on multiple frequency bands. In order to, predict the LNA design parameters to fulfill the system requirements.

REFERENCES

[1] Jabbar, M. M. (2012). *Design and Performance Analysis of Low-Noise Amplifier with Band-Pass Filter for 2.4-2.5 GHz.* Sweden: Department of Science and Technology, Linköping University.

[2] V. Gazis, N. Alonistioti and L. Merakos: "Toward a Generic Always Best Connected Capability in IntegratedWLAN/UMTS Cellular Mobile Networks (and Beyond)". IEEE Wireless Communications, pp. 20-29, June 2005.

[3] M. Brandolini, P. Rossi, D. Manstretta and F. Svelto: "Toward Multistandard Mobile Terminals –Fully Integrated Receivers Requirements and Architectures". IEEE Transactions on Microwave Theory and Techniques, Vol. 53, pp. 1026-1038, March 2005.

[4] Hansson, M. (2003). *Design of microwave low-noise amplifiers in a SiGe BiCMOS process.* Sweden: Linköping University.

[5] estergaard, P. W. (n.d.). Recent T rends in CMOS Low Noise Amplifiers. *ANALOG ELECTRONICS II* .

[6] Eric Marsan, S. M. (April 11, 2013). *Accurate System Level Design with Low Noise Amplifier's BlackBox Models.* Skyworks Solutions, Inc.

[7] X. Li and M. Ismail: Multi-Standard CMOS Wireless Design. Kluwer Academic Publishers, 2002.

[8] K. Kundert: "Challenges in RF Simulation". Proc. of the 2005 Radio Frequency Integrated Circuits Symposium, pp. 12-14, June 2005.

[9] Molavi, R. (2005). *ON THE DESIGN OF WIDEBAND CMOS LOW-NOISE AMPLIFIERS.* THE UNIVERSITY OF BRITISH COLUMBIA.

[10] Kung, S.-K. W. (2009). DESIGN OF 3 TO 5 GHz CMOS LOW NOISE AMPLIFIER FOR ULTRA-WIDEBAND (UWB) SYSTEM. *Progress In Electromagnetics Research C* , 25-34.

[11] B. Razavi: RF Microelectronics. Prentice-Hall, 1998.

[12] ZAVERI, M. (2013). COMPLEXITY IN DESIGNING OF LOW NOISE AMPLIFIER. *JOURNAL OF INFORMATION, KNOWLEDGE AND RESEARCH IN ELECTRONICS AND COMMUNICATION ENGINEERING*, 444-449.

[13] Edwall, M. (2008). *Low Noise-Amplifier Design and Optimization.* Luleå University of Technology.

[14] ALI, E. A. (2008). *Behavioral Modeling of RF front end devices in SIMULINK.* Göteborg, Sweden: Chalmers University of Technology.

[15] An, D. (2000). Design and Fabrication of a Wideband MMIC Low-Noise Amplifier using Q-matching. *Journal of the Korean Physical Society* , 837-841.

[16] Ha, H.-J. L. (n.d.). A Systematic Approach to CMOS Low Noise Amplifier Design for Ultrawideband Applications. *VTVT (Virginia Tech VLSI for Telecommunications) Lab* .

[17] Ahmad Saghafi and Abdolreza Nabavi "An Ultra-Wideband Low-Noise Amplifier for 3–5-GHz Wireless Systems" The 18th International Confernece on Microelectronics (ICM) 2006.

[18] Jian-Ming WU, C.-H. Y.-J. (JUNE 2012). High Dynamic Range RF Front End with Noise Cancellation and Linearization for WiMAX Receivers. *RADIOENGINEERING, VOL. 21, NO. 2,* , 704-711.

[19] Pankaj Jha, P. V. (2012). DESIGN OF RF FRONT-END LOW NOISE AMPLIFIER FOR AN ULTRA WIDEBAND RECEIVER. *Journal of Electron Devices* , 1006-1011.

[20] Alonso Morgado, R. d. (2007). A SIMULINK Block Set for the High-Level Simulation of Multistandard Radio Receivers. *IEEE* .

[21] Nicolle, B. (2007). System-Design-Oriented Low Noise Amplifier Modeling. *IEEE*, 1332-1335.

[22] Adsul, A. P. (2011). Design and Performance Evaluation of Transmitted Reference BPSK UWB Receiver using SIMULINK. *International Journal of Computer Science and Information Technologies Vol. 2 (6)*, 2752-2760.

[23] Nga, T. T. (July 2012). *Ultra low-power low-noise amplifier designs for 2.4 GHz ISM band applications.* Nanyang Technological University.

[24] Janmejay Adhyaru "Design and analysis of ultra wide band CMOS LNA" 2007,San Jose State University

[25] P-N Designs, I. a. (2015, September 06). *S-parameters.* Retrieved from www.microwaves101.com/encyclopedias: http://www.microwaves101.com/encyclopedias/438-s-parameters-microwave-encyclopedia-microwaves101-com

[26] Damen, J. L. (1999, February). LNA design for CDMA front end. *RF Design.*

[27] Mini-Circuits. (1999). *Modern Amplifier Term Defined* . Mini-Circuits. Inc.

[28] electrical4u. (2011-2015). *Amplifier Gain | Decibel or dB Gain.* Retrieved from electrical4u.com Online Electrical Engineering: http://www.electrical4u.com/amplifier-gain-decibel-or-db-gain/

[29] Rosu, I. (n.d.). *Understanding Noise Figure.* Retrieved from RF Technical Articles: http://www.qsl.net/va3iul/

[30] Pozar, D. M. (2006). *MIcrowave Engineering.* New Delhi, India: Wiley India Pvt. Ltd.

[31] Das, T. (2013). *Practical Considerations for Low Noise Amplifier Design.* Freescale Semiconductor.

[32] CHO, C. (2005). *RF CIRCUIT NONLINEARITY CHARACTERIZATION AND MODELING FOR EMBEDDED TEST.* UNIVERSITY OF FLORIDA.

[33] Hui Wang, G.-S. L.-G. (n.d.). *Characterization of Third-Order Nonlinearity in Low Noise Amplifier.* Changsha, China: College of Electronic Science and Engineering, National University of Defense Technology.

[34] rfic.co.uk. (2015). *RF, RFICs & Microwave Theory, Design.* Retrieved from http://www.rfic.co.uk

[35] Rosa, J. M. (n.d.). Behavioral Modeling Techniques for Teaching Communication Circuits and Systems. *Instituto de Microelectronica de Sevilla*.

[36] The MathWorks Inc.: "Using SIMULINK Version 6.0", 2004.

[37] Chen, J. E. (2011). *Modeling RF Systems.* The Designer's Guide Community.

[38] Jiang Liu, L. P. (2006, AUGUST). Large-Signal Behavioral Modeling of Nonlinear Amplifiers Based on Load–Pull AM–AM and AM–PM Measurements. *IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 54, NO. 8.*, pp. 3191-3196.

[39] Tatinian, W. (2007). System Design Oriented RF Block Modeling : When Top-Down Reaches Bottom-Up. *IEEE*, 1-5.

[40] Roy, A. (2014, February). *Low Noise Amplifier Design Methodology Summary*. Retrieved from Skyworks Solutions, Inc.: http://www.mpdigest.com/issue/Articles/2014/Feb/skyworks/default.asp

[41] Akhtar, N. (n.d.) (2009). *Improvement in Bandwidth of Low Noise Amplifier using Electromagnetic Band gap*

[42] Kumar, A. M. (2010). MODELLING RF POWER AMPLIFIER TO STUDY ITS NON LINEAR EFFECTS ON RF COMMUNICATION SYSTEM, WITH BER AS A PERFORMANCE MEASURE. *International Journal of Next-Generation Networks (IJNGN) Vol.2, No.4*, 73-81.

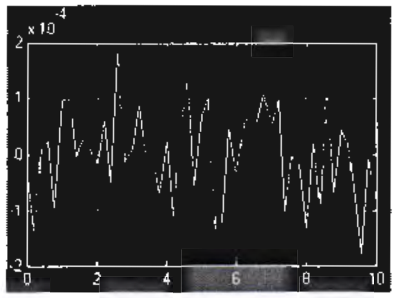


Figure 5. 4: Input Noise Voltage Signal of Proposed LNA Model.

- The voltage gain (G_v) of the LNA is 4.003V, at the given values of S-parameters and power gain (G_p).
- The model is capable of displaying the effects of noise and nonlinearity on the input signal along with the input, linear output, nonlinear output, 3rd order IM and noise signals in time domain. If the amplitude of the input signal is $5.6V_{p-p}$, then the output should be $22.4V_{p-p}$ but due to nonlinearity and noise effects the output voltage comes out to be $20V_{p-p}$ as shown in the graph in figure 5.5.

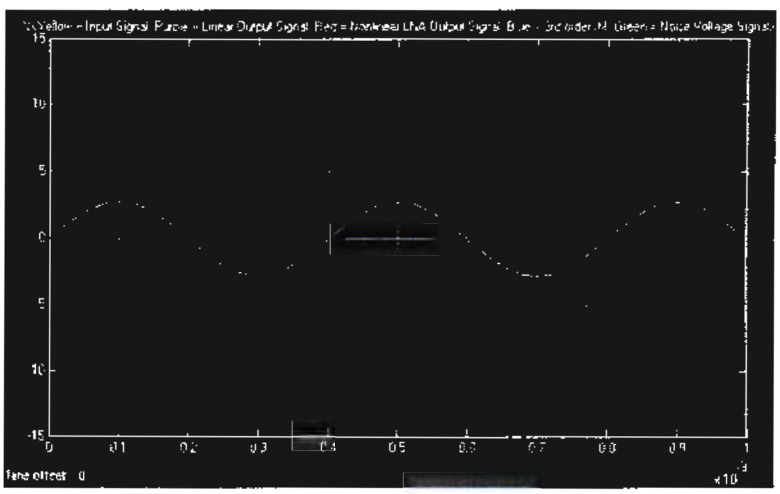


Figure 5. 5: Time domain waveform signalsYellow (Input), Purple (Linear Output), Red (Nonlinear Output), Blue (3rd Order IM) and Green (Noise voltage signal).

- The model can also predict the values of P_{1dB} and P_{ip3} as shown in the graphs of figure 5.6.

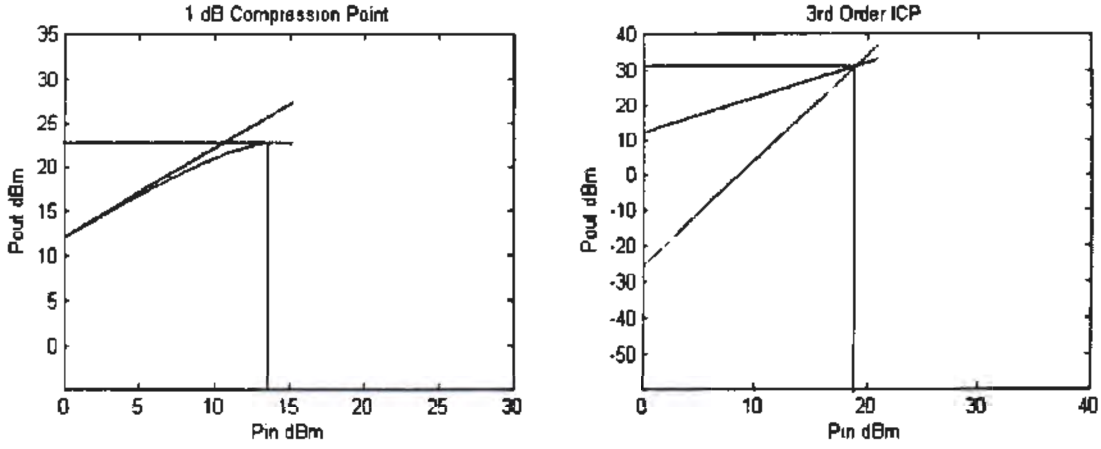


Figure 5. 6: Graphs of P_{1dB} (23dBm) and P_{ip3} (31dBm) of Proposed LNA Model.

- Table 5.5 shows a comparison among the amplitudes of Input, Linear Output, Nonlinear Output, 3rd Order IM and LNA Output Signals and their respective representation in figure 5.7.

Table 5. 5: Comparison among the amplitudes of Input, Linear Output, Nonlinear Output, 3rd Order IM and LNA Output Signals.

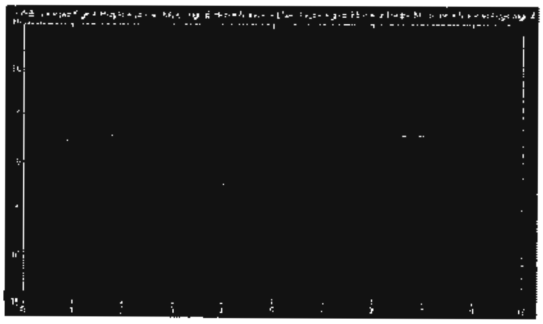
Amplitude of Input (V_{p-p})	Linear Signal (V_{p-p})	Nonlinear Signal (V_{p-p})	3rd order IM (V_{p-p})	LNA Output Signal (V_{p-p})	Figure 5.9
2	8.0	7.951	0.055	7.9	(a)
4	16.0	15.12	0.88	15.1	(b)
6	24.0	21.0	3.0	21.0	(c)
8	32.0	25.0	7.0	25.0	(d)
10	40.0	26.3	13.7	26.0	(e)

- On the other hand, the graphs in figure 5.7 show, the Input (Yellow), Linear Output (Purple), Nonlinear Output (Red), 3rd Order IM (Blue) and Noise voltage signal (Green) and the effect of nonlinearity and noise on the LNA Output Signal (RED), by increasing the amplitude of the input signal (Yellow).
- The graphs in figure 5.7 depict, that for smaller amplitudes of the input signal (Yellow), the effect of 3rd order inter-modulation products (Blue) and noise (Green) on the LNA output signal (Red) is low, but by increasing the amplitude of

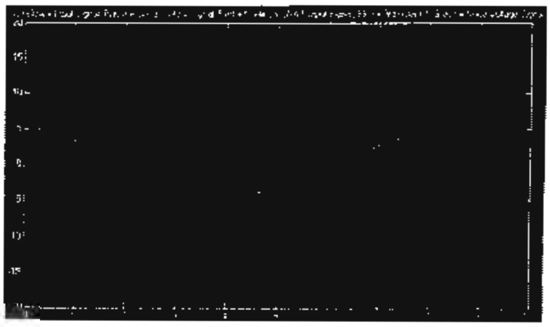
the input signal (Yellow), the amplitude of the 3rd order inter-modulation products (Blue) also increase, as a result distorting the LNA Output Signal (Red).

(a) (V_i= $2V_{p-p}$)

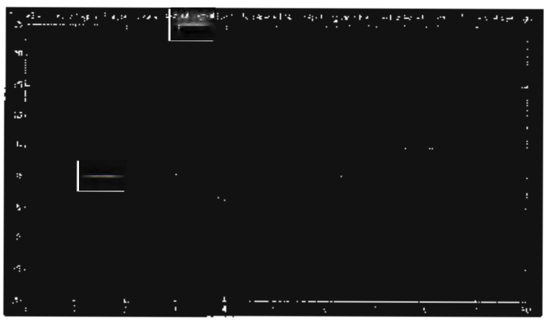
(b) (V_i= $4V_{p-p}$)



(c) (V_i= $6V_{p-p}$)



(d) (V_i= $8V_{p-p}$)



(e) (V_i= $10V_{p-p}$)

Figure 5. 7: Time domain waveform signals; Effects of 3rd order IM products (Blue) on the LNA Output Signal (Red) by varying amplitude of Input Signal (Yellow).

- Table 5.6 shows the comparison between the results, as well as the features of SIMULINK and ADS models of LNA. It depicts, that the proposed model can predict the relation between the amplitudes of input (V_i) and output (V_o) signals at the given P_{1dB}. Moreover, the model can demonstrate the effect of Gain, Noise and Nonlinearity on the input signal as well.

Table 5. 6: Comparison between the SIMULINK and ADS LNA Models.

Design Parameter	SIMULINK Model	ADS Model
Power Gain (G_p)	12.05 dB	11.51dB
Voltage Gain (G_v)	4.003V	4.0V
Stability Factor (K)	1.007	1.007
Input Noise Voltage	Yes	No
Relation Between Input and Output Voltage	Yes	No
Pout at 1-dB Compression Point	23dBm	20dBm
P_{out} at 3^{rd} Order Intercept Point	31dBm	29.5dBm
V_{1dB}	3.23 V	No
V_{ip3}	9.815 V	No
Ratio of V_{ip3} to V_{1dB}	9.654 dB	No
Variation of Input Signal w.r.t Noise, Gain and Nonlinearity	Yes	No

Chapter 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

In this thesis, a unique and interactive MATLAB/SIMULINK based behavioral model for an LNA is proposed, to analyze the effect of all LNA design parameters i.e. gain, noise and nonlinearity on the input RF signal. In this regard, for the design feasibility regarding different applications, top-down behavioral modeling approach has been adopted to model each LNA design parameter separately based on its characteristic equation. All the individual parameter blocks of LNA are brought together with the help of MATLAB code, written for LNA in "Embedded MATLAB Function" block. S-parameters, P_{1dB}, P_{ip3} and NF are used as input parameters for the proposed model, whereas the values are taken from the datasheet/ADS circuit of LNA having device # ATF-34143.

This approach is adopted, so as to validate the design feasibility and for the performance optimization of the proposed SIMULINK model. Moreover, the results obtained from the proposed SIMULINK model are compared with the results of the ADS model. In this regard, table 5.6 shows a comparison between the results, as well as the features of SIMULINK and ADS models of LNA. It depicts, that the proposed model can provide the values of stability factor (K), power as well as voltage gain and can predict the relation between the amplitudes of input (V_i) and output (V_o) signals at the given P_{1dB}. Moreover, the model can demonstrate the effect of Gain, Noise and Nonlinearity on the input signal, as shown in figure 5.7. The graphs in the figure depict, that for smaller amplitudes of the input signal (Yellow), the effect of 3^{rd} order inter-modulation products (Blue) on the LNA output signal (Red) is low, but by increasing the amplitude of the input signal (Yellow), the amplitudes of the 3^{rd} order inter-modulation products (Blue) also increase, which as a result distort the LNA Output Signal (Red). So, the proposed

LNA model can be used to see the effect of gain, noise and nonlinearity altogether on the input RF signal.

6.2 Future Improvements

Some of the future improvements regarding the design, as well as the performance approximation of the proposed SIMULINK LNA model are as follows

- As far as, the design of the proposed LNA model is concerned, it can further extended by adding up the sensitivity, dynamic range and Fourier transform blocks, to analyze the spurious free dynamic range SFDR, as well as to analyze the output signal in frequency domain.
- The presented model can be further utilized by RF designers to optimize the LNA design parameters e.g. stability, voltage and power gains, noise factor and nonlinear behaviors of those LNAs which have no models in any other CAD tools, but their measured parameters, such as S-parameters and other information are available in datasheets as provided by manufacturer.
- Can be integrated in multi-standard receiver architectures operating on multiple frequency bands. In order to, predict the LNA design parameters to fulfill the system requirements.

REFERENCES

[1] Jabbar, M. M. (2012). *Design and Performance Analysis of Low-Noise Amplifier with Band-Pass Filter for 2.4-2.5 GHz.* Sweden: Department of Science and Technology, Linköping University.

[2] V. Gazis, N. Alonistioti and L. Merakos: "Toward a Generic Always Best Connected Capability in IntegratedWLAN/UMTS Cellular Mobile Networks (and Beyond)". IEEE Wireless Communications, pp. 20-29, June 2005.

[3] M. Brandolini, P. Rossi, D. Manstretta and F. Svelto: "Toward Multistandard Mobile Terminals –Fully Integrated Receivers Requirements and Architectures". IEEE Transactions on Microwave Theory and Techniques, Vol. 53, pp. 1026-1038, March 2005.

[4] Hansson, M. (2003). *Design of microwave low-noise amplifiers in a SiGe BiCMOS process.* Sweden: Linköping University.

[5] estergaard, P. W. (n.d.). Recent T rends in CMOS Low Noise Amplifiers. *ANALOG ELECTRONICS II* .

[6] Eric Marsan, S. M. (April 11, 2013). *Accurate System Level Design with Low Noise Amplifier's BlackBox Models.* Skyworks Solutions, Inc.

[7] X. Li and M. Ismail: Multi-Standard CMOS Wireless Design. Kluwer Academic Publishers, 2002.

[8] K. Kundert: "Challenges in RF Simulation". Proc. of the 2005 Radio Frequency Integrated Circuits Symposium, pp. 12-14, June 2005.

[9] Molavi, R. (2005). *ON THE DESIGN OF WIDEBAND CMOS LOW-NOISE AMPLIFIERS.* THE UNIVERSITY OF BRITISH COLUMBIA.

[10] Kung, S.-K. W. (2009). DESIGN OF 3 TO 5 GHz CMOS LOW NOISE AMPLIFIER FOR ULTRA-WIDEBAND (UWB) SYSTEM. *Progress In Electromagnetics Research C* , 25-34.

[11] B. Razavi: RF Microelectronics. Prentice-Hall, 1998.

[12] ZAVERI, M. (2013). COMPLEXITY IN DESIGNING OF LOW NOISE AMPLIFIER. *JOURNAL OF INFORMATION, KNOWLEDGE AND RESEARCH IN ELECTRONICS AND COMMUNICATION ENGINEERING*, 444-449.

[13] Edwall, M. (2008). *Low Noise-Amplifier Design and Optimization.* Luleå University of Technology.

[14] ALI, E. A. (2008). *Behavioral Modeling of RF front end devices in SIMULINK.* Göteborg, Sweden: Chalmers University of Technology.

[15] An, D. (2000). Design and Fabrication of a Wideband MMIC Low-Noise Amplifier using Q-matching. *Journal of the Korean Physical Society* , 837-841.

[16] Ha, H.-J. L. (n.d.). A Systematic Approach to CMOS Low Noise Amplifier Design for Ultrawideband Applications. *VTVT (Virginia Tech VLSI for Telecommunications) Lab* .

[17] Ahmad Saghafi and Abdolreza Nabavi "An Ultra-Wideband Low-Noise Amplifier for 3–5-GHz Wireless Systems" The 18th International Confernece on Microelectronics (ICM) 2006.

[18] Jian-Ming WU, C.-H. Y.-J. (JUNE 2012). High Dynamic Range RF Front End with Noise Cancellation and Linearization for WiMAX Receivers. *RADIOENGINEERING, VOL. 21, NO. 2,* , 704-711.

[19] Pankaj Jha, P. V. (2012). DESIGN OF RF FRONT-END LOW NOISE AMPLIFIER FOR AN ULTRA WIDEBAND RECEIVER. *Journal of Electron Devices* , 1006-1011.

[20] Alonso Morgado, R. d. (2007). A SIMULINK Block Set for the High-Level Simulation of Multistandard Radio Receivers. *IEEE* .

[21] Nicolle, B. (2007). System-Design-Oriented Low Noise Amplifier Modeling. *IEEE*, 1332-1335.

[22] Adsul, A. P. (2011). Design and Performance Evaluation of Transmitted Reference BPSK UWB Receiver using SIMULINK. *International Journal of Computer Science and Information Technologies Vol. 2 (6)*, 2752-2760.

[23] Nga, T. T. (July 2012). *Ultra low-power low-noise amplifier designs for 2.4 GHz ISM band applications.* Nanyang Technological University.

[24] Janmejay Adhyaru "Design and analysis of ultra wide band CMOS LNA" 2007,San Jose State University

[25] P-N Designs, I. a. (2015, September 06). *S-parameters.* Retrieved from www.microwaves101.com/encyclopedias: http://www.microwaves101.com/encyclopedias/438-s-parameters-microwave-encyclopedia-microwaves101-com

[26] Damen, J. L. (1999, February). LNA design for CDMA front end. *RF Design.*

[27] Mini-Circuits. (1999). *Modern Amplifier Term Defined* . Mini-Circuits. Inc.

[28] electrical4u. (2011-2015). *Amplifier Gain | Decibel or dB Gain.* Retrieved from electrical4u.com Online Electrical Engineering: http://www.electrical4u.com/amplifier-gain-decibel-or-db-gain/

[29] Rosu, I. (n.d.). *Understanding Noise Figure.* Retrieved from RF Technical Articles: http://www.qsl.net/va3iul/

[30] Pozar, D. M. (2006). *MIcrowave Engineering.* New Delhi, India: Wiley India Pvt. Ltd.

[31] Das, T. (2013). *Practical Considerations for Low Noise Amplifier Design.* Freescale Semiconductor.

[32] CHO, C. (2005). *RF CIRCUIT NONLINEARITY CHARACTERIZATION AND MODELING FOR EMBEDDED TEST.* UNIVERSITY OF FLORIDA.

[33] Hui Wang, G.-S. L.-G. (n.d.). *Characterization of Third-Order Nonlinearity in Low Noise Amplifier.* Changsha, China: College of Electronic Science and Engineering, National University of Defense Technology.

[34] rfic.co.uk. (2015). *RF, RFICs & Microwave Theory, Design.* Retrieved from http://www.rfic.co.uk

[35] Rosa, J. M. (n.d.). Behavioral Modeling Techniques for Teaching Communication Circuits and Systems. *Instituto de Microelectronica de Sevilla.*

[36] The MathWorks Inc.: "Using SIMULINK Version 6.0", 2004.

[37] Chen, J. E. (2011). *Modeling RF Systems.* The Designer's Guide Community.

[38] Jiang Liu, L. P. (2006, AUGUST). Large-Signal Behavioral Modeling of Nonlinear Amplifiers Based on Load–Pull AM–AM and AM–PM Measurements. *IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 54, NO. 8.*, pp. 3191-3196.

[39] Tatinian, W. (2007). System Design Oriented RF Block Modeling : When Top-Down Reaches Bottom-Up. *IEEE*, 1-5.

[40] Roy, A. (2014, February). *Low Noise Amplifier Design Methodology Summary.* Retrieved from Skyworks Solutions, Inc.: http://www.mpdigest.com/issue/Articles/2014/Feb/skyworks/default.asp

[41] Akhtar, N. (n.d.) (2009). *Improvement in Bandwidth of Low Noise Amplifier using Electromagnetic Band gap*

[42] Kumar, A. M. (2010). MODELLING RF POWER AMPLIFIER TO STUDY ITS NON LINEAR EFFECTS ON RF COMMUNICATION SYSTEM, WITH BER AS A PERFORMANCE MEASURE. *International Journal of Next-Generation Networks (IJNGN) Vol.2, No.4*, 73-81.