136-941 MHZ LNA DESIGN FOR SOFTWARE DEFINED RADIO

by

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LIST OF ABBREVIATIONS, SYMBOLS AND UNITS

θ	Electrical Length (in degrees)
Ω	Unit of Resistance (Ohm)
β_F	BJT Transistor Forward Beta
Γ	Coefficient Reflection
Γ_I	Input Coefficient Reflection
Γ_S	Source Coefficient Reflection
Γ_O	Output Coefficient Reflection
Γ_{OPT}	Optimum Coefficient Reflection for Noise
π	Pi (configuration)
ε_r	Dielectric Constant
ω	Frequency (Radian per second)
μm	Micro-meter (10^{-6} m)
3G	Third Generation Mobile Communication Technology
A	Unit of Current (Ampere)
AC	Alternating Current
ADS	Advance Design System
ANT SW	Antenna Switch
B	Noise Bandwidth in Operating Frequencies (Hz)
B	Stability Measure
BBIC	Base Band Integrated Circuit/Microprocessor

BiCMOS	Bipolar Junction CMOS Transistor
BJT	Bipolar Junction Transistor
C	Capacitor
CAD	Computer Aided Design
C_{FB}	Shunt Feedback Capacitor
C_{gs}	FET Internal Gate-to-Source Capacitor
dB	Decibel (logarithmic unit ratio)
dBm	Power Ratio (dB) referenced to 1mW
DC	Direct Current
E-PHEMT	Enhancement Mode PHEMT Transistor
F	Unit of Capacitance (Farad)
f_1	Low End of Two-Tone Frequencies
f_2	High End of Two-Tone Frequencies
f_T	Transistor Maximum Operating Frequency
F	Friss Noise Factor (linear)
F_{min}	Minimum Noise Factor in a System (linear)
F_{Total}	Total Noise Factor in a System (linear)
FET	Field-Effect Transistor
FM	Frequency Modulation
Freq	Frequency
G	Gain of the System
G_P	Power Gain

G_A	Available Power Gain
G_T	Transducer Power Gain
g_m	FET Transconductance
$g_{m(min)}$	Minimum Transconductance of the FET Transistor
GaAs	Gallium Arsenide
GHz	Giga-Hertz (10^9 Hz)
H	Unit of Inductance (Henry)
H	PCB Substrate Thickness
h_{fe}	Amplification Factor
HB	Harmonic Balance Simulator
HBT	Heterojunction Bipolar Transistor
HEMT	High Electron Mobility Transistor
HW	Hardware
Hz	Hertz (Frequency unit)
I	Current
I_B	Base Current
I_C	Collector Current
I_d	Drain Current
I_{DC}	Supply Current
I_{ds}	Drain-to-source Current
I_{dss}	Saturated Drain-to-source Current
I_g	Gate Current

I_s	Source Current
IF	Intermediate Frequency
IIP2	Second Order Input Intercept Point
IIP3	Third Order Input Intercept Point
IM3	Third Order Intermodulation Product
IMD	Intermodulation Distortion
IMDR	Intermodulation Distortion Rejection
IRL	Input Return Loss (dB)
ISO	Isolation (dB)
IP3	Third Order Intercept Point
$j\omega$	Complex Frequency (Radian per second)
K	Rollet Stability Factor
k	Boltzmann's constant (1.38 x 10^{-23} J/K)
kHz	Kilo-Hertz (10^3 Hz)
L	Inductor
l	Microstrip Length
L_d	Drain Inductance
L_{FB}	Shunt Feedback Inductor
L_g	Gate Inductance
L_s	Source Inductance
LNA	Low Noise Amplifier
LTCC	Low Temperature Co-fired Ceramic

mA	Milliamp (10^{-3} A)
MESFET	Metal Semiconductor FET
MHz	Mega-Hertz (10^{6} Hz)
MOSFET	Metal Oxide Semiconductor FET
mm	Millimeter (10^{-3} m)
mW	Milliwatt (10^{-3} W)
N_{in}	Input Noise Power
N_O	Noise power of white noise in W
N_{out}	Output Noise Power
NF	Noise Figure (decibel)
NFA	Noise Figure Analyzer
$NF_{\min}$	Minimum Noise Figure in a System (decibel)
nH	Nano-Henry (10^{-9} H)
NWA	Network Analyzer
OIP3	Third Order Output Intercept Point
ORL	Output Return Loss
P25	Public Safety Digital radio Standard
P_{avn}	Power Available from the Network
P_{avs}	Power Available from the Source
P_L	Power Delivered to the Load
P_I	Input Power of a Network
PCB	Printed Circuit Board

PCS	Personal Communication Service
pF	Pico-Farad (10^{12} F)
PHEMT	Pseudomorphic HEMT
Pwr	Power
Q	Quality Factor
R	Resistor
R_g	Gate Resistance
R_{FB}	Shunt Feedback Resistor
$R_{FBseries}$	Series Feedback Resistor
r_n	Normalized Noise Resistance of a system
R_N	Noise Resistance of a system
R-C	Shunt Resistor-Capacitor Feedback
R-L-C	Shunt Resistor-Inductor-Capacitor Feedback
RF	Radio Frequency
RFIC	Radio Frequency Integrated Circuit
RSSI	Received Signal Strength Indicator
RXFE	Receiver Front End
S	Complex Frequency ($j\omega$)
S	Siemens ($1/\Omega$)
S_{in}	Input Signal Power
S_{out}	Input Signal Power
SAW	Surface Acoustic Wave

SDR	Software Defined Radio
Si	Silicon
SiGe	Silicon Germanium
Sigen	Signal Generator
SMT	Surface-Mount Technology
SINAD	Signal-to-Noise and Distortion Ratio
SNR	Signal-to-Noise Ratio
SP	S-Parameter Simulator
SW	Software
T	PCB Metal Thickness
T_e	Noise Temperature
T_o	Standard Room Temperature (290K)
TanD	PCB Substrate Dissipation Factor
TIA	Telecommunication Industry Association
TIA-603C	TIA Land Mobile FM or PM Communications Equipment Measurement and Performance Standards – Version C
TMA	Tower Mounted Amplifier
TOI	Third Order Intercept Point Analysis
UHF	Ultra High Frequency
V	Unit of Voltage (Volt)
Vc	Voltage Across the Transistor Internal Cgs Capacitance
Vce	Collector-to-Emitter Voltage
Vds	Drain Voltage

Vdc	Supply Voltage of the Circuit
Vgs	Gate-to-Source Voltage
VHF	Very High Frequency
VSWR	Voltage Standing Wave Ratio
W	Unit of Power (Watt)
w	Microstrip Width
Xls	Reactive Component (Inductive)
Y	Admittance
Y_{OPT}	Optimum Admittance for Minimum Noise Figure
Y_S	Source Admittance
Z	Impedance
Z_{IN}	Input Impedance
Z_L	Load Impedance
Z_{OUT}	Output Impedance
Z_S	Source Impedance
Z_O	Characteristics Impedance

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REKA BENTUK PENGUAT HINGAR RENDAH PADA 136-941 MHZ UNTUK RADIO DITENTU PERISIAN

ABSTRAK

Penyelidikan tesis ini menerangkan kaedah terperinci mengenai reka bentuk penguat hingar rendah (LNA) jalur lebar pada 136-941MHz untuk Radio Ditentu Perisian (SDR) stesen pangkalan bagi tujuan aplikasi komunikasi radio dua hala. Frekuensi operasi reka bentuk berdasarkan standard TIA-603C untuk Peralatan Komunikasi FM Mobiliti Darat. Proses reka bentuk LNA merangkumi analisis litar yang komprehensif, kaedah reka bentuk dan perbandingan prestasi kedua-dua topologi jalur lebar dipilih untuk kajian ini, iaitu teknik penguat maklum balas negatif dan topologi reka bentuk penguat seimbang. Tesis penyelidikan ini juga mengenal pasti spesifikasi menyeluruh terhadap reka bentuk penguat hingar yang jalur lebar dan dalam masa yang sama mencadangkan pendekatan reka bentuk praktikal berstruktur yang menggunakan simulasi CAD dalam mengimbangi reka bentuk penguat hingar untuk memenuhi semua ciri-ciri spesifikasi yang diperlukan, dan menyelesaikan masalah hasil gandaan dalam reka bentuk dan akhir sekali penghasilan lukisan papan litar. Proses reka bentuk juga termasuk kaedah menepati persamaan di antara simulasi dan reka bentuk sebenar. Peringkat akhir dalam proses kajian adalah penghasilan dua reka bentuk penguat hingat menggunakan papan litar Rogers RO4003C dan ujian pengukuran reka bentuk penguat hingar secara praktikal menggunakan peralatan frekuensi radio untuk mengesahkan prestasi penguat hingar yang direka. Reka bentuk maklum balas negatif menunjukkan kuasa keluaran yang melebihi

12dB dan seimbang keseluruhannya, kekuatan linear yang tinggi sekitar 13dBm IIP3, angka hingar yang lebih rendah daripada 1.5dB dan menggunakan arus 80mA daripada satu bekalan kuasa 5V. Manakala reka bentuk penguat seimbang menghasilkan kuasa keluaran yang stabil lebih besar daripada 17dB, kekuatan linear sekitar 13.5dBm IIP3, angka hingar yang lebih rendah daripada 1 dB dan menggunakan arus 120mA daripada dua bekalan kuasa 5V. Kedua-dua reka bentuk LNA yang berbeza telah disimulasikan, dioptimumkan dan diukur, yang mana keputusan pengukuran kedua-duanya dibandingkan di dalam jadual. Sumbangan penyelidikan ini adalah LNA yang dihasilkan akan merealisasikan pelbagai jalur SDR kerana keupayaan jalur lebarnya jika berbanding dengan sistem radio kini yang didapati pelbagai untuk aplikasi yang berbeza dalam standard TIA- 603C.

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ABSTRACT

This research thesis describes the detailed methodology on the design of the 136-941MHz wideband low noise amplifier (LNA) for Software Defined Radio (SDR) Base Station in Two-Way radio applications. The operating frequencies of the design are based on the full spectrum (wideband requirement) of the TIA-603C standard for Land Mobile FM Communication Equipment. The LNA design process includes a comprehensive circuit analysis, design methodology and performance comparisons of the two wideband topologies selected for this research, the negative feedback technique and balanced amplifier topology. This research thesis also illustrates the simultaneous amplifier requirements in wideband application and proposed a structured practical design approach which utilizes the CAD simulations in optimizing the amplifiers to meet all the required specs, to balance the design tradeoff and the drawing of the PCB layouts. The design process also includes the method of achieving accurate correlation between the simulation and the actual design. The final stage of the research process was the fabrication of the two topologies using Rogers RO4003C PCB board and the practical testing measurement of the design using RF equipment to verify the performance of the designed LNA. The negative feedback design exhibited an unconditional stable gain greater than 12dB, high linearity of around 13dBm IIP3, noise figure lower than 1.5dB and consumes 80mA from a single 5V supply, whereas the balanced amplifier design produces an unconditional stable gain greater than 17dB, high linearity of around

CHAPTER 1.
INTRODUCTION

1.1 Motivation for the thesis

Traditional radios lacked interoperability, which caused the failure to readily communicate between the law officers, fire-fighters and medical emergency medical service personnel in critical situations, which reduces the effectiveness of the emergency response of effort and in the same time poses lethal risk towards the emergency personnel themselves during emergency situations [1]. Although the Public Service spectrum allocations follow the same standard, which is the Telecommunications Industry Association standard for Public Services (TIA-603C) but this standard is segmented into different spectrum allocation for different applications (police, fire-fighter, ambulance, etc) thus making the rescue effort difficult when involving multiple service units [2].

The realization of this multi-mode/multi-band system requires the development of the Software Defined Radio (SDR) as the system architecture. Some of the intermediate solutions have been proposed by contemporary radio engineers such as S.M. Hasan and S. W. Ellingson to re-structure the current "stove-piped" system, the ultimate goal is to realize an autonomous system which is fully cognitive in standardizing the communication between the different modes/bands of the public service communication system [3]. To achieve this, both the hardware (HW) and software (SW) must be developed for the SDR radio architecture. A part of the HW development is to have a wideband low noise amplifier system at the SDR radio front-end receiver (RXFE) which must be able to achieve the signal-to-noise ratio of the radio system and meet the standard employed in the public safety applications [4]. The wideband LNA development is the major component in the SDR radio, and is the topic of this Master research study.

A lot of difficulties were faced during the design of the LNA of this research. The main problem was to balance the LNA design between performance and design size. Due to the low frequencies in some of the Public Services applications, the balanced amplifier design will be difficult to achieve without having a very large PCB size.

Due to the very few or non-existence literatures on a wideband LNA design system that covers the full spectrum of the Public Sector applications as well as the double ended studies on the lower spectrum application has produce an opportunity for the author to contribute in the technical development of the wideband SDR LNA.

Two new LNA have been designed in this research, both which covers the full spectrum of Public Service spectrum with the difference in the topologies selected. One LNA was designed in a negative feedback (single ended) design and another in a balanced amplifier topology (double-ended). Recent trend in wideband LNA design is to integrate the negative feedback and balanced amplifier in a single architecture, thus by designing these two separate design will help the designers to have more understanding of these separate design before doing future work in combining them for future works. This will be discussed in chapter 7 of this thesis.

Realizing the wideband LNA for the SDR radio will ensure a major milestone is achieved in making this multi-mode and multi-band system in Public Services rescue mission to be achieved.

1.2 Problem Statement

1. The detailed analysis and methodology of designing a wideband LNA that covers the full spectrum of the SDR application which includes the initial stage of specification analysis to selecting the transistor, matching components, PCB layout design and finally the measurement characterization of the design board are currently non-existence.

2. A detailed analysis on the comparison of the negative feedback and balanced amplifier wideband LNA design has not been available on current literatures to the best of the author's knowledge. Detailed analysis on the individual design is available but not on comparing the advantages and disadvantages of the two designs in determining which is the best option for the SDR Radio LNA, as well as to provide the knowledge to the designers on the future wideband LNA design trend in incorporating these two designs in a single architecture.

3. Presently there are not many literatures which comprehensively compare the performance of the simulated analysis and the actual circuit performance of a wideband LNA design in the 136-941MHz frequency band. Most literatures, as

discussed in chapter 2, described the comprehensive LNA design for parts of the TIA-603 bands, but not the total spectrum.

4. Although currently there is a lot of MMIC transistors which are fully matched at wideband frequencies, these transistors have lower noise figure and IP3 performance required for the SDR applications. Thus a non-matched transistor is still desired for the LNA design to meet all the required specifications for SDR at 136-941MHz applications. Studies of the current MMIC LNAs limitations are described in chapter 2 of this thesis.

1.3 Objective

The objectives of this research are:

1. To develop and design the wideband Low Noise Amplifier design from specification analysis to circuit design and up to test characterization for 136-941MHz Software Defined Radio application.

2. To analyze the two topologies of the LNA design, which are the negative feedback design and balanced amplifier designs. The two topologies will be thoroughly investigated and analyzed as well as compared between each other to summarize the benefit of each topology in the SDR Radio application.

3. To design the LNA with the state of the art circuit simulator and matches the simulation results with the fabricated design measurement results.

1.4 Research Scope

In this research the wideband LNA is defined as the first stage amplifier of the SDR radio RXFE as described in Figure 1-1. The LNA is part of the SDR RXFE, which in turn is part of the overall SDR transceiver Radio system. The SDR radio is the system architecture proposed in the multi-mode/multi-band application of the Public Service communication system networks.

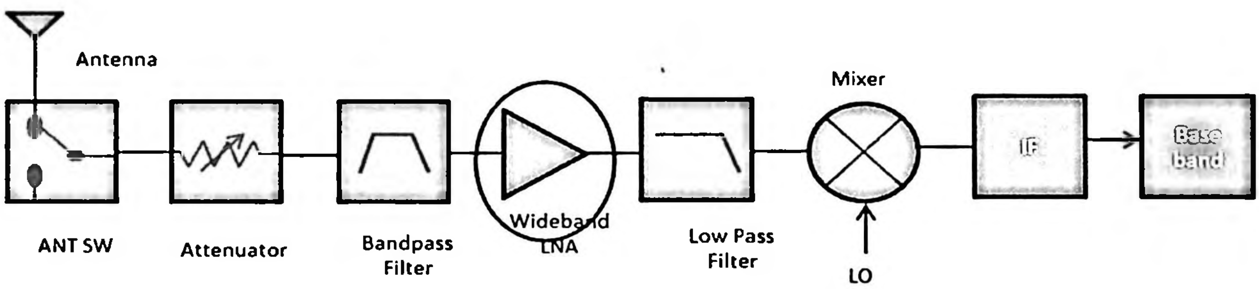

Figure 1-1 The LNA in RXFE

The LNA design is focused in the circuit design trade-offs between two topologies. The components selected for designs will be from the current off-the-shelf components. The design process flow chart of this research is described in Figure 1-2, in which covers from the design definition until the design characterization. The scope of the research comprises as follows:

1. The detailed analysis of the Wideband SDR Radio LNA design specification, which will be based on the TIA-603C standard. The RF parameters such as the operating frequencies, noise figure, gain and IIP3 will be derived from this standard.

2. Two LNA topologies will be thoroughly analyzed and design, from the transistor selection to the simulation and up to the board fabrication and measurement.

3. The LNA designs will be simulated and modeled in the selected CAD circuit simulator, which will also include PCB parasitic simulations and layout designs.

4. The fabricated boards will be measured and verified with the identified specifications.

5. The two designs will be compared and the best LNA design for SDR radio is selected.

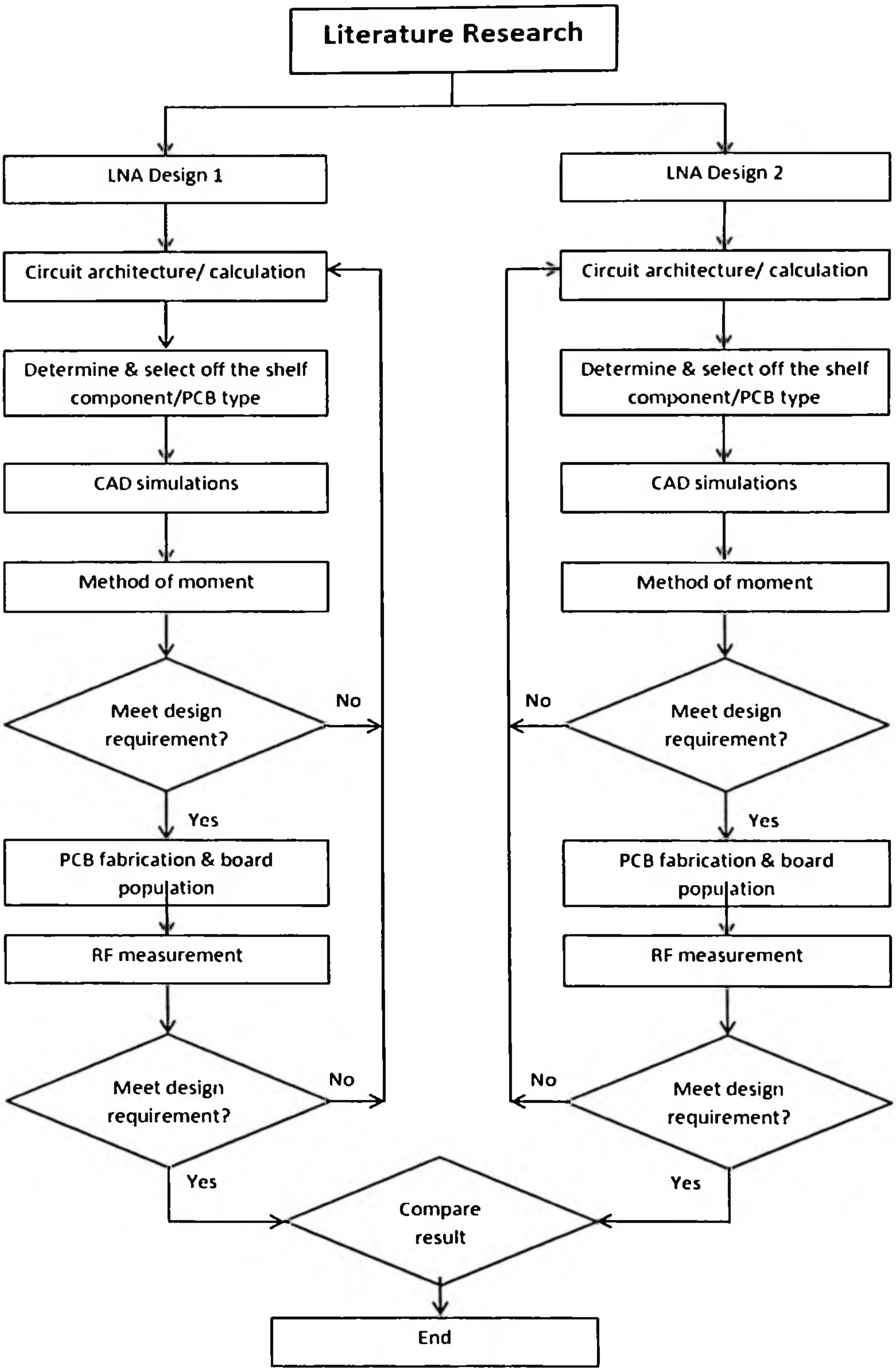

Figure 1-2 The Research Flow Chart

1.5 Contributions

The following are the contributions from the accomplishments of this research project:

1. A comprehensive study on the LNA designs which covers the full TIA-603C full spectrum of 136-941MHz band.

2. A systematic and detailed methodology on designing the Wideband LNA design for SDR Radio application. The methodology starts from the analysis of the TIA-603C SDR LNA requirements, followed by the circuit simulation and components selection. The design process includes the circuit matching networks and the PCB parasitic simulations as well as designing the LNA for best balanced of noise figure, gain and IIP3.

3. The designs are simulated and fabricated on the PCB, in which the boards are characterized for the RF measurement.

4. Comparative study of the designs and simulated performances between the negative feedback LNA design and balanced LNA design were detailed out in this thesis.

1.6 Organizations of the thesis

The thesis is organized into seven chapters to cover the research work related to the wideband LNA design. This chapter is the introductory section of the thesis which outlines the research objective and research scope.

Chapter 2 is the theoretical background and literature review of the LNA design. This includes the brief overview of the LNA in SDR RXFE and the theoretical review of the negative feedback and the balanced amplifier LNA. The technical specifications for the overall RXFE requirements are discussed, in which the RF parameters specifications of the LNA designs in this project are specified. The LNA specifications are summarized in the technical specifications table. Overviews of different LNA architectures are also thoroughly discussed, together with the selection of the best topologies selected for this project. This chapter concludes with the discussion on the types and selection of transistor to be used for this project.

Chapter 3 described the design methodology for the two selected LNA topologies of the project. The design methodologies discussed include the conceptual understanding and the calculation required to design the wideband LNA, as well as the initial design circuitry of the LNA design process.

Chapter 4 discusses the design process of the LNA, which includes the simulation and optimization of the LNA design using the CAD software. The process describes the circuit simulations and the optimization of the LNA to achieve the required specifications of the project. This chapter concludes with the layout generation for both designs as well as the PCB parasitic simulations for both designs.

Chapter 5 discusses the simulations as well as the final LNA board measurement results. The chapter starts with the explanation on the measurement setups, followed by the discussion and analysis of the simulation and the measurement results of the LNA designs. The simulations and practical measurements of both designs are tabulated at the end of the chapter.

Chapter 6 discussed and analyzed the final results of the LNA designs. The comparisons and analysis of the simulations and measurements result are explained in the chapter. A comparison of the LNA performances of this project and other comparable reported works are tabulated and analyzed at the end of the chapter.

Chapter 7 presents the overall conclusion of the LNA design conducted in this research. The findings from the research work are summarized. Finally, future works and recommendations for further research conclude this chapter.

1.7 Summary

This chapter is an introductory chapter that highlights the objectives and research scope of the project as well as the thesis outline.

CHAPTER 2.
THEORITICAL BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

Low Noise Amplifiers (LNA) is an important component in a communication receiver system. The LNA amplifies the low signal received from the antenna and at the same time suppressed the noise level, thus increasing the signal-to-noise ratio (SNR) of the receiver chain and improve its sensitivity (RSSI), which reflects to the lowest signal that can be detected by the receiver. Apart from the gain and noise requirement to improve the received signal sensitivity, the LNA must also be stable across the operating bandwidth to prevent the signal from oscillating, as well as having high linearity to prevent the signal to become distorted.

In this chapter, the theoretical background of the LNA for SDR applications and the literature review of the wideband LNA are discussed. In the theoretical background section, a brief overview of the LNA in radio receiver front end (RXFE) system is described, followed by the discussion on the TIA-603 SDR frequency band. Also, the technical specification required for the general RXFE in the SDR 136-941MHz application is also explained, as well as the targeted specification for the wideband LNA section, which will be the basis of the requirements for the wideband LNA designs in this project. This is followed by the discussion on the RF specifications and performance metrics required for this project.

In the literature review section, the literature survey of different wideband LNA topologies and the implementation method of the wideband LNA design are discussed. The performance of each topology are gathered from the current literatures will be discussed together with its advantages and disadvantages. From the all the topologies, the best two topologies will be selected for further development of this project which also include the basic design theory and calculation for the two designs.

The last part of this chapter explores the different type of transistors suitable to be used in this project and the justification of the selected transistor, as well as the PCB design parameters, equations and material type utilized in the project. These selections are also based on the literature review on the selected architectures for this project.

2.2 Theoretical background

In the radio communication system, the SDR is a radio architecture where the band/mode tuning modules are implemented using software on the embedded computing devices, as compared to the traditional method of utilizing multiple hardware components (such as mixers, filters, amplifiers, modulators/demodulators, detectors) for separate band/mode. The concept of SDR is not new, but implementing the architecture was difficult in the past and has only been explored in theory. However, the rapid evolution of digital electronics has enabled the realization of SDR architecture. Apart from the wideband LNA, other critical components in the SDR RXFE are the reconfigurable filter and the wideband mixer [1].

2.2.1 Overview of the LNA in RXFE

LNA represents the main active component in the communication system RXFE. A simple block diagram of the LNA in the receiver front end can be described in Figure 1-1. As shown in the figure, the LNA is the first major component in the RXFE. Since the received signal can be very small, as per the TIA standard which can be as low as -120 dBm, the designs must be able process very low power levels. The LNA is also the main component in improving the received signal SINAD ratio, or signal to noise plus distortion (similar to SNR, signal to noise ratio) [2]. S.W. Ellingson explained for a two-way radio receiver system, a received signal of -116dBm should be expected at the antenna terminals and the receiver SINAD at the audio output must be better than 12 dB [5]. Hence the LNA needs not just to handle low signal at the input, but to also amplify the signal and at the same time suppress the level of the noise to maintain high signal-to-noise ratio.

In general, to achieve the required signal-to-noise ratio in the RXFE system, the LNA must be able to produce sufficient gain, reduced the noise level of the received signal and must be stable across the frequency band. Apart from that, the LNA must also be able to meet the linearity or distortion requirement, particularly the third order intercept point or IIP3. The RF parameters of the LNA are dependent on the matching circuits as well as the biasing consideration. Lastly, to achieve the wideband capability, the LNA circuitry must follow the wideband amplifier techniques in order to make it operable at the required wideband frequencies.

2.2.2 Frequency band for TIA-603C Software Defined Radio

The goal of the SDR radio in for public safety application is to utilize existing and emerging technology to realize a single hardware platform to support the frequency modes of TIA-603 applications and enable multi-band/multi-mode radio to be controlled by SDR. Table 2-1 summarizes the frequency bands which are used for TIA and P25 applications [1]. The channel spacing for TIA-603 is 25 kHz apart [2].

Table 2-1 Frequency Bands/Modes for Public Safety Radio Communications [1]

Band	Frequency (MHz)	Mode
VHF	138*-174	TIA-603, P25
UHF	406-512	TIA-603, P25
700 MHz	764-776	TIA-603, TIA-902,P25
	794-806	TIA-603, TIA-902,P25
800 MHz	806-817	TIA-603, P25
	869-894*	TIA-603

* *In TIA-603C, the frequencies were extended from 136MHz to 941MHz* [2]

The SDR Radio main emphasis is to have the capability of tuning the modulators by using the software which enables the radio to utilized single hardware for multi-band/multi-mode operations. Hence the hardware modules need to be capable of providing wideband performance to the radio system for the SDR to work. The focus of this research is then to develop the wideband design of the LNA, which is one of the major wideband/tuning capabilities required to enable the development of an SDR RXFE.

A. A. Abidi in his paper explained that the three major hardware modules in the SDR RXFE are the configurable (tunable) filter, wideband LNA and the wide range mixer [6]. Figure 2.1 illustrates the main hardware modules setup for the SDR RXFE.

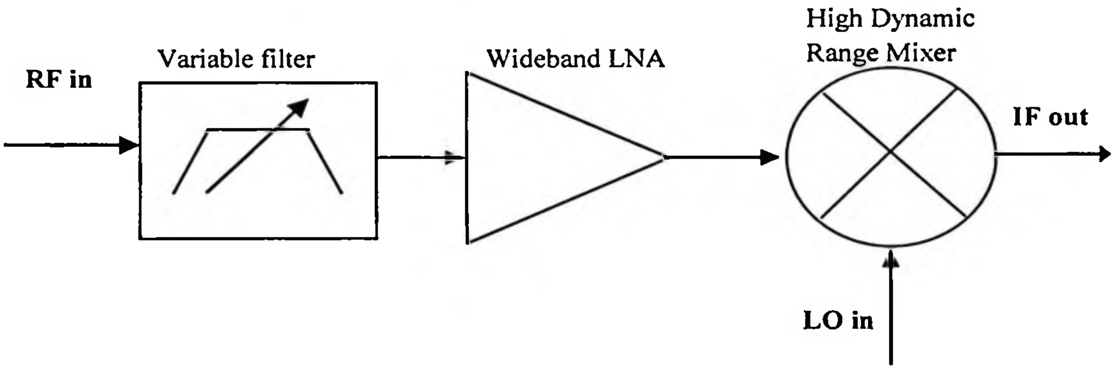

Figure 2-1 Hardware modules in the SDR RXFE

In summary, the LNA is a major component in the SDR radio and thus designing the LNA for wideband capabilities and in the same time meeting the required specification presents a lot of challenges to the designer. A few techniques to design for wideband LNA are described in the next section. Discussion on the LNA parameters and specifications are detailed in chapter 2.2.4.

2.2.3 TIA-603C SDR RXFE Requirements

The LNA specifications are based on the TIA-603C (Land and Mobile FM Radio standard, version C) compliance two-way communication radio receiver system. The TIA-603C standard specified the receiver system specifications (SINAD, DC Power, Intermodulation), and from the required system performance the specifications of all the sub-modules of the system can be deduced [2]. Apart from the electrical performance, the

TIA-603C standard also covers the Public Safety and civilian radio frequency bands (Police, Ambulance, Ham & Amateur radio, etc.) which are highlighted in Table 2-1. In the conventional radio system, these separate frequency bands require separate receiver chain (and overall system) for its unique and singular frequency operation. The vision of the SDR radio is to eventually replace these multiple and separate receiver hardware into a single system which has only one RXFE path (and hardware) but are capable to switch between the frequency bands by software control, resulting a system with less parts, smaller size and reduced cost. Another factor worth mention is the ability of the SDR radio to operate all modulation types. The multi-mode/multi-band SDR radio receiver presents challenges in both the hardware and software implementation of the system. This paper will focus on the development of the wideband LNA (which is part of the hardware implementation) design to achieve the multi-mode/multi-band capability of the SDR radio.

S. W. Ellingson reported in 2006 in his technical memo on the requirement for an experimental Multiband/Multimode analog FM radio, which is the first report on the wideband SDR radio technical specification outline. In the report, the requirements of the modes of operation are derived from TIA-603B which covers the actual implementation for the public safety radio application bands [5]. The frequencies of interest cover from 138-862MHz (analog FM). On TIA-603C (as of 2012), these bands have been extended to 136-941MHz. In his paper, S. W. Ellingson summarized the required specification for the SDR receiver and transmitter sections. In the receiver section, there are 8 requirements needed to be achieved, but these covers all the front end (RXFE) and back end sections. Of these 8 parameters, only two are of interests for the LNA in the SDR RXFE, which are the *Reference Sensitivity* (SINAD) and *Intermodulation Rejection* (IMDR) [5].

S. M. S. Hasan and S. W. Ellingson reported in 2008 a design and development of the experimental RXFE for SDR radio [3]. In this paper it is stated that to meet the TIA-603 standard, the SINAD for the RXFE is -117dBm and IMDR is 80dB.

2.2.4 The LNA Specifications

In this section, the overview of the SDR receiver system, its application and the potential benefit of implementing the wideband LNA in realizing the SDR radio have been discussed. The specification of the wideband SDR receiver is described in Table 2-2, which includes the requirement needed for the wideband LNA. Apart from meeting the required sensitivity and intermodulation specification of the TIA-603 standard, the wideband LNA also needs to be compact, using minimum components and robust in design. The selected architectures should also exhibit reliable performances across the wideband operating bands as well as feasible for low cost mass production and seamless integration with the whole SDR system architecture. The specific technical requirements of the LNA design for wideband SDR radio, which is derived from Table 2-2, is shown in Table 2-3. All the specification parameters are defined and discussed in detail in the next section.

Table 2-2 Design Specification for TIA-603 Standard SDR Receiver

Stage/Module Specifications	ANT SW	Filter1	Attenuator	LNA	Filter2	Preamp	MIXER	SAW Filter	IF AMP	BBIC
Gain (dB)	-1	-1.5	-0.3	11	-2.2	8	-6.5	-3	14	N/A
NF (dB)	1	1.5	0.3	1.5	2.2	2	7	3	2.5	10
IIP3 (dBm)	20	20	40	11	35	15	20	15	-15	-10
IIP2 (dBm)							40			
Selectivity @50kHz(dB)	0	0	0	0	0	0	0	25	0	0
Selectivity @100kHz(dB)	0	0	0	0	0	0	0	30	0	0
Current (mA)	0	0	0	100	0	75	25	0	50	250
Gain (linear)	0.79	0.71	0.93	12.59	0.6	6.31	0.22	0.5	25.12	N/A
NF (linear)	1.26	1.41	1.07	1.41	1.66	1.58	5.01	2	1.78	10
IIP3 (dBm)	20	20	40	11	35	15	20	15	-15	-10
Fsystem (linear)	3.68	2.92	2.07	1.93	7.52	4.53	19.59	4.26	2.14	10
NFsystem (dB)	5.66	4.66	3.16	2.86	8.76	6.56	12.92	6.3	3.3	10
12 dB SINAD (dBm)	-122.01	-123.01	-124.51	-124.81	-118.91	-121.11	-114.75	-121.37	-124.37	-117.67
20dB SINAD (dBm)	-117.71	-118.71	-120.21	-120.51	-114.61	-116.81	-110.45	-117.07	-120.07	-113.37
IIP3system (dBm)	1.73	0.8	-0.65	-0.95	10.16	7.97	16.94	13.39	-24.51	-10
IMDR (dB)	80.99	81.04	81.07	81.07	84.54	84.55	86.29	88.34	65.07	70.28

Table 2-3 The Wideband SDR LNA design specifications

Parameter	**Specs**
Gain, G	> 11dB
Noise Figure, *NF*	< 1.5 dB
IIP3	> 11 dBm
Rollet Stability Factor	> 1
Stability Measure	> 0
Input Return Loss	>10 dB
Output Return Loss	>10 dB
Current	< 150 mA
Operating Frequency	136-941 MHz

2.2.5 LNA Performance Metrics

LNA design is a two-port design (input and output port). In LNA design process, once the specifications are specified, the designer will start the design with the selected transistor S-parameter analysis. The S-parameter analysis will design for the gain and return losses of the two-port design. This is followed by optimization using the selected topology mathematical solutions and aided by using graphical method or CAD software for further improvement, stability improvement and balancing between best noise and gain. For the linearity improvement, a steady-state analysis in frequency domain using CAD software can be used to improve the parameters.

2.2.5.1 Scattering Parameters (S-Parameters) of a two-port network

Scattering Parameters or S-Parameters is used to describe the signal response of a two-port network. Unlike the other parameters (Z, Y, ABCD, etc) which analyze the network response in terms of voltage and current, the S-Parameters utilize the incident and reflected waves of the two-port network. S-Parameter analysis is an important tool in designing the LNA, either by manual calculations or to be imported into the CAD design software. Figure 2-2 represents the S-parameters of a two-port network driven from the source (input) with a characteristics impedance Z_O, which drives a load (at the output port) of impedance Z_L.

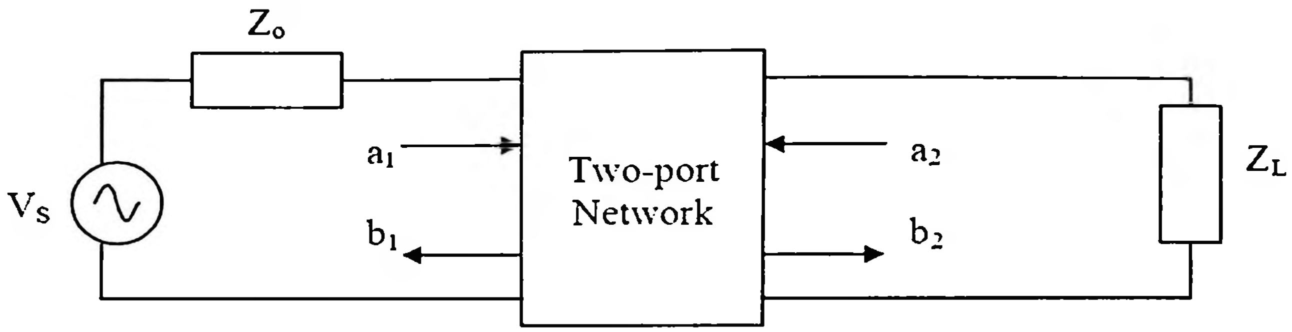

Figure 2-2 A two-port network S-Parameter diagram

As shown in the figure, a_1 and a_2 represents incident voltage waves, while b_1 and b_2 represent reflected voltages waves. These four waves can be related to the S-parameter components for two port network (S_{11}, S_{22}, S_{21} and S_{12}) by the following equations [7]:

$$b_1 = S_{11}a_1 + S_{12}a_2, \tag{2-1}$$

$$b_2 = S_{21}a_1 + S_{22}a_2. \tag{2-2}$$

For a unilateral gain amplifier, the S-Parameters represent the reflection and the transmission coefficient. For a properly terminated output port of the two-port network, the input reflection coefficient, S_{11} can be defined as in equation (2-3) [7]

$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0}. \tag{2-3}$$

For the input return loss (IRL), it is the equal to equation (2-3) expressed in decibels (dB), as shown in equation (2-4) [7]

$$IRL(dB) = \left|20\log_{10} S_{11}\right|. \tag{2-4}$$

Likewise, the output reflection coefficient with a properly terminated input, S_{22} can be defined as in equation (2-5) [7]

$$S_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0}. \tag{2-5}$$

For the output return loss (ORL), it is the equal to equation (2-5) expressed in decibels (dB), as shown in equation (2-6) [7]

$$ORL(dB) = |20\log_{10} S_{22}|. \tag{2-6}$$

S_{21} is the forward transmission coefficient with the output properly terminated, and is defined as in equation (2-7) [7]

$$S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0}. \tag{2-7}$$

The forward transmission coefficient, or the small signal gain in the amplifier system, is equal to equation (2-7) expressed in decibels as in equation (2-8) [7]

$$G(dB) = |20\log_{10} S_{21}|. \tag{2-8}$$

The reverse transmission coefficient with the input properly terminated, S_{12} can be defined as in equation (2-9) [7]

$$S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0}. \tag{2-9}$$

The reverse transmission coefficient, or amplifier isolation can be defined as equation (3-9) expressed in decibels as in equation (2-10) [7]

$$Iso(dB) = |20\log_{10} S_{12}|. \tag{2-10}$$

2.2.5.2 LNA Gain

Figure 2-3 shows the block diagram of the different gains in a two-port amplifier system. The effective gain of the amplifier in the two-port network is G_T, which is the amplifier transducer gain. It is defined by the output power (PL) received by the network load, Z_L divided by the input power available from the network source, P_{avs} as depicted in equation (2-11) [8]

$$G_T = \frac{P_L}{P_{avs}}. \tag{2-11}$$

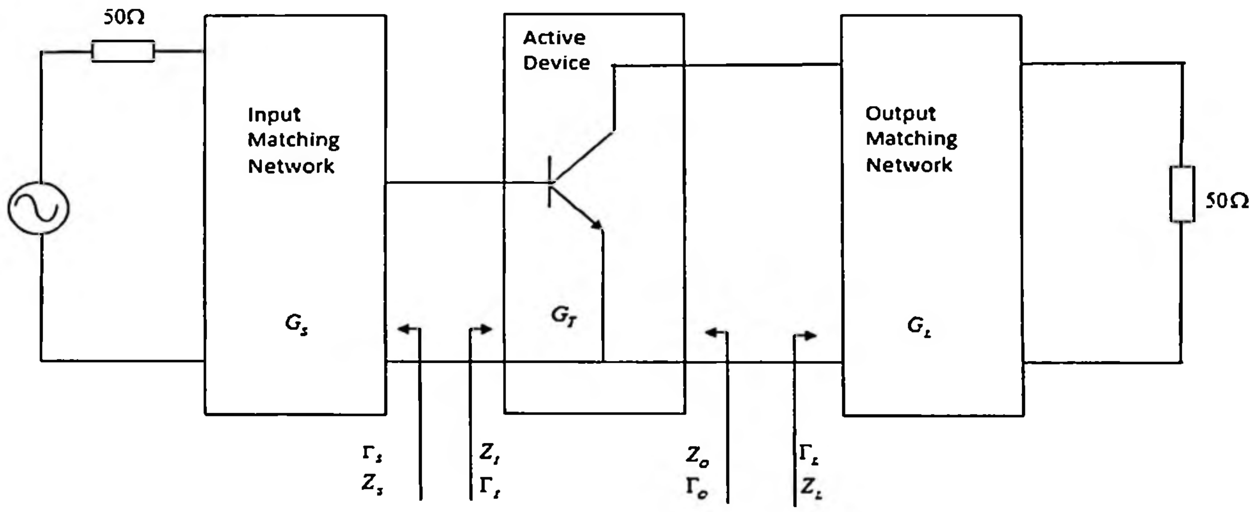

Figure 2-3 The RF amplifier block diagram depicting different gains

This can be expressed by the two-port S-Parameters by equations (2-12) and (2-13) [8]

$$G_T = \frac{(1-|\Gamma_S|^2)|S_{21}|^2(1-|\Gamma_L|^2)}{|1-S_{11}\Gamma_S|^2|1-\Gamma_O\Gamma_L|^2}, \tag{2-12}$$

$$G_T = \frac{(1-|\Gamma_S|^2)|S_{21}|^2(1-|\Gamma_L|^2)}{|1-\Gamma_I\Gamma_S|^2|1-S_{22}\Gamma_L|^2}. \tag{2-13}$$

where

$$\Gamma_I = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L}, \tag{2-14}$$

$$\Gamma_O = S_{22} + \frac{S_{12}S_{21}\Gamma_S}{1 - S_{11}\Gamma_S}. \tag{2-15}$$

2.2.5.3 Bandwidth

Bandwidth is defined by the difference between the low and high end of the operating frequencies. The bandwidth is very important in LNA design because different transistors have different bandwidth characteristics for different application. Some transistors are more suitable for narrowband design while others can be used for wideband design.

For the Wideband SDR Radio application, the LNA is ideally expected to give constant gain at 136-941 MHz (TIA-603C full spectrum), while maintaining low noise figure and high IIP3 for good receiver sensitivity. To ensure maximum power transfer between adjacent modules, the input and output ports should be matched to 50 ohms impedance.

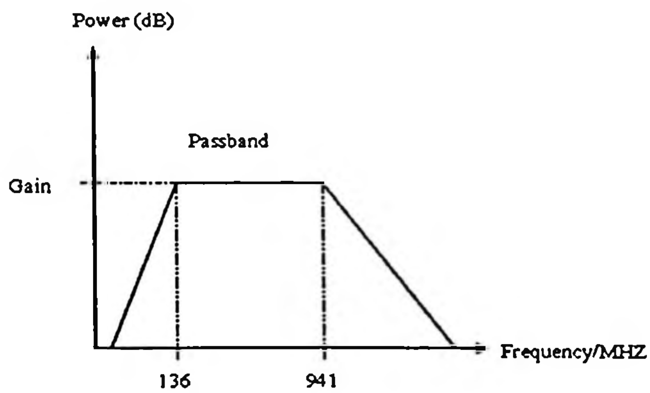

Figure 2-4 Ideal gain response of the wideband SDR LNA

2.2.5.4 DC Biasing Network

In the amplifier design, the DC bias network enables the selected transistor to be set at the desired working conditions. Normally, manufacturers include the S-Parameter and Noise Parameter tables of the transistor in the datasheet for multiple bias conditions. Specifically for FET, the transistor bias point can be used to control or tune the performance of the amplifier gain, *NF*, matching, and linearity by biasing the gate-to-source voltage of the transistor, (Vgs) and the transistor drain current (I_{ds}) at the suitable values. Apart from the datasheet, the transistor SPICE model can be used to provide the simulated transistor performance by using the CAD simulator. Examples of biasing topologies/techniques are the voltage divider, passive biasing, fixed-bias, current mirroring and active biasing. The importance of DC biasing is due to the cost per decibel of the RF amplifier (such as the LNA) gain or *NF* is very high in the communication system link, the LNA performance cannot afford to be degraded due to poor biasing.

2.2.5.5 Stability

The stability of an amplifier is very important, as it is the resistance of the amplifier from oscillation. If the LNA is not designed properly, it can behave as an oscillator at a certain frequency within the operating band. For small signal circuit design, the stability of the circuit can be determined by using the S-Parameters. Oscillations can occur in a two-port network when the input or output reflection coefficient is greater than unity. In a unilateral case amplifier, this can be translated as either $|S_{11}| > 1$ or $|S_{22}| > 1$.