UNIVERSITI PUTRA MALAYSIA

SOFTWARE-DEFINED INSTRUMENTATION FOR MICROWAVE NETWORK ANALYSIS MEASUREMENT SYSTEM INCORPORATING VIRTUAL CALIBRATION TECHNIQUE

MOHD NAZRIN BIN MOHD YASSIN

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By

MOHD NAZRIN BIN MOHD YASSIN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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May 2019

Chair : Shaiful Jahari Hashim, PhD
Faculty : Engineering

Network analysis field has existed for decades, but the most commercial analyzers were larger stand-alone benchtop instruments, expensive for individual investment, low volume of production, complex collections of multiple extra components, cables and support instruments. Today, the vector network analyzer (VNA) still considers a huge investment for education, small-medium industries, and researcher lab.

In this thesis, we make measurement evolution, delivering promising low-cost VNA measurement system based reconfigurable Software Defined Radio (SDR) platform. The main contribution of this research is the design of a low-cost reconfigurable VNA based on SDR platform using minimal components and utilize open source signal processing framework, GNU Radio software. The traditional method utilizing the GNU Radio relies on its GUI Sink module only were unable to extract baseband complex data immediately. A new methodology to perform data acquisition from the GNU Radio Software is developed in order to establish signal characteristic from SDRs.

This work was motivated by the possibility to realize a low cost and fast development cycle time implementation of VNA using SDR integrate with the test set components to define new terminology known as VNA of Software Defined Instrumentation (VNA-SDI). This VNA-SDI platform operates in the 70 MHz to 6 GHz range, and support channel bandwidths from 200 kHz to 56 MHz. The commercial mechanical calibration standard used to validate one-port calibration process applied on VNA-SDI. This proposes a measurement system is to replace the commercial VNA with a low-cost portable unit that can characterize, generate, transmit and receive signals, across a wideband with good repeatability and stability.

The performance of the measurement system is verified by showing that the Scattering parameters (S-parameters) of the one-port antenna as devices under test have closed an agreement to results from a commercial VNA within +/-10 dB offset.

The second contribution is introduced a method one-port self-calibration or known virtual calibration, which uses impedance emulation block to provided characteristic of OPEN, SHORT, and LOAD during performing calibration. This impedance emulation block was implemented on GNU Radio block to manipulate magnitude factor, phase offset and, phase delay. In consideration of the application, the proposed approach reduces the mechanical complexity of the calibration procedure significantly, by eliminating external calibration. This enables simplified automation of the measurement setup, thus to make VNA-SDI calibration faster, simpler, and easier than traditional mechanical calibration.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah.

PENGALATAN TEKTAKRIF PERISIAN SEBAGAI SISTEM PENGUKURAN ANALISIS RANGKAIAN VEKTOR YANG MENGABUNGKAN TEKNIK PENENTUKURAN MAYA

Oleh

MOHD NAZRIN BIN MOHD YASSIN

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Lapangan analisis rangkaian telah wujud sejak berabad lamanya, tetapi kebanyakan penganalisis komersial adalah alatan besar yang berdiri sendiri, terlalu mahal untuk pelaburan secara individu, pengeluaran yang rendah, pelbagai komponen tambahan yang kompleks, kabel-kabel dan alatan sokongan yang lain. Hari ini, penganalisisi rangkaian vector masih dianggap pelaburan yang tinggi bagi pendidikan, industry kecil-sederhana, dan makmal penyelidik.

Di dalam tesis ini, kami menghasilkan suatu evolusi pengukuran, petanda yang baik bagi sistem pengukuran analisis rangkaian vektor (VNA) berkos rendah berdasarkan Radio Tektakrif Perisian (SDR). Sumbangan utama penyelidikan ini adalah reka bentuk VNA yang boleh dikonfigurasi semula berkos rendah berdasarkan platform SDR yang menggunakan komponen yang sedikit dan gunakan rangka kerja pemprosesan isyarat sumber terbuka, iaitu perisian GNU Radio. Kaedah tradisional dalam penggunaan GNU Radio hanya bergantung kepada antara muka pengguna grafik sahaja tanpa mendapatkan data jalur asasnya secara langsung. Maka, satu pendekatan mendapatkan pemerolehan data daripada perisian GNU Radio telah berjaya dihasilkan sehingga lengkok cirian isyarat diwujudkan daripada SDR.

Kerja ini terdorong daripada kemungkinan merealisasikan VNA yang menggunakan SDR bersama komponen kelengkapan ujian untuk menghasilkan istilah baru yang dikenali sebagai VNA Peralatan Tektakrif Perisian (VNA-SDI) yang berkos rendah dan jangka masa pembangunan yang pendek. Platform SDR ini beroperasi didalam julat 70 Mhz sehingga 6 GHz dan menyokong saluran jalur lebar dari 200 kHz sehingga 56 MHz. Piawaian mekanikal penentukuran daripada peralatan komersial digunakan untuk

mengesahkan penentukuran satu-pangkal oleh VNA-SDI. Alatan sistem pengukuran yang dicadangkan ini mampu menggantikan VNA komersial dengan unit mudah alih berkos rendah yang boleh mencirikan, menjanakan, menghantar dan menerima isyarat merentas sepanjang jalur lebar dengan kebolehulangan dan kestabilan yang baik.

Prestasi sistem pengukuran ini disahkan melalui parameter serakan (S-parameters) hasil peranti di bawah ujian ke atas antenna satu-pangkal dimana keputusannya menyamai hasil keputusan dari VNA komersial didalam lingkungan +/-10 dB ofset.

Sumbangan kedua ialah memperkenalkan sebuah kaedah penenyukuran diri bagi satu pangkal atau dikenali sebagai penentukuran secara maya dengan menggunakan penghantar yang tersedia ada di atas papan platform untuk membekalkan ciri bagi BUKA, PINTAS dan BEBAN ketika melaksanakan penentukuran. Di dalam mempertimbangkan sebuah aplikasi, pendekatan yang dicadangkan ini akan mengurangkan kekompleksan mekanikal pada kaedah penentukaran secara nyata dengan menghapuskan penentukaran luaran. Ini membolehkan sebuah pengautomatikan diringkaskan ketika persediaan pengukuran, oleh itu menjadikan penentukuran VNA-SDI ini lebih pantas, ringkas dan mudah berbanding kaedah tradisional melalui penentukuran mekanikal.

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I certify that a Thesis Examination Committee has met on 24th May 2019 to conduct the final examination of Mohd Nazrin bin Mohd Yassin on his thesis entitled "Software-Defined Instrumentation for Microwave Network Analysis Measurement System Incorporating Virtual Calibration Technique" in accordance with the Universities and University Collage Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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Signature: ______________________

Name of Member of Supervisory Committee: Professor. Dr. Borhanuddin bin Mohd Ali

Signature: ______________________

Name of Member of Supervisory Committee: Associate Professor. Dr. Fakhrul Zaman bin Rokhani

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ADC	Analog to Digital Converter
ALU	Arithmetic Logic Unit
ARM	Advanced RISC Machine
ASCII	American Standard Code for Information Interchange
ASIC	Application-Specific Integrated Circuit
BW	Bandwidth
CAD	Computer Aided Design
CPU	Central Processing Unit
CW	Continuous Wave
DAC	Digital to Analog Converter
DMA	Direct Memory Access
dB	Decibels
DDS	Direct Digital Synthesis
DSP	Digital Signal Processing
DUT	Device Under Test
e_{00}	Directivity
e_{11}	Source Match
e_{10}	Reflection Tracking
FMC	FPGA Mezzanine Card
FPGA	Field Programmable Gate Array
GPP	General Purpose Processors
GRC	GNU Radio Companion
HDL	Hardware Description Languages

I	In-Phase
IF	Intermediate Frequency
IIO	Industrial Input Output
IMD	Intermodulation Distortion
LNA	Low Noise Amplifier
LPF	Low Pass Filter
LO	Local Oscillator
MIMO	Multiple Input Multiple Output
MSPS	MegaSamples Per Second
PA	Power Amplifier
PC	Personal Computer
PLL	Phase Locked Loops
Q	Quadrature
R&D	Research and Development
RF	Radio Frequency
RX	Receiving / Receiver
SDI	Software Defined Instrumentation
SDR	Software Defined Radio
SMA	SubMiniature Version A
SoC	System On Chip
S-Parameters	Scattering Parameters
TCP/IP	Transmission Control Protocol/Internet Protocol
TX	Transmitting / Transmitter
VDMA	Video Direct Memory Access
VNA	Vector Network Analyzer

VSA	Vector Signal Analyzer
VSG	Vector Signal Generator
VSWR	Voltage Standing Waveform Ratio
Z_0	Characteristic Impedance
Z_L	Load Impedance
Γ	Reflection Coefficient

CHAPTER 1

INTRODUCTION

1.1 Background

Software Defined Radio (SDR) is new technology being developed in the 21st century widely used in academic research [1-3], engineers [4], and test industry [5]. Recently, SDR approach for microwave instrumentation raised high attention since adaptability in different environments and very convenient for fast prototyping. The SDR transceivers are used in different instrumentation and measurement system from magnitude and phase measurement [6], an avionic system [7], and reference signals measurement [8].

SDR mainly dedicated to wireless communication but if the SDR used for instrument or microwave testing platform, the new terminology called as Software Defined Instrumentation (SDI). The SDI is a radical change from traditional box-style instruments, where its functionality defined by their hardware and limited software only, to instruments which are defined less by their hardware but more accessible to the software that is under user control [9]. Figure 1.1 shows the different physical structure between SDR and SDI. Antenna or wireless communications channel are the front end components entry, but in SDI, the devices under test (DUT) or wired cable are medium for measurement.

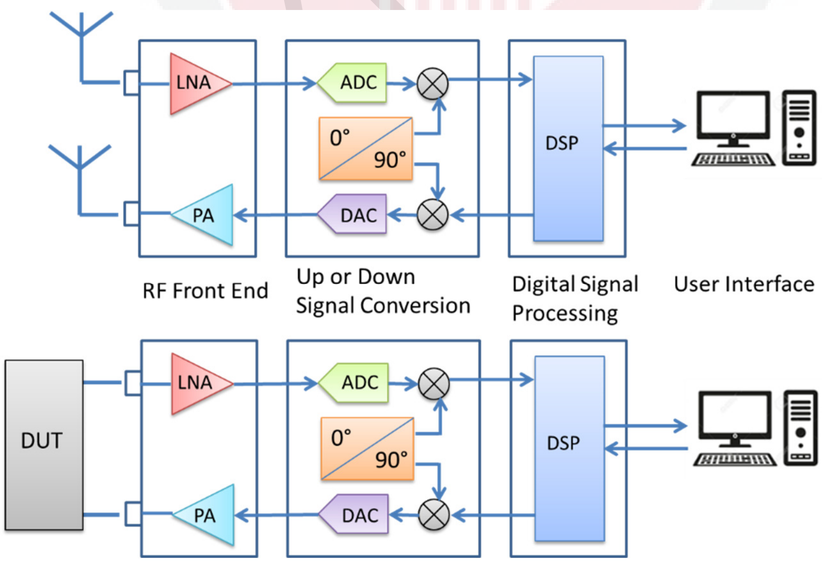

Figure 1.1: General Block Diagram of SDR (top) and SDI (bottom)

Three categories of conventional measurement equipment: benchtop boxes, modular and handheld type. The benchtop boxes instrument type used in laboratory and manufacturing test applications required static test location and at the same time, the device under test must bring to benchtop instrument port for measurement [10]. The modular type instrument is defined as the RF digitizer interfaces with processing software residing on the embedded controller at the host personal computer (PC). One of the examples this modular approach is Peripheral Component Interconnect extension for instrumentation (PXI) currently a proven PC-based platform for measurement and RF signal analysis [11]. Handheld instruments are low power utilization consumption and regularly utilized for testing devices in the field, but this instrument performs a limited set of measurements [12].

This work introduces a new category of SDI for vector network analyzer (VNA). The VNA is a high precision instrument to measure magnitude and phase signal properties from devices under test in the high frequency range. It is used in applications in various fields in research and development (R&D), product designers, manufacturing test engineers, brain tumour detection in biomedical [13] and material defect detection [14]. VNA measurements characterize active and passive RF components, such as an amplifier, filters, mixers, and antenna in any development applications, where relatively small and low power VNAs can be utilized. In production or testing, the VNA measurements are used to determine the selected device under test meets user or client specification.

The calibration of a VNA is essential for precise measurements to characterize devices under test. Numerous method calibrations were studied for N-port VNA [15-18] to acquire systematic error models. In the basic practice, the error terms can be derived from model equations by using a set of ideal standards or user-fabricated or user-defined standards. Finally, the measurement of DUT can be adjusted to show error-free measurement.

SDIs have developed as a promising approach for RF measurement or microwave instrument due to advantages in low-cost hardware and flexible software solutions. Instead of using fixed analog circuits, the latest SDI technology are implemented using computing engine, for example, broadly general-purpose microprocessor [19-20], digital signal processors (DSP) [21], FPGA or advances ARM processor [22]. This preferred of new processing engines, high level language such as Python is being utilized for post processing in an open source framework [23].

The test equipment market analysis for SDR form Frost and Sullivan shows the revenues in 2014 is $1.57 billion and expected to reach $2.83 billion in 2021[24]. This study obviously indicated the RF test equipment is most promising for the development, manufacture and testing area. Now the test equipment manufacturers have started to implement an instrument module using SDI techniques.

1.2 Related Works

Some previous work has been done with the low-cost SDR hardware but in order to complete the SDR/SDI environment, they still acquire commercial Computer Aided Design (CAD) software, for example, MATLAB and Simulink for DSP or communication system toolboxes [25-26]. This methodology appears to the researcher in computer science lost to demonstrate fundamental RF communication since they only apply a predefined block without understanding the detail operation involved.

Most of the SDR is intended for RF wireless communication [27-28], but there are some SDR implementation aims for RF measurement segments. In [4], Lime Microsystems' LimeSDR platform can be configured as scalar and vector measurement. In this implementation, they not demonstrate a full standard calibration procedure but only use a short standard for calibration. Consequently, the accuracy of measurement is not addressed in detail.

In [29], the researchers work on the implementation of SDR based microwave imaging system, which is built using a bladeRF SDR platform. The tunable frequency range is between 300 MHz to 3800 MHz with 28 MHz bandwidth and 12-bit Analog to Digital Converter (ADC) bit resolution. This paper is more focus on biomedical imaging application and limited VNA architecture has been discussed.

A low-cost VNA implementation many discrete components are presented [30] using Direct Digital Synthesizer (DDS), integrated detector, a STM32F4 processors General Purpose Input-Output (GPIO), many external switches and a customize PCB board. This non-integrated system may reduce accuracy measurement since many paths of the circuits contribute systematic error.

In [31], they introduced the concept of software-defined measurements (SDM) to validate the functionality of VNA using a vector signal generator (VSG) for up-conversion and a vector signal analyzer (VSA) for down-conversion of Intermediate Frequency (IF). The proposed SDM architecture required a solid-state switch in order the system utilizes an only single receiver. This configuration considers bulky and expensive since two main commercial RF instrument used to construct the complete network analysis system.

Phase measurement inconsistency highlighted in [32] when they implement a stepped frequency of Ground Penetrating Radar on USRP-X310 SDR. This is due the targeted hardware have a separate Phase Lock Loop (PLL) for the transmitter and the receiver. As a sequence, the phase coherent is very important especially design any instrumentation involved phase measurement like network analyzer.

An embedded auto-calibration method is presented in [33] used for VNA one port calibration. This electronic module comprises of switches, known calibration standards and thru transmission line. The actual implementation appears to be more on design external kits or fixture between VNA and measurement port, not the actually embedded calibration inside of VNA system.

1.3 Problem Statement

The fast and rapid changing in chip innovation in RF front-end conveys the need to design an RF application without hardware-software limitation on radios platform like SDR based. For clarity, the RF application can be deployed quickly on an SDR just updating functionality of RF scheme by software running on it without upgrading the hardware part [34].

To construct an RF measurement platform based on SDR technology, it must ready to support measurement operation in multi-domains signals properties in bandwidth, power and dynamic range. Not only concerns on RF domain, but the robust RF measurement also needs to be an open source [35] where measurement system design can meet minimum development time by the concept of software reuse. This facilitates the RF measurement system more scalability and compatible with new up and coming technology. This rise an idea of a concept of user-programmable and reconfigurable test instruments to testing and measurement field community which is previously they only depends to the stringent commercial instrument.

There is a tremendous barrier between the concept of an RF microwave signal and the implementation of SDR technology which is involved in many design entry, simulation, and validation. To minimize this barrier normally involves of researchers with multi-skill knowledge including RF microwave, the software-hardware programming language in DSP and FPGA or embedded Linux as well. The most well-known software that integrates analog and digital domain is MATLAB and Simulink [36-37]. These resources may troublesome for RF microwave researcher who lack in high level programming language and it is highly cost investment for small RF measurement manufacturer or newly researcher.

System on Chip is technology that combining different hardware components in the one integrated chip like Xilinx Zynq chip together with ARM processor and FPGA in the same chipset. However, developing any Zynq based applications must be using proprietary software, for example, Xilinx Vivado IDE [38-39] used to pin assignment, address register assignment, design communication drivers and developing the high-level application program to interact between user and system. This process is very tedious and consumes a lot of development cycle time because requires abilities and expertise on Hardware

Description Languages (HDL) and hardware interfaces which is less attractive for non-hardware RF designer.

The RF measurement instrument using application-specific integrated circuit (ASIC) based implementation require longer development cycle time for production and restricted hardware-software interaction or interface. This drawback in ASIC based design must replace with integrated circuit (IC) or processor chips are more affordable, less expensive, have many resources support, and equip with host target interfaces infrastructure [40].

Today, RF measurement instruments are closely identified to R&D segment, test product functionality and characterization new devices or components in the electronics industry [41]. To support this industrial demand, a proper measurement infrastructure must be characterized accurately. This infrastructure consists of the hardware itself, the device under test, and calibration procedures. However, development RF measurement especially network analyzer based on SDR platform appears to be less consideration from researchers since they more incline toward characterizing their DUT using commercial VNA.

VNA is a profoundly precision instrument used to measure the performance of circuits or networks such as antennas, amplifiers, filters, and cables. To obtain this type of instrument for individual investment is exceptionally costly because very expensive, a larger stand-alone benchtop instrument, complex collections of components, cables, and calibration kits [42]. The primary factor of high investment to get a VNA is coming from a combination of signal generator and measurement in one instrument together with the ability to sweep a wide frequency range. Consequently, there is demand for designing a compact, portable, less test set, low cost and ability to perform self-calibration are required for education [43], small-medium industries or researcher lab.

Calibration is crucial in any hardware instrument including VNA before actual measurement is measured. To perform a particular calibration, the VNA need some external high precision component called standard kit or fixture which as expensive if more exact and precise standard kits used. This type of calibration involved manual human interaction, time consuming and high potential for the wrong step during the calibration process. Another type of calibration is using automatic calibration units or ECal (Electronics Calibration) module to replace manual traditional mechanical standard calibration [44]. The drawback of this module is only supported for the new model of commercial VNA, selected VNA manufacturers and not compatible with industry standards SMA connectors [45]. The researcher needs to maximize reconfigurable of SDR features to emulate virtual standards calibration properties by changing impedances connected to SDI measurement system.

1.4 Thesis Objectives

This study aims to provide these three objectives are listed below:

1. To design an S-parameter measurement system on targeted SDI platform. The architecture of proposed SDI based on one-port measurement system which utilizes only two receivers that can operate up to 6 GHz frequency band, good isolation between transmitter-receiver chain, established good calibration technique and should to produced high repeatability and reproducibility.

2. To validate measurement system by measuring reflection coefficient of S_{11} and perform calibration on sample DUT. The system performance should be compared against existing commercial vector network analyzer, to show that the proposed system can qualify into practice.

3. To develop a new calibration technique as known as virtual calibration. This technique will utilize transmitters on board to emulate reflection wave of standard short-open-load to replace traditional one-port calibration procedure. The calibration should produce the comparison result with the existing calibration technique, improve accuracy and make calibration easier.

4. To validate and evaluate the functionality of virtual calibration by comparing result measurement on the same sample unit against results from objective number two. The result should show closed agreement performance in accuracy, standard deviation, and uncertainty estimation.

1.5 Scope of Thesis

RF measurement can be categorized into the linear and nonlinear measurement [46]. This study is focused on the small signal measurement or linear measurement which is no non-linear or large signal of devices considered as measurement data such as intermodulation distortion (IMD) or 1 dB gain compression. Therefore, the results show in this thesis is related to the magnitude and phase at the fundamental frequency. In this scope of work, the functionality of a VNA is selected for implemented using the concept of software-defined instrumentation known as VNA-SDI. The signal continuous wave (CW) generator and receiver are integrated into one platform and no additional RF measurement instrument required for the realization of proposes VNA based on SDI platform.

There are generally two architectures option to build VNA-SDI measurement system where the signal processing different in implementation path. The first architecture is to utilize FPGA where all DSP blocks are designed and instantiate into it. The second choice is to have host PC equips with General

Purpose Processors (GPPs) used to run GNU Radio signal processing computation that off-loads from the main SDR board [47]. In this work, all implementation or design entry completely on the host PC and this execution way most appropriate for rapid prototyping and fast cycle design development.

The targeted SDI is based on principle direct conversion receiver or homodyne receiver [48]. This type of conversion allows the RF frequency is being transmitted with the same frequency of LO for conversion to zero baseband I/Q signal frequency. Subsequently, fewer parts required to construct receiver and minimum cost as well.

The speed of measuring is not the main research because the processing baseband signals are done in remote PC which signals processing software run on the host PC itself. All post processing to display any kind of plot graph and calibration adjustment are compute in host PC, not in SDI itself.

The targeted SDI has two transceivers available on SDR platform. This limited hardware configuration delivered only reflection coefficient measurement S_{11}. Only SMA-based antenna used as a DUT while measuring the sample devices. This sample antenna is commercial dipole antenna from [49] where the optimal frequency ranges are between 1 GHz until 3 GHz only.

1.6 Summary of Research Methodology

There are three phases to executes the research methodology in this work as shown in Figure 1.2. The first phase is the design phase which is focused on the development of a reflection coefficient block and impedance emulation block where its implemented using GNU Radio. The next phase is implementation activities on the targeted hardware and software. The targeted hardware is RF Transceiver SDR which is consisting of Xilinx Zedboard and FMCOMMS2 board from Analog Devices. The final phase is the measurement phase. This part will verify the functionality of any design or scheme developed during the design phase by measuring a sample device under test.

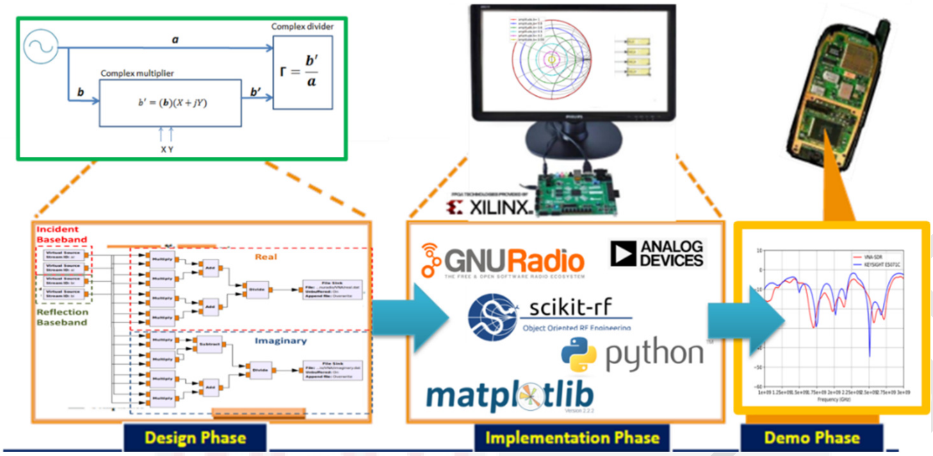

Figure 1.2: The Three Phases of Research Methodology

This research area can be specifically divided into several individual methodologies from RF domain to the digital domain as shown in Figure 1.3. In the RF domain, design the travelling wave path and waveform separation using discrete RF devices such as directional coupler and coaxial cable are necessary to connect device under test and transceiver SDR. In SDR hardware, identification and characterization of key parameters are needed to ensure the hardware is performing in optimum condition. For example, the maximum amplitude of CW or receiver gain value should be defined before this SDR can generate or receive RF signal correctly from the RF domain. Combination of SDR hardware and discrete components in the RF domain formed SDI hardware portion. In SDI software, all post processing and plotting graphical view are performed in host PC which connected to SDI hardware through Gigabyte Ethernet infrastructure. A user application runs on host PC is developed using Python programming language to prompt command to the user, write files, import open source package and plot a good graphical presentation of the measurement result. Finally, the integration of this SDI hardware and SDI software are established a new concept of VNA-SDI measurement system.

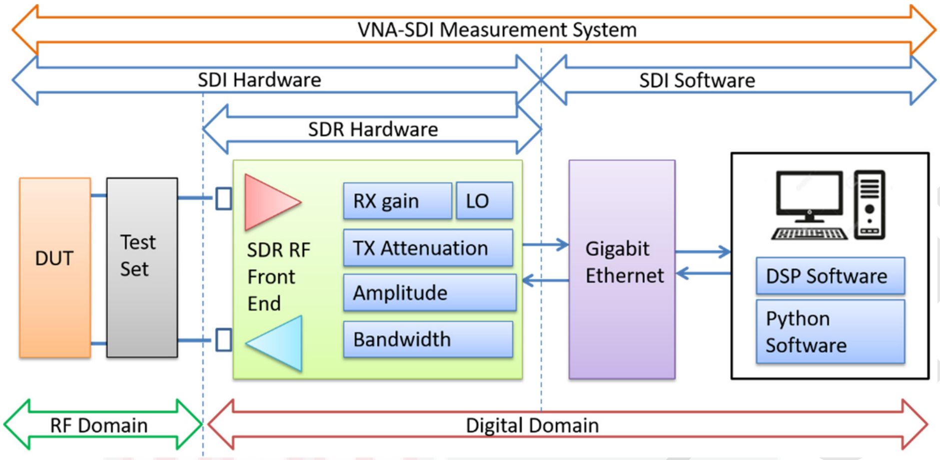

Figure 1.3: Block Diagram of VNA-SDI Measurement System

The research study area will focus on the left side of Figure 1.4 which design of network analyzer based on SDI technology as another classification of instrument type. The SDI is the main framework to propose a new concept and methodology for measuring key parameters of network properties, for example, gain, reflection coefficient, phase, and voltage standing waveform ratio (VSWR). This new concept of SDI also proposes a new technique of self-calibration where no external standards kit used after SDI allow a user accessing the any RF chain for baseband signal manipulation on sampling rate, amplitude CW, bandwidth, gain, Automatic Gain Controller (AGC) and local oscillator (LO). The best approach to reach and changes those RF chains are applying Python programming language as a bridge between an application programming interface (API) and RF hardware.

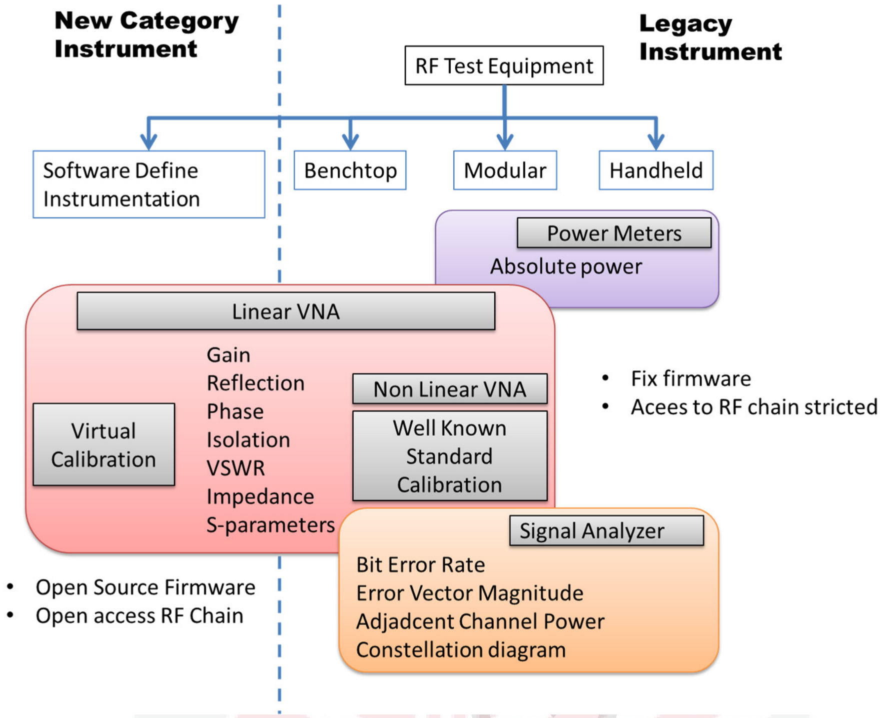

Figure 1.4: Study Area of Work

Current calibration kits available in any commercial VNA can divide into mechanical calibration or electronics calibration. Typically, a mechanical VNA calibration kit consists of the following set of standards from OPEN, SHORT, LOAD, adapters or waveguide [50]. Meanwhile, electronic calibration kits consist of a module that can electronically provide various impedance states to the VNA's test port. In this work, a new method calibration is proposed by the introduced the magnitude and phase impedance to compensate amplitude of traveling wave, thus a good precision and lower cost can be achieved as shown in Figure 1.5.

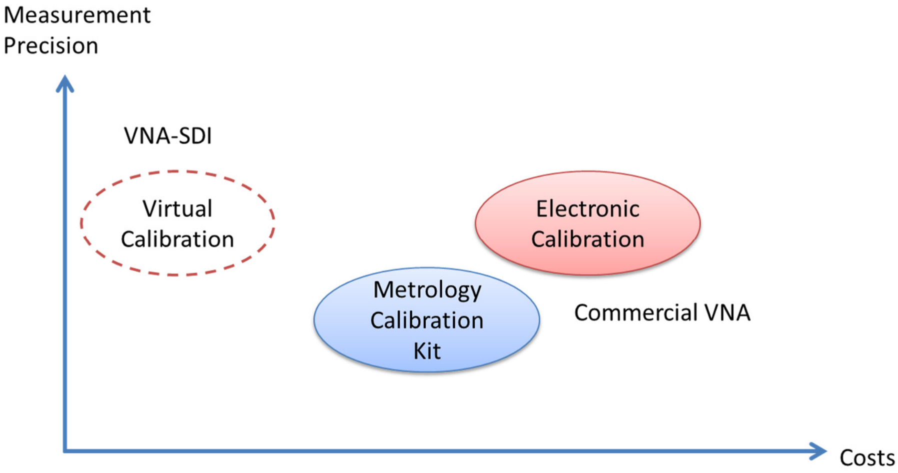

Figure 1.5: Calibration Type in VNA-SDI and Commercial VNA

Finally, the summaries methodology flow can be depicted in Figure 1.6 to achieve all the objectives of this thesis. The work starts with design a reflection coefficient block that implemented through GNR Radio software. Then, the realization of a complete SDI measurement system using the targeted board and discrete RF components are assembled. Mechanical calibration is applying in the following step before the S_{11} measurement is corrected and well match with the measurement taken from commercial VNA system. This validation process to ensure the implemented measurement system produces an almost similar response as a commercial measurement system.

The next flow is to design an impedance emulation block used to emulate virtual calibration. This successful design impedance emulation is very important so that the S_{11} measurement using virtual calibration is a similar response with the measurement taken from mechanical calibration.

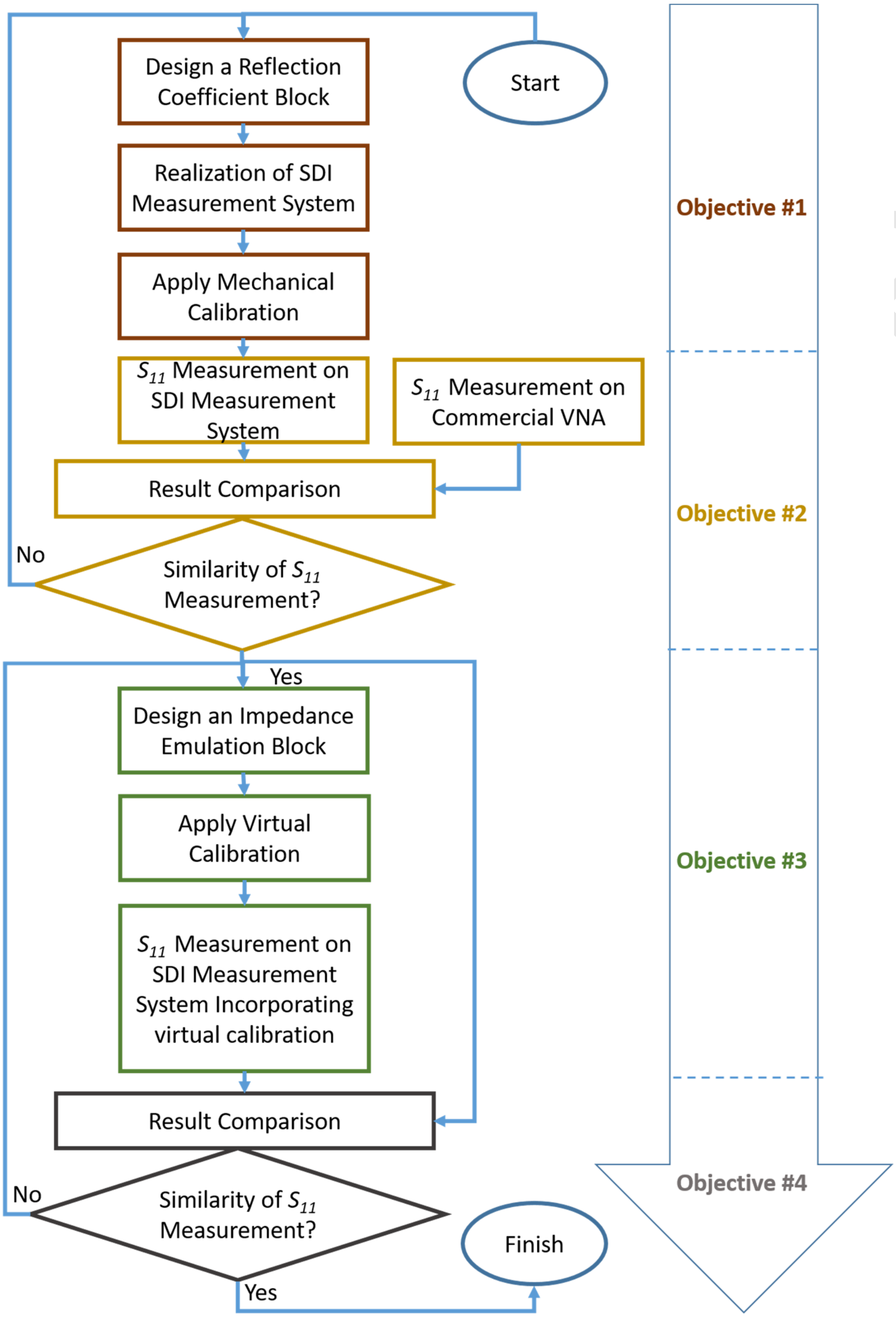

Figure 1.6: The Work Flowchart Methodology

1.7 Thesis Contributions

There are two main contributions of this thesis. The first contribution is the implementation of a low-cost SDI-based measurement system for network analysis. The definition of low cost in this project is not aiming for capital investment, but more on open source resources for signal processing in remote PC. On this contribution, the dependency on proprietary software and high-level hardware programming to design dedicated signal processing blocks are eliminated. Shorter design cycle time, shorter environment learning & minimum system development tools are the benefit. Researchers in microwave background can apply this advantage without fear they need to learn intensive hardware design in programming mode. Now someone can produce a high-end measurement product from off-the-shelf reconfigurable SDI for wideband VNA. A hardware testbed is presented for compactness, low complexity, networkability, mobility and field-deployable platform designed for data acquisition.

The second contribution is the further development and characterization of the reconfigurable calibration technique on SDR as an instrument measurement system. This study allows a VNA measurement system based on SDR technology to perform calibration without external standard kits which is necessary tools used for commercial VNA system. A new technique to emulate any impedance across the frequency band was implemented on SDI in a cost-efficient way. This technique generates standard characteristic in virtual calibration. Dependency on external calibration kits is eliminated, remove expensive well-known standards, and no human error during calibration.

1.8 Thesis Organization

The documentation of this thesis is organized into six chapters. This thesis is organized as follows. The second chapter will give an overview of the small signal RF measurement system. The chapter explains how the measurement of magnitude and phase of the signals will be defined namely S-Parameters. The general structure of VNA, the source of error, and the calibration method applied to give an overview of the research work. Finally, SDR technology for VNA implementation is presented with utilizing some open source software for baseband processing environment.

The third chapter focuses on the design of VNA based on targeted SDI platform. A new methodology to optimize the open source of digital signal processing software is contributed to this chapter. This technique then applies to SDI on how signal characterization is performed to ensure SDI limitation and capability generates CW signal and acquired valid data acquisitions. Implementation VNA on SDR based is presented with design transceivers and complex divider on GNU Radio software. Finally, the development of VNA-SDI

system capable to display multiple format data presentation such as magnitude, phase and Smith chart for user analysis and validation.
The fourth chapter describes the demonstration VNA-SDI measurement system that capable to perform calibration and produce the high accuracy of magnitude reflection coefficient measurement on the passive device under test. The commercial mechanical calibration standard from Anritsu calibration kit used to the realization of one-port S_{11} calibration in VNA-SDI system.

A new concept calibration using reconfigurable SDR is described in the fifth chapter. The concept of magnitude and phase manipulation is explained clearly when the magnitude and phase reflection coefficient emulation block is introduced. This chapter gives a new method of calibration without using external standard kits but utilizes on-board transceiver to emulate SHORT-OPEN-LOAD standard conditions.

Finally, the sixth chapter presents a summary of the results from the previous chapter as well as ideas on how these results can be used in the future.

REFERENCES

[1] R. J. Hartnett and P. B. Crilly, "Combining MATLAB® simulation with telecommunications instructional modeling (TIMSTM) in a senior level communications course," 2015 IEEE Frontiers in Education Conference (FIE), El Paso, TX, 2015, pp. 1-4.

[2] M. Petrova, A. Achtzehn and P. Mähönen, "System-oriented communications engineering curriculum: teaching design concepts with SDR platforms," in IEEE Communications Magazine, vol. 52, no. 5, pp. 202-209, May 2014.

[3] B. Uengtrakul and D. Bunnjaweht, "A cost efficient software defined radio receiver for demonstrating concepts in communication and signal processing using Python and RTL-SDR," 2014 Fourth International Conference on Digital Information and Communication Technology and its Applications (DICTAP), Bangkok, 2014, pp. 394-399.

[4] Travis F. Collins, Robin Getz, Di Pu, and Alexander M. Wyglinski, "Software-Defined Radio for Engineers," 2018, ISBN-13: 978-1-63081-457-1.

[5] J. Budroweit and A. Koelpin, "Design challenges of a highly integrated SDR platform for multiband spacecraft applications in radiation enviroments," 2018 IEEE Topical Workshop on Internet of Space (TWIOS), Anaheim, CA, 2018, pp. 9-12.

[6] D. N. Grujiá, P. Jovanović and M. Savić, "Using software defined radio for RF measurements," 2017 Zooming Innovation in Consumer Electronics International Conference (ZINC), Novi Sad, 2017, pp. 18-21.

[7] O. A. Yeste-Ojeda and R. Landry, "Software defined radio approach to distance measuring equipment," 2014 IEEE/ION Position, Location and Navigation Symposium - PLANS 2014, Monterey, CA, 2014, pp. 680-685.

[8] C. Andrich, A. Ihlow, J. Bauer, N. Beuster and G. Del Galdo, "High-Precision Measurement of Sine and Pulse Reference Signals Using Software-Defined Radio," in IEEE Transactions on Instrumentation and Measurement, vol. 67, no. 5, pp. 1132-1141, May 2018.

[9] T. Helaly and N. Adnani, "A new category of software-defined instrumentation for wireless test," 2016 IEEE AUTOTESTCON, Anaheim, CA, 2016, pp. 1-8.

[10] J. Teyssier, J. Dunsmore, J. Verspecht and J. Kerr, "Coherent multi-tone stimulus-response measurements with a VNA," 2017 89th ARFTG Microwave Measurement Conference (ARFTG), Honololu, HI, 2017, pp. 1-3.

[11] R. Martinek et al., "Modelling of wireless fading channels with RF impairments using virtual instruments," 2016 IEEE 17th Annual Wireless and Microwave Technology Conference (WAMICON), Clearwater, FL, 2016, pp. 1-6

[12] K. Will, T. Meyer and A. Omar, "Low-cost high-resolution handheld VNA using RF interferometry," 2008 IEEE MTT-S International Microwave Symposium Digest, Atlanta, GA, USA, 2008, pp. 375-378.

[13] J. Marimuthu, K. S. Bialkowski and A. M. Abbosh, "Software-Defined Radar for Medical Imaging," in IEEE Transactions on Microwave Theory and Techniques, vol. 64, no. 2, pp. 643-652, Feb. 2016.

[14] J. Moll, M. Manavipour, C. Sklarczyk, V. Krozer and C. Boller, "Millimeter-wave non-destructive testing of a cured in place pipe sample," 2013 38th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), Mainz, 2013, pp. 1-2.

[15] F. Verbeyst and M. Vanden Bossche, "Speeding up N-port VNA calibration eliminating one-port calibrations," 2013 European Microwave Conference, Nuremberg, 2013, pp. 448-451.

[16] J. Szatkowski and W. Wiatr, "Study of residual VNA measurement errors due to imperfect Thru-Reflect-Match calibration standards," 2018 22nd International Microwave and Radar Conference (MIKON), Poznan, 2018, pp. 664-667.

[17] U. Stumper and T. Schrader, "Calibration Method for Vector Network Analyzers Using One or Two Known Reflection Standards," in IEEE Transactions on Instrumentation and Measurement, vol. 63, no. 6, pp. 1648-1655, June 2014.

[18] R. A. Monsalve, A. E. E. Rogers, T. J. Mozdzen and J. D. Bowman, "One-Port Direct/Reverse Method for Characterizing VNA Calibration Standards," in IEEE Transactions on Microwave Theory and Techniques, vol. 64, no. 8, pp. 2631-2639, Aug. 2016.

[19] K. Tan, H. Liu, J. Zhang, Y. Zhang, J. Fang, and G.M. Voelker, “Sora: high-performance software radio using general-purpose multi-core processors”, Proceedings of the 6th USENIX Symposium on Networked Systems Design and Implementation, NSDI 2009, April 22-24, 2009, Boston, MA, USA

[20] G. Berardinelli, P. Zetterberg, O. Tonelli, A. F. Cattoni, T. B. Sørensen and P. Mogensen, "An SDR architecture for OFDM transmission over USRP2 boards," 2011 Conference Record of the Forty Fifth Asilomar Conference on Signals, Systems and Computers (ASILOMAR), Pacific Grove, CA, 2011, pp. 965-969.

[21] M. Bansal, A. Schulman, S. Katti, Atomix: a framework for deploying signal processing applications on wireless infrastructure, 12th USENIX Symposium on Networked Systems Design and Implementation (NSDI 15), (2015), pp. 173–188.

[22] X. Cai, M. Zhou and X. Huang, "Model-Based Design for Software Defined Radio on an FPGA," in IEEE Access, vol. 5, pp. 8276-8283, 2017.

[23] T. W. Mathumo, T. G. Swart and R. W. Focke, "Implementation of a GNU radio and python FMCW radar toolkit," 2017 IEEE AFRICON, Cape Town, 2017, pp. 585-590.

[24] https://ww2.frost.com/news/press-releases/high-flexibility-sdr-demands-enhanced-technology-breadth-test-equipment/

[25] M. Mishra, A. Potnis, P. Dwivedy and S. K. Meena, "Software defined radio based receivers using RTL - SDR: A review," 2017 International Conference on Recent Innovations in Signal processing and Embedded Systems (RISE), Bhopal, 2017, pp. 62-65.

[26] H. Hassan, C. K. H. C. K. Yahaya, N. Ahmad and N. I. S. Bakhtir, "Low complexity SDR transceiver design using Simulink, Matlab and Xilinx," 2012 International Conference on ICT Convergence (ICTC), Jeju Island, 2012, pp. 55-60.

[27] M. Kloc, R. Weigel and A. Koelpin, "SDR implementation of an adaptive low-latency IEEE 802.11p transmitter system for real-time wireless applications," 2017 IEEE Radio and Wireless Symposium (RWS), Phoenix, AZ, 2017, pp. 207-210

[28] Y. H. Lin, Q. Wang, J. S. Wang, L. Shao and J. Tang, "Wireless IoT Platform Based on SDR Technology," 2013 IEEE International Conference on Green Computing and Communications and IEEE Internet of Things and IEEE Cyber, Physical and Social Computing, Beijing, 2013, pp. 2245-2246.

[29] K. S. Bialkowski, J. Marimuthu and A. M. Abbosh, "Low-cost microwave biomedical imaging," 2016 International Conference on Electromagnetics in Advanced Applications (ICEAA), Cairns, QLD, 2016, pp. 697-699.

[30] J. Verhaevert and P. Van Torre, "A low-cost vector network analyzer: Design and realization," Loughborough Antennas & Propagation Conference (LAPC 2017), Loughborough, pp. 1-5.

[31] E. Zenteno, M. Isaksson, D. Wisell, N. Keskitalo and O. Andersen, "An envelope domain measurement test setup to acquire linear scattering parameters," 2008 72nd ARFTG Microwave Measurement Symposium, Portland, OR, 2008, pp. 54-57.

[32] C. H. J. Jenks and S. R. Pennock, "The use of a Software Defined Radio as an OFDM GPR," 2017 9th International Workshop on Advanced Ground Penetrating Radar (IWAGPR), Edinburgh, 2017, pp. 1-4.

[33] H. Xiaodong, Z. Wei and Y. Qing, "An embedded auto-calibration approach used in one-port calibration of VNA," 2013 IEEE 11th International Conference on Electronic Measurement & Instruments, Harbin, 2013, pp. 503-505.

[34] Sinha, Devarpita & Verma, Anish & Kumar, Sanjay. (2016). Software defined radio: Operation, challenges and possible solutions. pp 1-5.

[35] A. Bhatta and A. K. Mishra, "Implementation of GSM channel estimation using open-source SDR environment," 2015 International Conference on Microwave, Optical and Communication Engineering (ICMOCE), Bhubaneswar, 2015, pp. 322-325.

[36] A. B. Sergienko, "Software-defined radio in MATLAB Simulink with RTL-SDR hardware," 2014 International Conference on Computer Technologies in Physical and Engineering Applications (ICCTPEA), St. Petersburg, 2014, pp. 160-161.

[37] S. J. Upase and R. P. Labade, "Design and Implementation of Encrypted SDR and Study of Noise in High Level System Architecture Using MATLAB," 2018 International Conference On Advances in Communication and Computing Technology (ICACCT), Sangamner, 2018, pp. 197-202.

[38] D. O'Loughlin, A. Coffey, F. Callaly, D. Lyons and F. Morgan, "Xilinx Vivado High Level Synthesis: Case studies," 25th IET Irish Signals & Systems Conference 2014 and 2014 China-Ireland International Conference on Information and Communications Technologies (ISSC 2014/CIICT 2014), Limerick, 2014, pp. 352-356.

[39] Huan Li and Wenhua Ye, "Efficient implementation of FPGA based on Vivado High Level Synthesis," 2016 2nd IEEE International Conference on Computer and Communications (ICCC), Chengdu, 2016, pp. 2810-2813.

[40] Johannes Nehring, Ph.D. Thesis. Highly Integrated Microwave Vector Network Analysis Circuits and Systems for Instrumentation and Sensing Applications. FAU University Press, 2017.

[41] Frost & Sullivan. 2018 Global Radio Frequency Test & Measurement Market Leadership Award (https://about.keysight.com/en/newsroom/awards/frost-sullivan-2018-keysight-global-radio.pdf). Retrieved 20 February 2019.

[42] Keysight Technologies. Vector Network Analyzer. (http://literature.cdn.keysight.com/litweb/pdf/5989-7603EN.pdf) . Retrieved 23 March 2019.

[43] MiniCircuits. Microwave Transceiver Kit. (https://ww3.minicircuits.com/pdfs/UVNA-63.pdf). . Retrieved 19 December 2018.

[44] J. Stenarson, C. Eiø and K. Yhland, "A calibration procedure for electronic calibration units," 84th ARFTG Microwave Measurement Conference, Boulder, CO, 2014, pp. 1-6.

[45] M. Abramowicz and A. Lewandowski, "Electronic calibration unit for DC-8 GHz vector-network-analyzer measurements," 2016 21st International Conference on Microwave, Radar and Wireless Communications (MIKON), Krakow, 2016, pp. 1-4.

[46] Cam Nguyen.(2015). *Radio-Frequency Integrated-Circuit Engineering*. Wiley.

[47] Ryan L. Marlow. Master. Thesis. Making Radios with GReasy: GNU Radio With FPGAs Made Easy. (https://pdfs.semanticscholar.org/15ab/fe70496b1d026350f4425fef7a9bfab76e71.pdf) . Retrieved 2 December 2018.

[48] U.Sravani and G. Srivalli, "Direct Conversion RF Digital Receiver in L-Band for QPSK", International Journal of Research, Volume 04 Issue 08 ,July 2017

[49] Pulse electronics/Larsen antennas. LTE dipole (https://pulselarsenantennas.com/wp-content/uploads/2017/01/L118.pdf). Retrieved 2 Jun 2019.

[50] Tektronix. Introduction to VNA Basics. (https://download.tek.com/document/70W_60918_0_Tek_VNA_PR.pdf). Retrieved 12 December 2018.

[51] H.Matzner and S.Levy, "Experiment 2 - New Vector Network Analyzer Measurement," 2008. Retrieved 15 April 2018 form http://www.hit.ac.il/.upload/engineering/Experiment_2_-_New_Network_Analyzer.pdf

[52] National Instrument "Introduction to Network Analyzer Measurements Fundamentals and Background," Retrieved 20 September 2018 form http://download.ni.com/evaluation/rf/Introduction_to_Network_Analyzer_Measurements.pdf

[53] Michael Hiebel.2011. Fundamentals of Vector Network Analysis, pp.17. Germany: Rohde & Schwarz.

[54] G. Avolio, A. Raffo, V. Vadalà, G. Vannini and D. M. M. -. Schreurs, "Dynamic-Bias S-Parameters: A New Measurement Technique for Microwave Transistors," in IEEE Transactions on Microwave Theory and Techniques, vol. 64, no. 11, pp. 3946-3955, Nov. 2016.

[55] F. Caspers, "RF engineering basic concepts: S-parameters," Retrieved 20 September 2018 form https://cds.cern.ch/record/1415639/files/p67.pdf

[56] AS Aldoumani.2017. *Calibration Enhancement Of Non-Linear VNA System*, PhD Thesis, Cardiff University.

[57] S. Kurokawa, M. Hirose, Y. Toba, M. Onizawa and J. Ichijo, "Optical fiber link port extender for vector network analyzer," 2017 General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS), Montreal, QC, 2017, pp. 1-4.

[58] H. Chung, Q. Ma, M. Sayginer and G. M. Rebeiz, "A 0.01–26 GHz single-chip SiGe reflectometer for two-port vector network analyzers," 2017 IEEE MTT-S International Microwave Symposium (IMS), Honololu, HI, 2017, pp. 1259-1261.

[59] W. C. Black, "Power line S-parameter characterization using open-source tools," ISPLC2010, Rio de Janeiro, 2010, pp. 62-66.

[60] S. M. Mousavi, S. A. Mirtaheri, M. A. Khosravani-Moghaddam, B. Habibi and J. S. Meiguni, "Design, fabrication and test of a broadband high directivity directional coupler," 2015 23rd Iranian Conference on Electrical Engineering, Tehran, 2015, pp. 168-170.

[61] L.V. Govekar, P.C. Patil, and. Y.S. Rao, "Evaluation of SDR using open source technology," 2017 First International Conference on Information Technology, Communications and Computing (ICITCC 2017) 24-December-2017, Bhopal, M.P., India.

[62] McDermott, T. "A Low-Cost 100 MHz Vector Network Analyzer with USB Interface" 2004.

[63] Nosherwan Shoaib, 2017 "Vector Network Analyzer (VNA) Measurements and Uncertainty Assessment," 2017. pp.3

[64] PicoVNA 106 6 GHz Vector Network Analyzer .Retrieved 17 September 2018 form https://www.picotech.com/download/datasheets/picovna-106-vector-network-analyzer-datasheet.pdf

[65] U. Stumper, "Uncertainty of VNA S-parameter measurement due to non ideal TRL calibration items," in IEEE Transactions on Instrumentation and Measurement, vol. 54, no. 2, pp. 676-679, April 2005.

[66] Thilo Bednorz , “Measurement Uncertainties for Vector Network Analysis.”1996 Retrieved 17 September 2018 form https://cdn.rohde-schwarz.com/pws/dl_downloads/dl_application/application_notes/1ez29/1ez29_1e.pdf

[67] F. A. Mubarak and G. Rietveld, "Uncertainty Evaluation of Calibrated Vector Network Analyzers," in IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 2, pp. 1108-1120, Feb. 2018.

[68] Xiaoming Chen, "Statistical analysis of random errors from calibration standards," IEEE MTT-S International Microwave Symposium Digest, 2005., Long Beach, CA, 2005, pp. 4

[69] Keysight Technologies, “Applying Error Correction to Vector Network Analyzer Measurements” .Retrieved 17 September 2018 form http://literature.cdn.keysight.com/litweb/pdf/5965-7709E.pdf

[70] Anritsu ,“Understanding VNA Calibration ,” Retrieved 17 September 2018 form http://anlage.umd.edu/Anritsu_understanding-vna-calibration.pdf

[71] U. Stumper, "Uncertainties of VNA S-parameter measurements applying the Short-Open-Load-reciprocal (SOLR) calibration method," 2008 Conference on Precision Electromagnetic Measurements Digest, Broomfield, CO, 2008, pp. 438-439.

[72] J. Stenarson and K. Yhland, "Residual error models for the SOLT and SOLR VNA calibration algorithms," 2007 69th ARFTG Conference, Honolulu, HI, 2007, pp. 1-7.

[73] L. Hayden, "VNA error model conversion for N-port calibration comparison," 2007 69th ARFTG Conference, Honolulu, HI, 2007, pp. 1-10.

[74] H. Qin, W. Zhao, Chun-Hua Yuan, Li Qiang and Huo-Rong Ren, "An extended error model for the mutliport vector network analyzer," Proceedings of the 9th International Symposium on Antennas, Propagation and EM Theory, Guangzhou, 2010, pp. 760-763.

[75] D. K. Rytting, "Network Analyzer Accuracy Overview," 58th ARFTG Conference Digest, San Diego, CA, USA, 2001, pp. 1-13.

[76] Michael Hiebel.2011. Fundamentals of Vector Network Analysis, pp.111-113. Germany: Rohde & Schwarz.

[77] A. Rumiantsev and N. Ridler, "VNA calibration," in IEEE Microwave Magazine, vol. 9, no. 3, pp. 86-99, June 2008.

[78] M. Hirose and K. Komiyama, "A novel full 2-port calibration method for antenna measurements using sol standards without through procedure," CPEM 2010, Daejeon, 2010, pp. 329-330.

[79] J. Lee, "Modeling of SOL calibration standards for PCB channel probing," in IEEE Electromagnetic Compatibility Magazine, vol. 5, no. 4, pp. 123-127, Fourth Quarter 2016.

[80] M. D. DuFault and A. K. Sharma, "A novel calibration verification procedure for millimeter-wave measurements," 1996 IEEE MTT-S International Microwave Symposium Digest, San Francisco, CA, USA, 1996, pp. 1391-1394 vol.3.

[81] Rami Akeela, Behnam Dezfouli, “Software-defined Radios: Architecture, state-of-the-art, and challenges,” Computer Communications, Volume 128,
2018, Pages 106-125,

[82] J. Demel, C. Bockelmann and A. Dekorsy, "Evaluation of a software defined GFDM implementation for industry 4.0 applications," 2017 IEEE International Conference on Industrial Technology (ICIT), Toronto, ON, 2017, pp. 1283-1288.

[83] I-Chun Chao, K. B. Lee, R. Candell, F. Proctor, Chien-Chung Shen and Shinn-Yan Lin, "Software-defined radio based measurement platform for wireless networks," 2015 IEEE International Symposium on Precision Clock Synchronization for Measurement, Control, and Communication (ISPCS), Beijing, 2015, pp. 7-12.

[84] Avnet Electronics Marketing, Xilinx and Analog Devices Release Two Zynq-7000 All Programmable SoC/Analog Devices Software-Defined Radio Kits from https://news.avnet.com/press-release/avnet-electronics-marketing-xilinx-and-analog-devices-release-two-zynq-7000-all

[85] Functional Overview. Retrieved 13 June 2018 from https://wiki.analog.com/resources/eval/user-guides/ad-fmcomms2-ebz/hardware/functional_overview

[86] Di Pu, Andrei Cozma, and Tom Hill, “Four Quick Steps to Production: Using Model-Based Design for Software-Defined Radio (Part 1)”, 2015. Retrieved 13 April 2018 form http://www.analog.com/en/analog-dialogue/articles/using-model-based-design-sdr-1.html

[87] Mike Donovan, Andrei Cozma, and Di Pu, “Four Quick Steps to Production: Using Model-Based Design for Software-Defined Radio (Part 4)”,2015. Retrieved 13 April 2018 form http://www.analog.com/en/analog-dialogue/articles/using-model-based-design-sdr-4.html

[88] N. S. A. Arshad, S. Z. Ibrahim and M. S. Razalli, "Six-port demodulator in homodyne direct conversion receiver," 2014 2nd International Conference on Electronic Design (ICED), Penang, 2014, pp. 499-504.

[89] M. Osoba, J. Irvine, R. Stewart, D. Crawford and F. Westall, "DC Offset Mitigiation in Homodyne Receiver," 2005 5th International Conference on Information Communications & Signal Processing, Bangkok, 2005, pp. 613-617.

[90] M. Kong, J. Li and Wang Fengming, "Study on educational mode of Linux majors in colleges," 2010 International Conference on Artificial Intelligence and Education (ICAIE), Hangzhou, 2010, pp. 623-626.

[91] J. Muslimin, A. L. Asnawi, A. F. Ismail and A. Z. Jusoh, "SDR-Based Transceiver of Digital Communication System Using USRP and GNU Radio," 2016 International Conference on Computer and Communication Engineering (ICCCE), Kuala Lumpur, 2016, pp. 449-453.

[92] B. S. K. Reddy and B. Lakshmi, "Adaptive Modulation and Coding for Mobile-WiMAX using SDR in GNU Radio," 2014 International Conference on Circuits, Systems, Communication and Information Technology Applications (CSCITA), Mumbai, 2014, pp. 173-178.

[93] J. Unpingco, "Some Comparative Benchmarks for Linear Algebra Computations in Matlab and Scientific Python," 2008 DoD HPCMP Users Group Conference, Seattle, WA, 2008, pp. 503-505. doi: 10.1109/DoD.HPCMP.UGC.2008.49

[94] S. van der Walt, S. C. Colbert and G. Varoquaux, "The NumPy Array: A Structure for Efficient Numerical Computation," in Computing in Science & Engineering, vol. 13, no. 2, pp. 22-30, March-April 2011.

[95] N. Ari and M. Ustazhanov, "Matplotlib in python," 2014 11th International Conference on Electronics, Computer and Computation (ICECCO), Abuja, 2014, pp. 1-6.

[96] Arsenovic, A & Forsten, Henrik & Bauwens, Mathew & Eller, Michael & Sauber, Noah & Weikle, Robert. (2018). scikit-rf-Open Source Microwave Network Analysis and Calibration in Python.

[97] M. Magerl, T. Mandic and A. Baric, "Broadband characterization of SMA connectors by measurements," 2014 37th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO), Opatija, 2014, pp. 104-109.

[98] D. N. Grujiá, P. Jovanović and M. Savić, "Using software defined radio for RF measurements," 2017 Zooming Innovation in Consumer Electronics International Conference (ZINC), Novi Sad, 2017, pp. 18-21.

[99] E. N. Nishida, O. O. Dutra, L. H. C. Ferreira and G. D. Colletta, "Application of Savitzky-Golay digital differentiator for QRS complex detection in an electrocardiographic monitoring system," 2017 IEEE International Symposium on Medical Measurements and Applications (MeMeA), Rochester, MN, 2017, pp. 233-238.

[100] T. Pan et al., "Joint Optimization of Savitzky-Golay Smoothing Modes and PLS Factors Was Applied to Near Infrared Spectral Analysis of Serum Cholesterol," 2010 4th International Conference on Bioinformatics and Biomedical Engineering, Chengdu, 2010, pp. 1-4.

[101] K. Vachhani and R. A. Mallari, "Experimental study on wide band FM receiver using GNURadio and RTL-SDR," 2015 International Conference on Advances in Computing, Communications and Informatics (ICACCI), Kochi, 2015, pp. 1810-1814.

[102] Y. P. Saputera, M. Wahab and Y. Wahyu, "Linear frequency modulation - continuous wave (LFM - CW) radar implementation using GNU radio and USRP," TENCON 2015 - 2015 IEEE Region 10 Conference, Macao, 2015, pp. 1-5.

[103] H. Miyashiro, M. Medrano, J. Huarcaya and J. Lezama, "Software defined radio for hands-on communication theory," 2017 IEEE XXIV International Conference on Electronics, Electrical Engineering and Computing (INTERCON), Cusco, 2017, pp. 1-4.

[104] Touchstone® File Format Specification Version 2.0 , Ratified by the IBIS Open Forum April 24, 2009 https://ibis.org/touchstone_ver2.0/touchstone_ver2_0.pdf

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LIST OF PUBLICATIONS

Journals:

M.Nazrin, S.J Hashim and Z.Yusoff, “Off-the-Shelf Reconfigurable Software Define Radio Approach for Vector Network,” Journal of Applied Technology and Innovation (e-ISSN: 2600-7304) vol. 2, no. 2, (2018).

M. Nazrin, S. J. Hashim, F. Z. Rokhani, Z. Yusoff, (2018). “Error correction and uncertainty measurement of short-open-load calibration standards on a new concept of software defined instrumentation for microwave network analysis”. Accepted to Journal of Measurements in Engineering.

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