GSOC 2014: Vector Network Analyzer (VNA)

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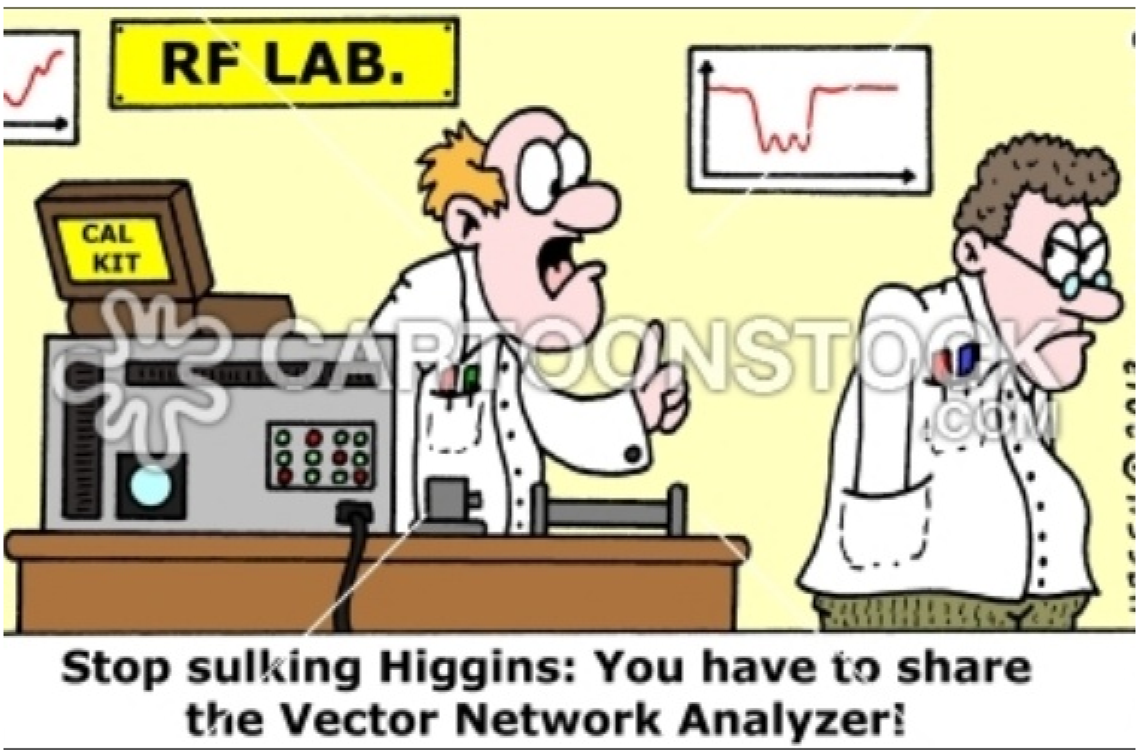

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Abbreviation

DUT	Device Under Test
FFT	Fast Fourier Transform
IF	Intermediate Frequency
LO	Local Oscillator
MIMO	Multiple Input Multiple Output
RF	Radio Frequency
RX	Receiver
SWR	Standing Wave Ratio
TX	Transmitter
UHD	USRP Hardware Driver
USRP	Universal Software Radio Peripheral
VNA	Vector Network Analyzer

Introduction

Don't confuse the name Vector Network Analyzer with "computer networks". VNA has nothing to do with computer networks – it's totally different thing. VNA is useful to measure important parameters of electrical network. At high frequency; it is not possible to monitor voltage and current for measure h or z parameters. So instead s parameters are used. VNA is useful in measurement of S-parameters.

Working principle of VNA

At high frequency, behavior of device is quite different. When a stimulus signal is applied to the device, some part of signal will travel through the device (transmitted signal) and some part will reflect back.VNA measure transmitted and reflected signal accurately. There are mainly three blocks of VNA i.e. source, detector and analyzer module.

Source

The pure tone sinusoidal wave is generated by VNA. It generates the stimulus to the DUT. It may either frequency sweep or power sweep source [1]. For GSOC - I am restricting myself with frequency sweep source only. The minimum and maximum frequency of source will determine the range in which the DUT should operate. Under this range the source should be stable and introduce as low as possible harmonics.

Detector

The heterodyne receiver down converts the RF frequency to fixed IF frequency. Harmonics associated with source are also down-converted, but they'll be outside the passband of IF filter. A narrow band IF filter will reject the noise outside the passband of filter. This will improve the sensitivity and dynamic range of VNA. Other methods to improve dynamic range are explained in later part of the document.

Analyzer module

The analyzer module receives the transmitted and reflected signal along with reference signal. It will detect the phase difference of incoming signal and reference signal. From this information scattering parameters are calculated. It is possible to calculate Return loss, SWR, Reflection coefficient, Impedance, Insertion loss, Transmission coefficient from S-parameters [2]. Discussion of which is out of the scope of this proposal. Output from analyzer module will be given to the display.

The final arrangement will look like figure 1 [1]. Where A, B and R are reflected signal, transmitted signal and reference signal respectively. The power splitter splits the power in two branches – one of which will be given to DUT while another is used as reference signal. Transfer switch is used to automate the four S-parameter measurements. It changes the direction of reflected and transmitted signal.

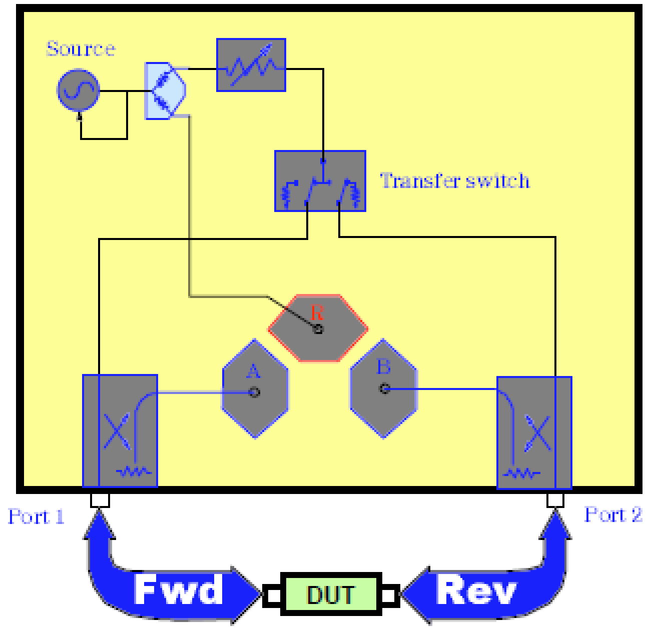

Figure 1 Block diagram of VNA

GNU Radio and USRP

GNU Radio is open source software which is based on dataflow model. It provides powerful modules for advance signal processing. USRP is good hardware solution for developing quick prototype of algorithms in hardware. Using gr_uhd of GNU Radio; one can interface with USRP devices. For this project USRP B210 is suitable because it has wide frequency range from 70 MHz to 6 GHz which provides stable signal source for VNA, 2X2 MIMO capability and coherent detection of transmitted and received channel [3]. At least two receiving channel is needed for the design of VNA (explained later in this document)

Work during GSOC 14

Device setup

The actual implementation of VNA will be a little different from arrangement shown in fig 1. The VNA shown in fig 1 has three receiver channels, but USRP B210 has only two. A solution is depicted in fig 2. Using RF switch to choose between transmitted and reflected signal, simultaneous measurement of S_{11} and S_{21} is possible.

As shown in fig 2 terminating DUT with matched load will guarantee that reflections from that port will be at its minimum. Similarly to get other two parameters - S_{22} and S_{12}, simply interchange the connection with the device and repeat the measurement.

Using the S-parameters - Return loss, SWR, Reflection coefficient, Impedance, Insertion loss, Transmission coefficient can be calculated. Derivation of these parameters using S parameters is out of the scope of this proposal.

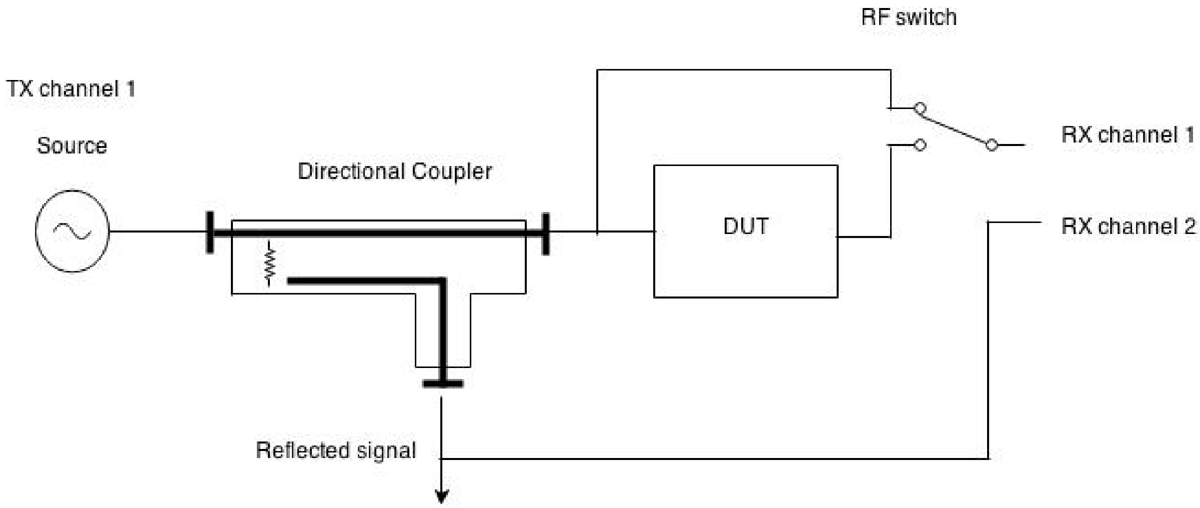

Figure 2 Block diagram of proposed VNA using USRP

Magnitude and Phase measurement

The main difference between spectrum analyzer and VNA is phase measurement. Phase information is crucial part of VNA. So, a signal processing block **measure_phase_diff** will measure phase difference between transmitted/reflected signal and reference signal. To cover frequency range from 70MHz to 6GHz, LO frequency must be sweep for signal generator (TX channel) and signal receiver (both RX channels). **usrp_spectrum_sense.py** provides good understanding about frequency sweeping and IF bandwidth control. How IF bandwidth affects dynamic range of VNA is explained later.

Calibration

There are several methods available to calibrate VNA like TRM, TRL, SOLT etc [4]. I am proposing SOLT (Short, Open, Load, Through) method. SOLT method is easy to perform and removes directivity error, source mismatch error and Tracking error. A conventional way to perform measurement is to calibrate device first then connect DUT or user can perform the test first save data file and then perform calibration. Based on calibration result, user can calibrate the data collected beforehand. So a python script **calibrate_frm_file.py** will be useful for this purpose.

Display result

GNU Radio does not have support for Smith Chart. Smith chart is useful to display S – parameters (S_{11}, S_{12}, S_{21} and S_{22}), Input impedance, SWR and reflection coefficient. Along with smith chart it will display parameters like Gain, Insertion loss, Return loss, Group delay etc. **freq_sink_f_impl.cc** will be useful to design gui for smith chart. Code to plot smith chart using qt is available here. Another way to plot graph is taking data from file like **gr_plot_fft.py** does.

Dynamic range improvement

Dynamic range defines the difference of the highest and the lowest power level measurement capability. There are three ways to improve dynamic range of VNA: exponential averaging, reduction of IF bandwidth and increasing in input power [5]. Though there is a tradeoff between improving dynamic range and system speed. For this reason all three parameters will be user controllable. So as per the application requirement user can choose between measurement speed and dynamic range.

Future scope

The proposed project only measures two parameters at a time. To measure all four parameters, one has to disconnect the DUT and reverse the connection and perform the experiment. This can result in systematic errors. To achieve fully automatic measurement, two USRP B210 with switch and two directional couplers can be used as shown in fig 3. Now with four receiver channel simultaneous measurement all S parameters are possible [1].

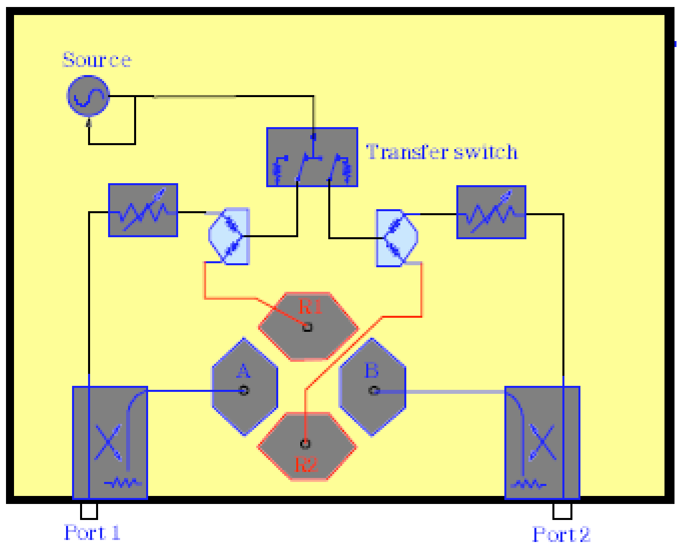

Figure 3 Block diagram of VNA with four ports

However this is not a part of gsoc project.

Deliverables

- **gr_vna:** out of the tree module using gr_modtool.
- **gr_phase_detect_vcf:** signal processing block that detects phase difference between input signal and reference signal.
- **basic_tests_vna.py:** Test bench without any external RF hardware to make sure that phase detection algorithm is working well.
- **smithchart_sink:** qt gui to display result of S parameters.
- **calibrate_vna.py:** perform SOLT calibration and save data to file.
- **calibrate_frm_file.py:** to calibrate data saved in file.
- **plot_smith_chart.py, plot_scatter_para.py, plot_insertion_loss.py, plot_impedance.py, plot_swr.py:** utilities for plotting smith chart, reflection coefficient, phase etc from file.
- **usrp_vna.py:** final script that integrates all blocks and performs measurement.
- Comparison of results with VNA available in college laboratory.

- Documentation and examples.

Timeline

- **Before GSOC (21st April, 2014 to 18th May, 2014):** Get to know the mentor. Learn more and more about VNA – the theory behind the calibration, mathematical equations for it. Familiarized myself with USRP B210 board and RF components.
- **Week 1:** get hands on USRP B210. Practice couple of programs to familiarize with USRP board. Setup device as shown in figure 2
- **Week 2 & 3:** phase detection signal processing block, Test bench for amplitude and phase detection
- **Week 4 to 6:** methods for improving dynamic range i.e. exponential averaging, input power and IF bandwidth control; preparing for midterm evaluation
- **Week 7 to 9:** calibration of VNA
- **Week 10:** write application programs to plot smith chart, s-parameters, insertion loss, impedance, swr etc. using data from file
- **Week 11 & 12:** usrp_vna.py by integration of all blocks
- **Week 13:** perform test on various devices available. Prepare documentation and comparison of results with VNA available in university

Personal Background

I am final year under graduate student of Electronics and Communication at Nirma University, India. I worked with VNA in the past during lab sessions. It amazes me how these instruments work. That's my motivation to choose this project. I came across GNU Radio during my third semester when I was studying Digital signal processing using Matlab. Right now I am doing internship at National Instruments which will be finished on 28th March, 2014. During the internship I learned many things about NI's USRP platform. I am looking forward to work with Ettus research's USRP kit.

I have good experience of coding using C, C++ and shell script. During last semester, I also designed ECG machine using Beaglebone running angstrom OS, Linux device drivers and QT gui. So, I am comfortable with Linux environment and programming.

Conclusion

VNA is considered as most delicate and awesome device among some RF engineers. This proposal shows the fundaments to software defined radio into VNA. With wide frequency span of USRP B210, advance calibration methods and methods to improve dynamic range – VNA made out of USRP can sure compete some VNA available in market. Besides that student can get chance to have VNA at their hands as well as continue to contribute in the field of software defined radio, too.

Components required

- USRP B210 board
- Directional coupler
- Power splitter
- Co-axial cable
- Filter for testing
- Calibration kit

Reference

1) Agilent Network Analyzer Basics, August 31, 2004.
2) Reflection coefficient transformation, January 26, 2005.
3) USRP B210, Ettus Research.
4) Vector Network Analzer calibration : The Basics, White Paper, Rohde and Schwarz,2008.
5) Understanding and Improving VNA dynamic range, Application note 1363-1, Agilent