sciendo

DOI: 10.2478/ijasitels-2024-0002

Implementation of SDR as a Vector Network Analyzer: Methodology, Configuration, and Software Insights

Fabian Török[1],

[1]*Department of Computer Science and Electrical Engineering, Lucian Blaga University of Sibiu,4 Emil Cioran, Str., 550025, Sibiu, Romania*

fabian.torok@ulbsibiu.ro

Abstract

Software-Defined Radios (SDR) offer unparalleled reconfigurability across a wide frequency spectrum, making them versatile tools in the RF domain, especially when capable of simultaneous data transmission and reception. This adaptability positions SDRs as cost-effective universal RF measurement devices. Leveraging these advantages, this article explores the utilization of an SDR as a Vector Network Analyzer (VNA), emphasizing an offset tuning measurement approach to mitigate negative effects inherent in SDR architectures. The research places particular attention on the software and measurement aspects of SDR-based VNA, distinguishing itself from existing recent research that predominantly concentrates on hardware setup and calibration. The study refines and generalizes existing approaches while presenting a universal methodology for VNA realization, for any SDR architecture with at least 1 full duplex transmit and receive port. By addressing the often-overlooked software aspects and proposing a novel measurement approach, this research provides a foundation for implementation, with the potential to significantly contribute to the evolution of SDR-based RF measurement methodologies.

Keywords: Software-Defined-Radio, Vector-Network-Analyzer, Configuration, Offset-Tuning

1 Introduction

VNAs characterize network properties in function of frequency using Scattering-Parameters (S-Parameters). These S-Parameters describe how signals of different frequencies are amplified/attenuated and their phase shifted when passing through a network. Vector-Network-Analyzers have come a long way since their initial appearance on the market in the 1960s [8]. However, they still remain pricy pieces of measurement equipment, as standalone entry price models from reputable manufacturers (e.g.: Rohde & Schwarz, Keysight) with a relatively low frequency bandwidth start above 5000€. The price of higher-performance VNAs can easily rise into the tens of thousands of euros [1].

In recent research SDRs have been utilized to realize functionalities of multiple types of measurement equipment, such as Spectrum Analyzer [11], [10]; Optoelectronics [14]; as well as VNA [16], [13], [12]. This proven versatility of Software-Defined Platforms enables them to be used as universal low-cost measurement equipment. The added value in this case is not that the SDR achieves more precise measurements than

the dedicated alternatives, but that it can be easily reconfigured to replace several measuring devices. The savings potential of a universal SDR measuring device is therefore enormous.
This article explores the implementation of a VNA using a SDR with particular attention to the configuration of the SDR and the methodology of the measurement with the software aspects involved. While the measurement approach in its essence is valid for any SDR with at least one transmit and receive full duplex ports, the LimeSDR mini is utilized as an example SDR model. Initially some SDR fundamentals are discussed and the features of the LimeSDR mini are presented. Subsequently additional hardware components, as well as the calibration of the system is discussed. This section is kept rather short, as other recent research covers this sufficiently [13], [12]. Finally, considerations for the SDR configuration is presented, taking into account the settings of the sample rate, transmit power levels, adequate tuning of receive power, filter settings as well as the interpretation of I/Q data to obtain a measurement with as little noise as possible. As the approach of a SDR VNA is not yet commercialized [8], the known weaknesses of the heterodyne and homodyne SDR architectures are mitigated in the proposed measurement method.

2 SDR Theory and Example SDR Used

2.1 SDR Theory

The basic principle behind SDR is to digitalize the signal processing of signals as near to the antenna as possible in a functional sense. The ideal SDR would consist of an antenna, and Analog-Digital-Converter (ADC) and a processing unit in which signal processing is executed. Due to sample rate limitations in currently available ADCs this is not practical. The typical receiving frequency range of such a system would range from 9 kHz to 55 MHz when respecting Nyquist's sampling theorem. Thus, additional analogue frontend RF hardware, usually pre-selector filters, I/Q mixers, and optionally frequency converters are required to extend the operation range [9].
Two established SDR architectures are the heterodyne and homodyne architectures. The heterodyne architecture, schematically depicted as a receiver in Figure 1, performs frequency conversion in two stages, where the first conversion stage converts the signals to an intermediate frequency (IF) band. The second stage converts the signals to baseband using an I/Q mixer. In comparison to the homodyne architecture, the heterodyne architecture may achieve superior filter selectivity, system sensitivity and system stability. In contrast to the heterodyne architecture, the homodyne architecture directly down converts signals to baseband and thereby features no IF frequency. This architecture is therefore often also referred to as Zero-IF. Figure 2 depicts this architecture for the receiver side. Generally, this architecture allows for a smaller form factor, lower cost, power consumption and a better image rejection ratio due to a single mixer stage [2]. Both SDR architectures struggle to varying degrees with LO Leakage which manifests itself as a DC Offset, observable as a spike at 0 Hz in the frequency domain. Image rejection techniques are required for both architectures, as the mixers involved in frequency conversion generate images from the signals to be transmitted or received. [9].

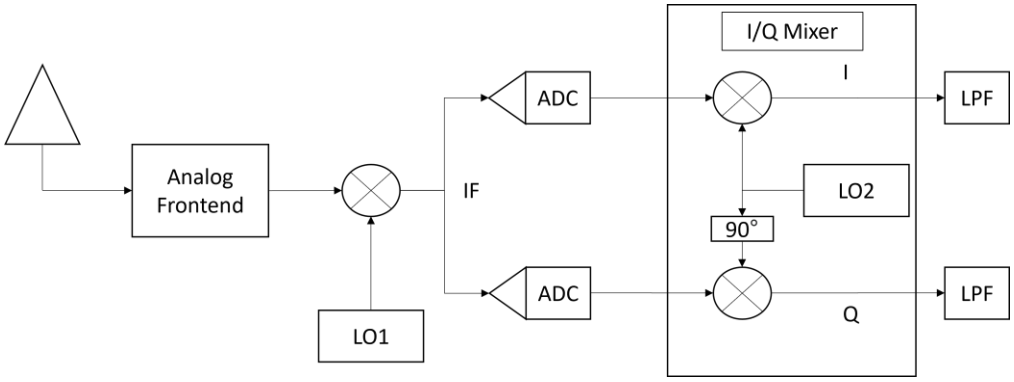

Figure 1 Heterodyne Receiver Architecture

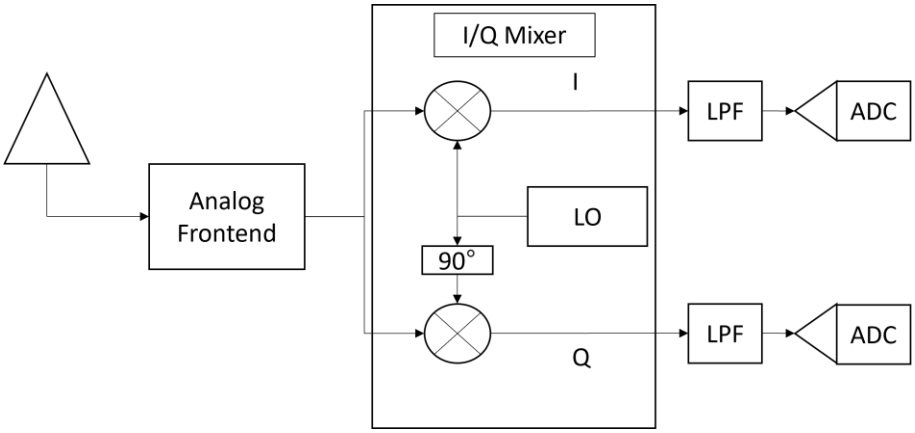

Figure 2 Homodyne Receiver Architecture

2.2 Example SDR

The example SDR referred to in this article is the LimeSDR mini v1. It based on a homodyne architecture, features a frequency range from 10 MHz to 3.5 GHz, a maximum sample rate of 30.72 MHz and a 12-bit ADC operating with up to 0.8 Vpp. It features one receive port and one transmit port which can be tuned independently of each other [17].

3 Hardware Setup and Calibration

While S_{21} and S_{12} measurements can be made in straight forward fashion by connecting the device under test (DUT) between the SDR transmit and receive port as shown in Figure 3, S_{11} and S_{22} measurements require additional hardware as they measure the reflected wave from the DUT [8], [13]. A directional coupler used as a reflectometer is used to measure the reflected wave from the DUT as seen in Figure 4. A 10dB attenuator can be added to reduce variation in impedance [12].

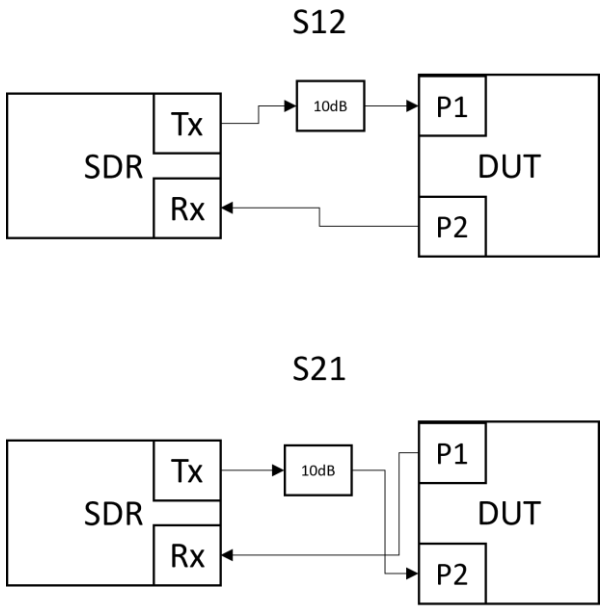

Figure 3 Hardware Setup for S12 and S21 Measurements

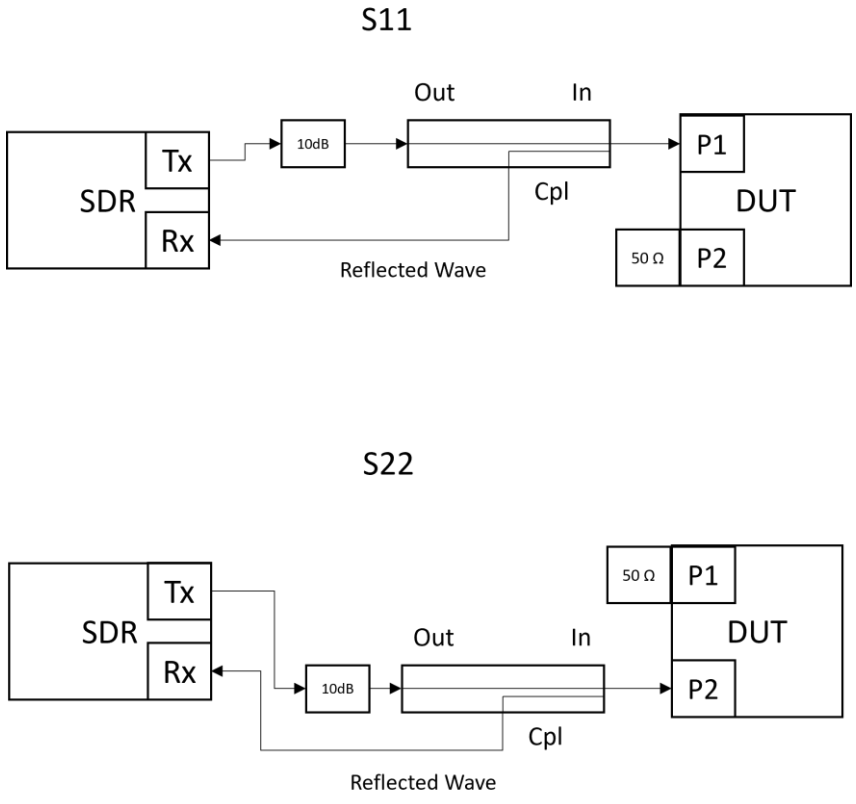

Figure 4 Hardware Setup for S11 and S22 Measurements

Calibration is a necessary operation that should be conducted before executing measurements. It captures changes which are induced by additional hardware components in the measurement setup and age-related degradation in the active components of the system. [15] A fleshed out SDR VNA should include an automated calibration routine. This however is not subject of this article. In terms of calibration recent research has found the application of the Short-Open-Load (SOL) [12] and

Through-Reflect-Line (TRL) [13] calibration standards to be accessible and effective calibration methods for a SDR VNA.

Alternatively, a commercial RF measurement equipment such as a power meter or spectrum analyzer can be used to calibrate the SDR VNA. It is important to note that two calibrations must be conducted: One for S_{12} and S_{21} measurements, and another for S_{11} and S_{22} measurements.

For the calibration of S_{12} and S_{21} measurements, the SDR should transmit the same signal that will be used for measurements. The calibration needs to be done in steps over the whole frequency range intended for measurements. The steps size can be chosen in function of the desired frequency accuracy of the SDR VNA. The RF measurement equipment of choice is used to receive the power level and phase of the signal instead of the SDR receive port. Instead of the DUT the two harnesses can be connected using an appropriate adaptor (this however will induce a small error into the calibration), or the calibration can be done twice: For the equipment between transmit port and the DUT, and once for the equipment between the DUT and the receive port.

For the calibration of S_{11} and S_{22} measurements, the same signal type as described above must be used. The calibration must be conducted once from the SDR transmit port to the DUT, with the coupled port of the directional coupler being terminated with a 50 Ω termination. The calibration must then be conducted with the SDR transmit port being connected instead of the DUT and the signal measured at the coupled port of the directional coupler. Here as well, all unconnected ports must be terminated with a 50 Ω termination. These two calibrations together characterize the path for the S_{11} and S_{22} measurements.

The obtained attenuations and phase shifts from the calibration measurements can then be interpolated in function of the frequency steps and the resulting calibration graphs or functions must be stored as they need to be available for further use in the software during measurements.

It is worth noting that most SDRs also offer internal calibration options to minimize the receive and transmit DC spike and to increase image rejection as shown in Figure 5 and Figure 6. An example how this is done for LimeSDR using phase and gain correction of the I/Q signals is shown in [3].

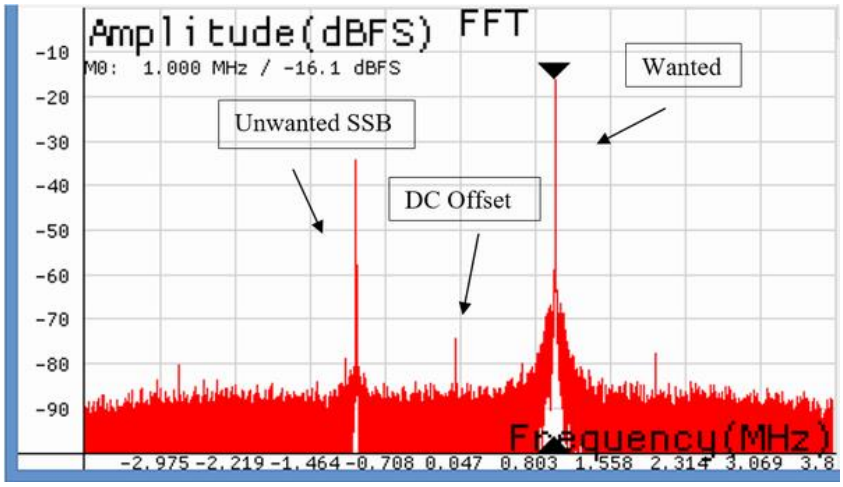

Figure 5 Receive Spectrum of a CW with 1 MHz Offset Before Internal Calibration [3]

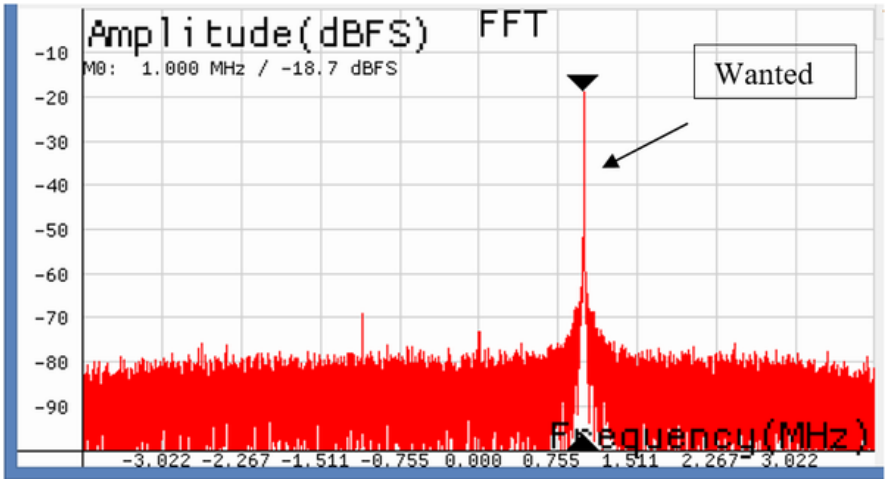

Figure 6 Receive Spectrum of a CW with 1 MHz Offset After Internal Calibration [3]

4 Measurement Approach, SDR Configuration, and Processing of I/Q Data

4.1 SDR Configuration

The SDR configuration before a measurement encompasses the definition of the used sample rates, transmit and receive gain, transmit and receive filter configurations and the I/Q frame size expected to be received from the SDR. The proposed measurement method uses an offset tuned continuous-wave (CW) signal which is transmitted by the SDR. Since only a single signal is present during the measurement, generated images of the transmitted signal can easily be ignored in the signal processing on the receiving side of the SDR, given that the DUT does not frequency shift the transmitted signal. The DC spike caused by LO Leakage could interfere with a CW located too close to the center frequency which the transmitter is tuned to. Thus, it is proposed to use a 1 MHz offset tuned CW as transmit signal.

The CW signal offset has an impact on the required sample rate and frame size of I/Q data. To properly sample the CW, the sample rate must be at least twice the CW frequency offset. If possible, the signal should even be oversampled. In this 8x oversampling is chosen, which would be 8 MHz. The sample rate of the receive and transmit channels can be the same. The frequency bin size achievable after the Fast-Fourier-Transform (FFT) depends on the sample rate and frame size as shown in (1). If the frequency width of one frequency bin should be as close as possible to 15 kHz, but still be a power of 2 to retain FFT conversion speed, the frame size 512 may be chosen. The frequency bin size of 15 kHz is chosen to fit the CW signal inside of a single bin with some margin for error. This will ease the signal processing in software.

$$F^{Binspan} = \frac{F_{Samplerate}}{N_{Framesize}} \tag{1}$$

4.2 Measurement Methodology

Figure 7 shows control flow of the proposed measurement methodology. It consists of the initialization which contains the SDR configuration and a measurement loop. The measurement must be repeated for each S-Parameter measurement. Two special buffers are used in this measurement method. The Calibration Data Buffer contains the frequency dependent calibration data. This buffer can either be an array containing calibration data at discrete frequency steps of the calibration, or it could be a function representing the interpolation of the calibration over the previously mentioned frequency steps. The Measurement Result Buffer contains the measurement results and is filled incrementally with each frequency step during the measurement.

It should be noted, that when switching from S_{21} and S_{12} measurements to S_{11} and S_{22} measurements, the hardware setup should be changed as described in chapter 3. Furthermore, also the calibration data required to be used differs. The signal processing steps highlighted in Figure 7 are described in chapter 4.2.1 to chapter 4.2.5.

4.2.1 Signal Processing Step A

Averaging of I/Q data frames helps to smooth out short-term fluctuations in the measurement at the cost of measurement duration. Averaging can be implemented using two buffers with the length of the I/Q data frame. One buffer is used to store newly received data from the SDR, while the other buffer stores the continuously updated averaging result.

4.2.2 Signal Processing Step B

Conversion from the time domain into the frequency domain is proposed to be managed using the Fast-Fourier-Transform (FFT) algorithm. To mitigate artefacts which are generated through the FFT of a finite data set, before converting to the frequency domain, a window function (e.g. Hanning) is applied to the time domain signal [6]. While it is possible to implement the FFT manually, there are several tested and proven libraries already implementing the FFT. An example is the fftw3 library

which implements the FFT for C and Fortran [4]. The exemplary usage of fftw3 in a LimeSDR Spectrum Analyzer application with C/C++ can be seen in [5].

4.2.3 Signal Processing Step C

To compute the phase of the CW signal on the receiving side of the SDR the correct bin of frequency domain I/Q data needs to be identified. Figure 8 shows the time domain and frequency domain plot of a I/Q data frame size of 512. It contains a 1 MHz CW sampled at 8 MHz. Utilizing (1) and keeping in mind that the first bin of the FFT result is DC, it can be concluded that the 65th bin contains is the I/Q data bin to be used for obtaining the phase of the CW signal through (2). The phase offset captured during the calibration will be corrected for in step E.

$$\phi = arctan(\frac{Q}{I}) \tag{2}$$

4.2.4 Signal Processing Step D

The power measurement requires the I/Q frame to be in the frequency domain as well. The amplitude shown in Figure 8 Time Domain and Frequency Domain Plot of a Complex Sine does not yet display the power in an SI-unit. To obtain the amplitude in Vrms, (3) must be applied, where A is the time domain I/Q frame and N is the frame size [1 Cerna NI]. S is the ADC step size in volt. It must be taken into account that the I/Q data sampled by the ADC is usually relative to the ADCs range. For the LimeSDR this means that an I/Q amplitude equaling the maximum 12-bit integer value correlates to the maximum voltage the ADC can represent, in this case 0.8 Vpp.

$$Amplitude_{V\,rms} = S * \frac{\sqrt{I[FFT(A)]^2 + Q[FFT(A)]^2}}{N} \tag{3}$$

To obtain the power of the CW signal in dBm the amplitude of the respective bin must be inserted in (4), where R is the system impedance, usually 50 Ohm.

$$Power_{dBm} = 10 * log_{10}(\frac{\frac{Amplitude^2_{Vrms}}{R}}{0.001}) \tag{4}$$

The difference between the obtained power level and the power level of the transmitted signal constitutes the attenuation or gain of the currently measured S-Parameter. The gain offset captured during the calibration will be corrected for in step E.

4.2.5 Signal Processing Step E

Ultimately for each frequency step, the calibration offsets for phase and gain must be corrected in the measured S-Parameters. These can simply be added to the measurement results obtained in chapter 4.2.4 and 4.2.3.

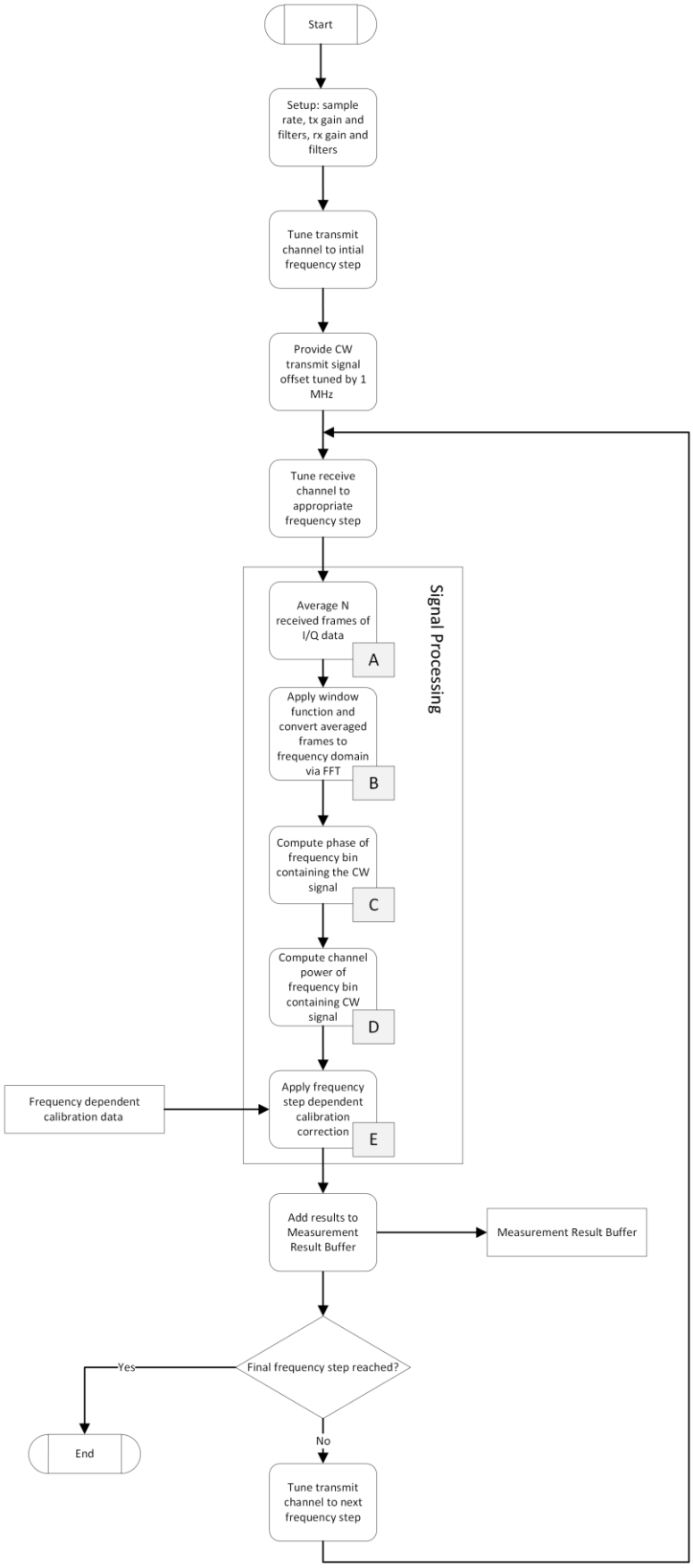

Figure 7 Measurement Methodology

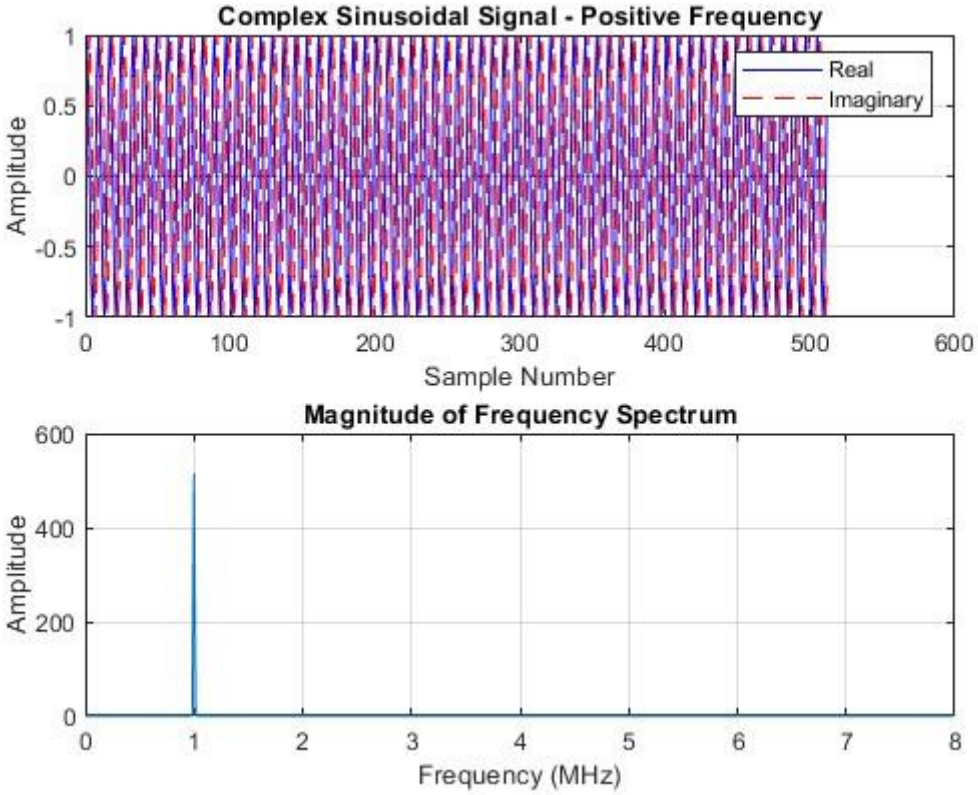

Figure 8 Time Domain and Frequency Domain Plot of a Complex Sine

5 Conclusions

The presented measurement methodology and SDR configuration goes beyond the hardware-related insights that recent research offers on the implementation of a SDR VNA. Based on the findings of this research it is possible to derive a software implementation using any of the common implementation tools such as MATLAB & Simulink, GNU Radio or in C. The proposed method is designed with known weaknesses present in current SDR architectures in mind, to offer S-Parameter measurements with as few noise as possible.

6 References

[1] Farnell, "farnell.com," [Online]. Available: https://de.farnell.com/w/c/messtechnik/hf-messgerate/vektor-netzwerkanalysatoren/prl/ergebnisse?st=vektor-netzwerkanalysator&gs=true&sort=P_PRICE. [Accessed 05 01 2024].

[2] National Instruments, "What Is the RF Architecture Used on USRP-RIO?," [Online]. Available: https://knowledge.ni.com/KnowledgeArticleDetails?id=kA00Z0000019Y9TSAU&l=en-US. [Accessed 06 01 2024].

[3] Myriad RF, "Getting Started with LimeSDR-USB and LimeSuiteGUI," 29 08 2017. [Online]. Available: https://wiki.myriadrf.org/Getting_Started_with_LimeSDR-USB_and_LimeSuiteGUI. [Accessed 06 01 2024].

[4] FFTW, "fftw.org," [Online]. Available: fftw.org. [Accessed 07 01 2024].

[5] F. Török, "Lime SDR Spectrum Analyzer," 2022. [Online]. Available: https://github.com/fabske98/Lime-SDR-Spectrum-Analyzer. [Accessed 07 01 2024].

[6] LDS-Group, "Aplication Note ANO14 - Understanding FFT Windows," 2003.

[7] M. Cerna and A. F. Harvey, "Aplication Note 041 - The Fundamentals of FFT-Based Signal Analysis and Measurement," National Instruments, 2000.

[8] M. Sayed and J. Martens, Modern RF and Microwave Measurement Techniques - Vector network analyzers, Cambridge University Press, ISBN 9781139567626, 2013.

[9] H. L. Hartnagel, R. Quay, U. L. Rohde and M. Rudol, Fundamentals of RF and Microwave Techniques and Technologies, Springer, ISBN 978-3-030-94100-0, 2023.

[10] P. Flak, "Hardware-Accelerated Real-Time Spectrum Analyzer With a Broadband Fast Sweep Feature Based on the Cost-Effective SDR Platform," IEEE Acess, DOI: 10.1109/ACCESS.2022.3215800, 2022.

[11] P. V. A. Freitas, R. F. Hanthequeste, G. B. A. Orofino, P. V. G. Castellanos, A. A. C. Canavitsas and R. C. Bentes, "Implementation of a Spectrum Analyzer Using the Software-Defined Radio Concept," *Journal of Microwaves, Optoelectronics and Electromagnetic Applications,* vol. 20, no. 4, DOI: 10.1109/ACCESS.2022.3215800, 2021.

[12] M. Nazrin, S. J. Hashim, F. Z. Rokhani, B. M. Ali and Z. Yusoff, "Error correction and uncertainty measurement of short-open-load calibration standards on a new concept of software defined instrumentation for microwave network analysis," DOI: https://doi.org/10.21595/jme.2019.20329 , 2019.

[13] A. Raza, A. Jabbar, D. A. Sehrai, H. Atiq and R. Ramzan, "SDR Based VNA for Characterization of RF Sensors and Circuits," in *1st International Conference on Microwave, Antennas & Circuits,* Islamabad, Pakistan, DOI: 10.1109/ICMAC54080.2021.9678273, 2021.

[14] L. M. Riobó, F. E. Veiras, M. T. Garea and P. A. Sorichetti, "Software-Defined Optoelectronics: Space and Frequency Diversity in Heterodyne Interferometry," *IEEE Sensors Journal,* vol. 18, no. 14, DOI: 10.1109/JSEN.2018.2842143, 2018.

[15] A. Rumiantsev and N. Ridler, "VNA Calibration," *IEEE Microwave Magazine,* no. DOI: 10.1109/MMM.2008.919925, 2008.

[16] M. I. Vidotto, F. E. Veiras and P. A. Sorichetti, "Software defined radio for vector network analysis: Configuration, characterization and calibration," *Measurement,* vol. 189, no. DOI: 10.1016/j.measurement.2021.110468, 2022.

[17] Lime Microsystems, "LMS7002M Datasheet 3.1r00," [Online]. Available: https://eu.mouser.com/datasheet/2/982/LMS7002M-Data-Sheet-v3.1r00-1600568.pdf. [Accessed 07 01 2024].