# Low-Cost Vector Network Analyzer for Communication Devices Testing - Brief Review

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**Abstract.** A low-cost and portable one-port vector network analyzer (VNA) which covered operating frequency between 50 MHz to 1 GHz is developed for vector reflection coefficient measurement of the communication devices. A four-port reflectometry technique is implemented in the VNA module design. To collect and analyze data from the VNA, graphical user interface (GUI) is designed using LABVIEW software. In addition, open-short-load calibration technique was programmed in GUI to counterbalance systematic errors of the VNA. The performance of this designed VNA is approximately equivalent to the available commercial VNA.

Keywords: Reflection coefficient, low-cost vector network analyzer, one-port calibration, microcontroller, graphical user interface.

## 1. Introduction

Vector Network Analyzer (VNA) is a vector instrument for performance testing and troubleshooting of the high-frequency communication devices. Previously, robust VNA is normally commercialized by several established manufacturers, such as Keysight Technologies (formerly Agilent Technologies), Anritsu, Rohde Schwarz and Advantest. However, during the past ten years, the application of VNA among ICT engineers is less likely widespread due to the higher cost (typically more than 10,000 USD), bulkiness and complexity of the instrument.

Nowadays, the robust VNA has been progressively commercialized by other emerging manufacturers, namely Copper Mountain Technologies, National Instruments, Techwin, TIANDA and ATTEN.EU. Furthermore, some of the robust VNAs are more likely to be built in the form of open industry-standard PXI (PCI eXtensions for Instrumentation) by National Instruments and Keysight. The PXI VNA will benefit in terms of cost, performance, space, and flexibility of the latest PC technology. In addition, the PXI feature also allows the VNA to be integrated with other test and automation modules in a single chassis. Notwithstanding, its performance and price are not much different from the bench-top VNA.

Fortunately, the rapid development of communication technologies has created a high demand for the test equipments [1-2]. Thus, within the past 10 years, a lot of cost efficient and compact PC-based VNAs have been commercialized by manufacturers, such as LA Techniques Ltd, AKELA Inc., MegiQ, AEA Technology Inc, Copper Mountain Technologies and Deepace. This is certainly a great advantage, for it can reduce the burden of the industry or university regarding the purchase of test equipments. Normally, compact PC-based VNAs are only capable of operating up to 6 GHz or 8 GHz and its prices are varied from 2000 USD to 9000 USD depending on the speed and performances of the VNA.

Besides, various economical portable PC-based VNAs which cost less than 1000 USD (recent price) are accessible in the market; details are tabulated in Table 1. Usually, the maximum dynamic range of the aforementioned VNAs is less than ±40 dB in the GHz range and less suitable to be used for laboratory research purposes. Nevertheless, it is very economical and convenient when it is used for the site measurement and simple troubleshooting. Moreover, the introduction of communication technology using this kind of VNA with operating frequency up to 3 GHz is adequate for undergraduate level students. This will provide more opportunities for the students/engineers in understanding the RF vector instrument.

**Table 1**: List of budget portable PC-based VNAs

| Manufacturer | Model | Frequency | Year |
|---|---|---|---|
| Ten-Tec TAPR | 6000 | 0.2-120MHz | 2005 |
| VNWA | DG8SAQ | 1kHz-1.3GHz | 2008 |
| Array Solution | VNA2180 | 5kHz-180MHz | 2011 |
| mini Radio Solutions | mini VNA Tiny | 1MHz-3GHz | 2014 |
| pocketVNA | Pocket VNA | 0.5MHz-4GHz | 2016 |

The development of portable VNAs product is mainly influenced by the rapid development of RF integrated circuits (ICs) nowadays [3]. The RF IC technology has solved the phase detection issues of the VNA as well as significantly reduced the size and cost of the VNA. Thus, the portable low-cost VNAs are occasionally denominated as

"RF multi-meter". Based on the development profile, the budget portable VNAs with operating frequency up to 6 GHz are expected to be commercialized by 2018.

However, research to generate complete RF test instruments using IC components is less popular in universities. This is due to the less involved mathematical calculations; in other words, the research is basically depending on the engineering technique skill and existing IC components. The above mentioned reasons might lead to the difficulty in publishing research works. Additionally, the price of the ICs purchased by researchers, which is usually in small quantities is much more expensive compared to the manufacturers that purchase IC components in a large scale.

In fact, simple VNA research can be carried out by undergraduate students as a final year project [4]. The quality of the VNA research may continually improve by the following final year students in order to reach the commercialized standard. This research is also appropriate to be cooperated with manufacturers and the required IC components can be enquired easily. This research may allow the future ICT engineers to practise calibration procedures, tackle the initial design of RF circuit using transmission line concept and experience the usefulness of the *S*-parameter and scattering matrix which are studied in classroom lesson.

In this paper, a simple one-port VNA module is developed for demonstration. The dynamic range of the measurement for the VNA is ±30 dB over the 50 MHz to 1 GHz bandwidth. The VNA consists of two ADC-15-4+ directional couplers (From minicircuits), AD8302 gain/phase detector [5], N5171B Keysight signal generator, and Arduino Nano v3.0 microcontroller, respectively, as shown in Figure 1. A graphical user interface (GUI) is designed using LABVIEW software.

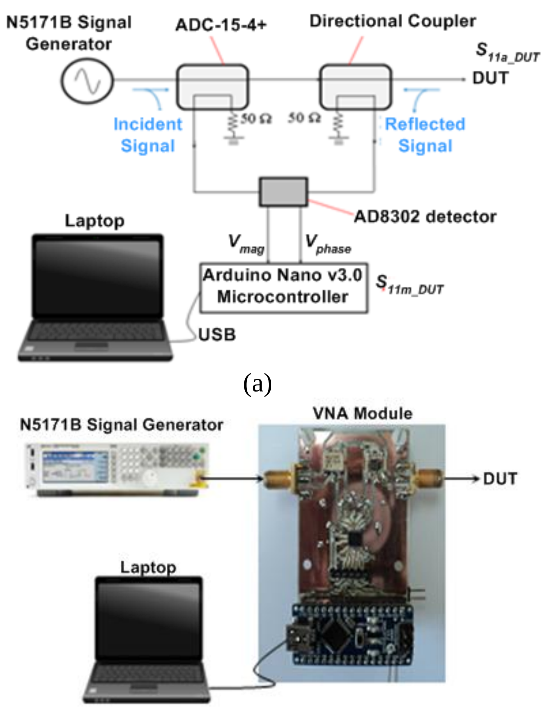



Fig.1. (a) Schematic diagram and the (b) actual assembly of the VNA.

In this study, the one-port VNA, so-called vector reflectometer, measures and computes on the complex ratio of reflected signal voltage to incident signal voltage. Two directional couplers are used in order to improve the isolation between incident signal voltage and reflected signal voltage. The incident signal from the signal generator will be transmitted to the device under test (DUT) through the directional couplers. As a matter of fact, a certain amount of signal will be loss into DUT and the rest of the signal will be reflected back to the VNA module, due to the impedance mismatch. The dual directional coupler will reverse couple the reflected signal and forward couple the incident signal to the detector. Based on the received coupled signal, the AD8302 detector measured and computed the magnitude ratio and phase difference of the coupled signal. From the AD8302 detector, the vector reflection coefficient is obtained. The size of the designed VNA module is (7.5 × 4.5) cm$^2$ and its estimated cost is approximately 60 USD including arduino microcontroller. Here, it should be noted that the cost of the AD8302 detector was considered as a price purchased by the manufacturer on a large scale.

## 2. One-port VNA module

### *2.1. Microstrip transmission line circuit*

The designed VNA module circuit was fabricated on RO 4360 substrate board ($\varepsilon_r$ = 6.15, tan $\delta$ = 0.004) with $d$ = 1.524 mm of thickness. The width, $W$ (=2.2 mm) of the microstrip transmission line with desired 500 MHz of the center frequency and characteristic impedance, $Z_o$ = 50Ω, Is calculated using TX-line calculator (in Figure 2). Here, the length, $l$ of the transmission lines are not discussed since the length, $l$ is less important than the width, $W$.

### *2.2. Relationship Between $V_{mag}$, $V_{phase}$, $|S_{11m\_DUT}|$, and $\phi$*

The AD8302 detector from manufactured Analog Devices is able to work efficiently with the support of other SMD chip resistors and capacitors. The measurement outputs from the AD8302 detector are interpreted in DC voltages ($V_{mag}$ and $V_{phase}$). Based on the [5], the calibration scale between the output $V_{mag}$ (in Volt) from the detector and the magnitude reflection coefficient, $20\times\log_{10}|S_{11m\_DUT}|$ (in dB) of the DUT can be obtained from relationship:

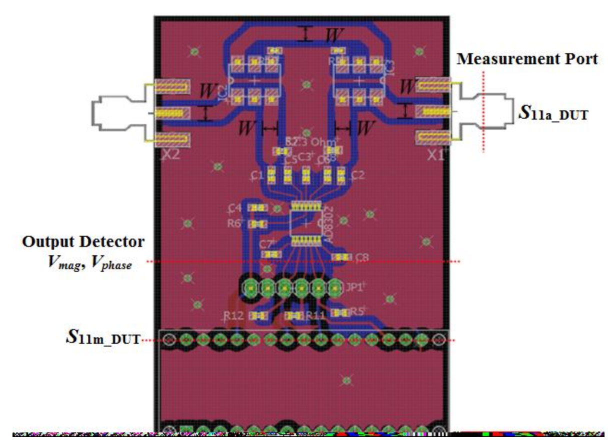



Fig.2. Part of transmission line with width, $W$ for the VNA module.

$$\left|S_{11m\_DUT}\right| = 10^{\frac{\gamma}{20}} \qquad (1)$$

For ($0 < V_{mag} \leq 0.9$) V case, the $\gamma$ in (1) is written as:

$$\gamma = \alpha_6 V_{mag}^6 + \alpha_5 V_{mag}^5 + \alpha_4 V_{mag}^4 + \alpha_3 V_{mag}^3 + \alpha_2 V_{mag}^2 + \alpha_1 V_{mag} + \alpha_o$$

where the polynomial coefficients are given as:

$\alpha_o$=-42.4726367464274 dB, $\alpha_1$=211.943203401082 dB/V,

$\alpha_2$=-1019.05702655087 dB/V$^2$, $\alpha_3$=2939.23929989415 dB/V$^3$,

$\alpha_4$=-4518.67035034208 dB/V$^4$, $\alpha_5$=3520.06111721046 dB/V$^5$,

$\alpha_6$=-1090.14798397968 dB/V$^6$

On the other hand, the $V_{phase}$ (Volt) can be converted to phase shift, $\phi$ (degree) using expression as Eq. (2).

$$\phi = \beta_5 V_{phase}^5 + \beta_4 V_{phase}^4 + \beta_3 V_{phase}^3 + \beta_2 V_{phase}^2 + \beta_1 V_{phase} + \beta_o \qquad (2)$$

where the polynomial coefficients in (2) for ($0 < V_{phase} \leq 0.9$) V, are given as:

$\beta_o$=-47.677903380751°, $\beta_1$=1299.16432458607 °/V,

$\beta_2$=-1314.42197688581 °/V$^2$, $\beta_3$=601.763368273347 °/V$^3$,

$\beta_4$=-210.216183277092 °/V$^4$, $\beta_5$=182.506874795524 °/V$^5$

On the other hand, for ($0.9 < V_{phase} \leq 1.8$) V case, the polynomial coefficients are given as:

$\beta_o$=1630.608202309291 °, $\beta_1$= -6.003.830135622119 °/V,

$\beta_2$= 9510.346167872143°/V$^2$, $\beta_3$= -7570.708041938438 °/V$^3$,

$\beta_4$= 2982.427156649023°/V$^4$, $\beta_5$= -465.4403049471512 °/V$^5$

However, based on the phase characteristic of Eq. (2), there is an inherent ambiguity of the phase shift, $\phi$, since there is no distinction between positive and negative phase shifts (in Figure 3 (a)). In fact, under regular operation, the phase shift, $\phi$ must be always in negative slope. This means that the phase shift must always be decreased to minimum -180° and repeated shift to maximum +180° again when the operating frequencies are sweeping from low to high. To solve the ambiguity of the phase shift, $\phi$, an algorithm is developed to compare one phase data point, $n$ to the next phase point ($n$+1) at a given frequency, $f$. If the phase shift, $\phi_{n+1}$ of the next frequency is greater than the phase shift, $\phi_n$ of the current frequency, the negative sign is assigned to the current phase, $\phi_n$ and vice versa:

If $\phi_{n+1}$ - $\phi_n > 0$, Ouput: $-\phi_n$
else $\phi_{n+1}$ - $\phi_n < 0$, Ouput: $+\phi_n$

Finally, the phase shift, $\phi$ will always exchange between –180° to +180° when the operating frequencies are sweeping as shown in Figure 3 (b).

## 2.3. One-port calibration

The calibration of the VNA is compulsory before measuring the reflection coefficient, $S_{11a\_DUT}$ for the DUT. The calibration is required to eliminate the systematic errors of the measurements that caused by the imperfection of the generator-module connection,

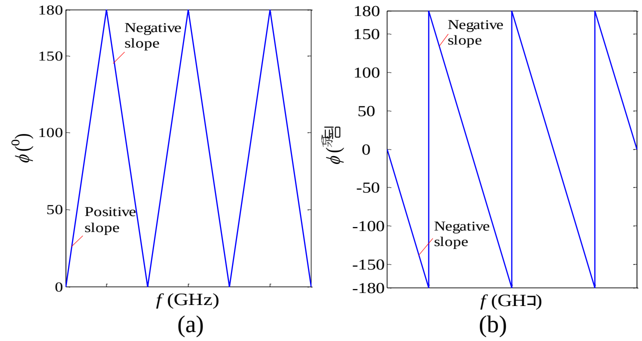



Fig.3. (a) Absolute and (b) practice phase shift across operating frequency.

circuit fabrication, components placement, and soldering. The relationship between the $S_{11m\_DUT}$ at the output of the AD8302 detector and $S_{11a\_DUT}$ at the measurement-port, as shown in Figure 2 is expressed as:

$$S_{11a\_DUT} = \frac{S_{11m\_DUT} - e_{00}}{e_{11} S_{11m\_DUT} + e_{10}e_{01} - e_{00}e_{11}} \qquad (3)$$

where $e_{00}$, $e_{11}$ and $e_{10}e_{01}$ are the unknown scattering parameters of the error network for the VNA. In this work, a three-standard calibration which open, short and match-load standards (OSL) are used to determine the values of the $e_{00}$, $e_{11}$ and $e_{10}e_{01}$ [6].

## 2.4. Graphical user interface (GUI)

Figure 4 shows the graphical user interface (GUI) of the measurement for the VNA. Initially, the command was given to the microcontroller to begin ADC on both gain, $V_{mag}$ and phase, $V_{phase}$ channel. The digital data returned from microcontroller on each channel were averaged based on the number of acquisitions taken. Lastly, the digital values of $V_{mag}$ and $V_{phase}$ are converted to reflection coefficient magnitude and phase based on the Eq. (2) and (3), respectively. The magnitude and phase (in degree) of the calibrated $S_{11a\_DUT}$ are plotted versus operating frequencies. Besides linear magnitude, $|S_{11a\_DUT}|$ and phase shift, $\phi$, the reflection coefficients are also interpreted as voltage standing wave ratio (VSWR), return loss (dB), Smith Chart and matching complex impedance. Each interpretation is shown in different graphs on the GUI.

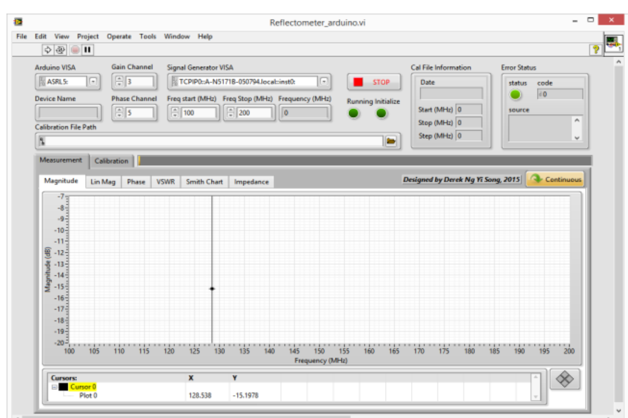


Fig.4. Graphical user interface on measurement mode.

## 3. Measurement and validation

For higher reliability comparison, three different models of commercial VNAs are selected to measure the performance of the Yagi-Uda array antenna and two helical monopole antennas (in Figure 5). The three models of the commercial VNAs are Keysight E5070C, Keysight FieldFox N9925A, and AEA Echo 2500, which representing high, moderate and low cost instrument, respectively. These VNAs are calibrated with their respective calibration kits before measurements.

The experimental setup is shown in Figure 6. The measured reflection coefficients, $S_{11a\_DUT}$ of the Yagi-Uda array antenna and monopole antenna are compared with the results from the designed VNA module as shown in Figure 7. The magnitude, $|S_{11a\_DUT}|$ and the phase shift, $\phi$ of reflection coefficient results are found to be in good agreement with measurement results using the three commercial VNA over the range of operating frequencies.

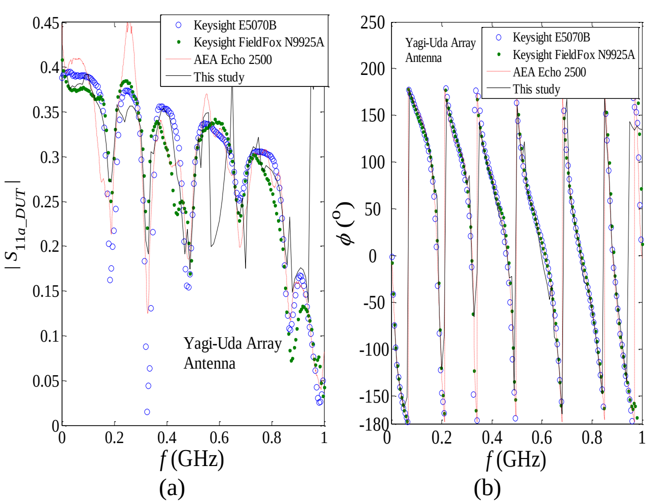
## 4. Conclusion

In this paper, a compact VNA module has been designed and fabricated successfully. The measured magnitude and phase shift of reflection coefficient were made simpler through the implementation of AD8302 detector IC.

(a) (b) (c)

Fig.5. (a) Yagi-Uda array antenna. (b) 433 MHz helical monopole antenna. (c) 350 MHz commercial helical monopole antenna.

Fig.6. Part of experimental-setup.



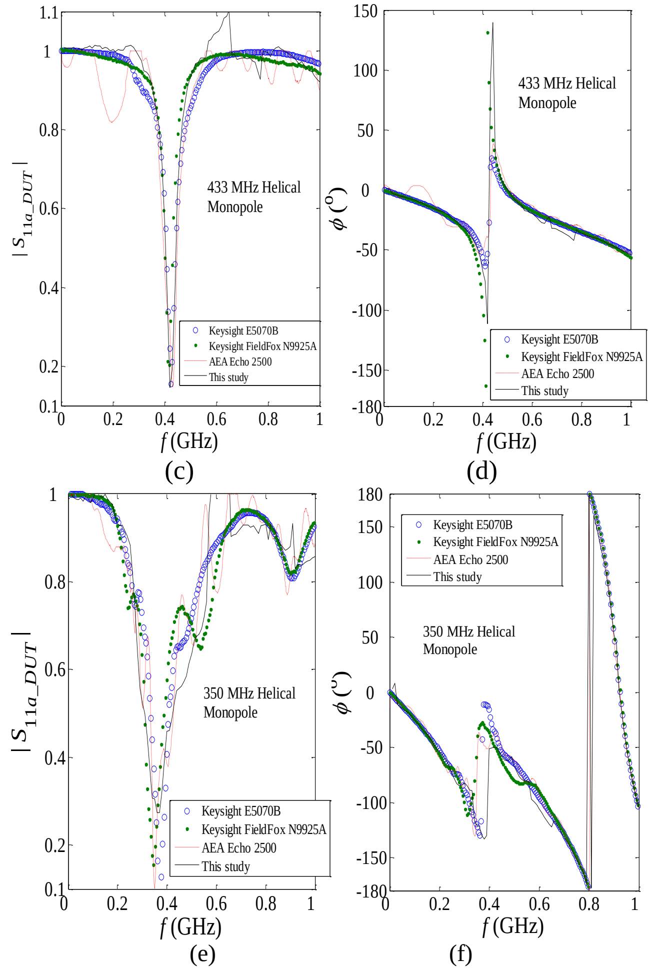




Fig.7. Comparison of $|S_{11a\_DUT}|$ and $\phi$ of the of the reflection coefficient for the three kinds of antennas.

In the future, a multi-port VNA can be developed by integrating two or more designed VNA modules, so that the reflection coefficient and the transmission coefficient of the DUT can be measured simultaneously. Besides communication, the low-cost multi-port VNA has the potential to be used in biomedical applications, such as breast microwave imaging [7] and body bio-impedance measurement [8].

## References

[1] Jisong Y. and H. Tao, Extraction algorithm of reflection coefficient for antenna VSWR meter based on directional coupler and integrated amplitude phase detector, *Cross Strait Quad-Regional Radio Science and Wireless Technology Conference* (CSQRWC), vol. 2, pp. 1129–1133, 2011.

[2] C. B. Thomas, A small, simple, USB-powered vector network analyzer covering 1 kHz to 1.3 GHz, *QEX Magazine*, vol. Jan/Feb 2009, pp. 32–36, 2009.

[3] T. G. Ruttan, B. Grossman, A. Ferrero, V. Teppati and J. Martens, Multiport VNA measurements, *IEEE Microwave Magazine*, vol. 9, no. 3, pp. 56–69, 2008.

[4] J. T. Nagy, Remotely operated reflectometer, Bachelor's Thesis, The Ohio State University, 2013.

[5] Analog Devices Inc., AD8302: LF-2.7 GHz RF/IF gain and phase detector data sheet. Available: http://www.analog.com/media/en/technical-document-ation/data-sheets/AD8302.pdf.

[6] D. Rytting, Network analyzer error models and calibration methods, Agilent Technologies Inc, 2005.

[7] D. Byrne, M. Sarafianou, and I. J. Craddock, Compound radar approach for breast imaging, *IEEE Transaction on Biomedical Engineering*, vol. 64, no. 1, pp. 40-51, 2017.

[8] Abhijit S. P. and R. B. Ghongade, Design of bioimpedance spectrometer, 2016 International Conference on Advances in Computing, Communications and Informatics (ICACCI), pp. 2724-2728, 2016.

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