Measurement and Application of VNA

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Abstract: The vector network analyzer is the most important measurement instrument in communication antennas. In order to characterize the microwave components and the front-end of wireless systems, the vector network analyzer is the most commonly used frequency domain measurement platform. The uncertainty analysis of its measurement results is one of the hot topics in the field of instrumentation and measurement. An in-depth analysis of measurement uncertainty introduced by different calibration methods is the quantitative basis for reasonable selections of self-calibration methods. In frequency domain channel measurement, multiple frequency points need to be measured, and there is a strong correlation between the measurement results of each frequency point, which effectively gives a reasonable choice of the measurement method. The impact of the effective assessment is combined with various experiments, tests and practical comparative analysis of the obtained data.

Keywords: Vector Network Analyzer; TDR Measurement; Multi-Port Expansion; Uncertainty Analysis; System Error Analysis.

1. Introduction

According to its function, the network analyzer is divided into vector network analyzer and scalar network analyzer. As the name implies, a vector network analyzer can measure the vector performance of devices, including amplitude and frequency characteristics and phase characteristics. A scalar network analyzer can only test device amplitude and frequency characteristics. Because the function of the vector network analyzer completely covers the scalar network fraction. In the current RF test, the scalar network analyzer is rarely used, and many small partners may not have seen it.

Circuit network analysis is one of the most common measurement tasks in radio frequency engineering. Vector network analyzer is an instrument designed to perform this task with high precision and efficiency. Vector network analysis instrument is a kind of electromagnetic wave energy testing equipment. It can not only measure the amplitude of the single port network or multi-port network parameters, but also measure the phase, rich function, is called "the king of instruments". Today, network analyzers can be used to analyze a wide range of circuits, from simple devices such as filters and amplifiers to complex modules used in communications satellites, radars, and navigation systems. The network analyzer plays an important role in radio frequency instrumentation and has a broad market prospect.

With the rapid development of the RF field, VNA's microwave network analyzer represented has been widely used [1-2]. However, previous studies on VNA measurement uncertainty only focused on analyzing its direct measurement result S- parameter [3]. It resulted in the loss of important information in calculating subsequent uncertainty propagation (other more concerning physical quantities derived from S-parameter) [4]. This information mainly includes the mutual correlation between S parameters, which is the key to ensuring the correct uncertainty propagation analysis.

In addition, nonlinear vector measurement and accompanying behavior modeling technology have become one of the research hotspots in the field of microwave millimeter wave in recent years [5-7]. Nonlinear measuring instruments represented by NVNA and LSNA are becoming more and more perfect and widely used [8-9]. Since harmonics and intermodulation distortion in the nonlinear domain are obtained based on multi-frequency measurements in the frequency domain, the mutual correlation between measurements at different frequency points is a factor that must be considered in the measurement uncertainty analysis. Literature [10] only qualitatively analyzed the random

uncertainty of the original measured values of NVNA and LSNA. So far, there are no reports on stochastic uncertainty analysis and a systematic uncertainty of effective measurements. [11]

In this paper, data collection and comparative analysis are carried out for the measurement calibration of a vector-based network analyzer, so as to take feasible adjustments and application, so as to reduce the data error generated by the vector-based network analyzer in the measurement process, improve the measurement accuracy and reduce the interference factors.

2. The measuring principle of VNA

2.1 TDR measurement principle of VNA

VNA analysis of time domain measurement function is not used directly. The test but the frequency domain response of the first testing device that S parameters of the amplitude and phase, and then using Fourier inverse transformation, a mathematical operation. The frequency domain information is transformed into time domain information, due to the time domain and frequency domain transformation is through the Fourier transform. Fourier inverse transformation is the theoretical basis of VNA time domain measurement. The implementation of VNA time domain analysis is the inverse Fourier transform from the frequency domain to the time domain. It is achieved by the internal computer of VNA through the Fourier transform technology, specifically using an algorithm called linear frequency modulation-Z inverse transform, which includes two fast inverse Fourier operations and one convolution. The final result after transformation is the time domain response of the device. It shows the values of measured parameters over time that correspond to transmission or emission measurements in the frequency domain.

The reflected and transmitted frequency response characteristics acquired with the VNA may be used to perform an inverse Fourier transform to determine the impulse response characteristics in the time domain. Additionally, combining the impulse response characteristics will provide the step response characteristics. These response characteristics match those seen on the sample oscilloscope's TDR. The actual approach utilized is based on the convolution principle of the Fourier transform in the frequency domain since the integration computation is exceedingly time-consuming. In other words, the frequency response properties of the test device are combined with the input signal's Fourier transform, and the result is then subjected to the inverse Fourier transform. It is also possible to explain the integration in the time domain.

VNA is an instrument for measuring the frequency response of the part under test (DUT). During the measurement, a sine wave excitation signal is input to the device under test. Then the measurement result is obtained by calculating the vector amplitude ratio between the input signal and the transmitted signal (S_{21}) or reflected signal (S_{11}) (Fig. 1). The frequency response characteristics of the device under test can be obtained by scanning the input signal in the measured frequency range (Fig. 2). The use of band-pass filtering in the measurement receiver can remove the noise and unwanted signals from the measurement results and improve the measurement accuracy [12].

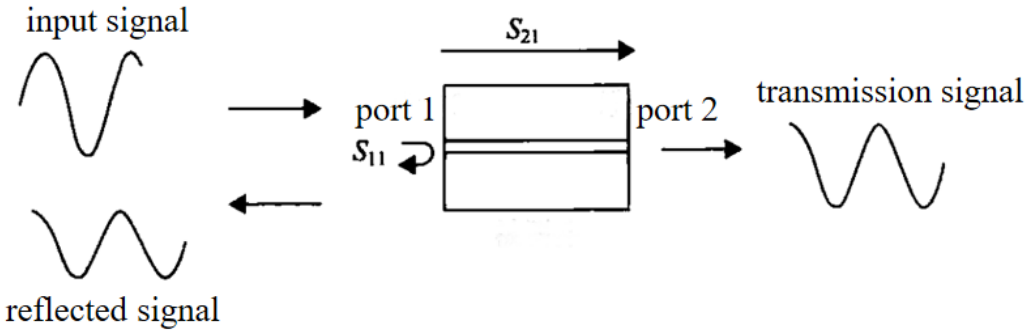


Figure .1 Schematic of representation of input,reflected and transmitted signals

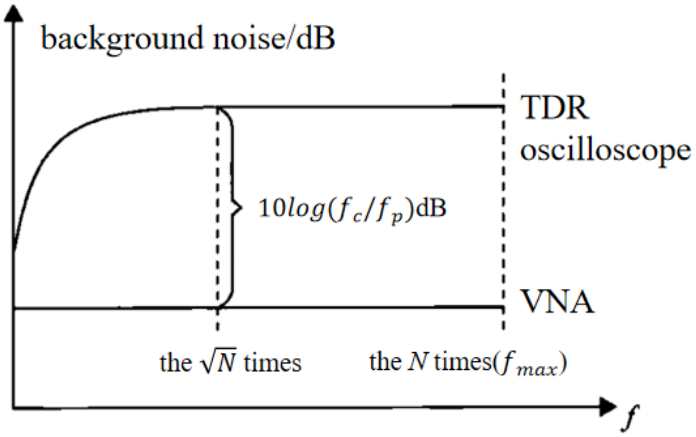


Figure. 2 Comparison of TDR dynamic range between VNA and sampling oscilloscope in the frequency domain

2.2 Multi-port expansion principle of VNA

VNA multi-port expansion device is mainly switched matrix. Generally speaking, port expansion by switching matrix is edited by switching logic according to port number and port link requirements, so as to realize the expansion of test ports from few to many, and the expansion of two VNA ports into multiple ports, which can improve the testing efficiency of VNA, as shown in Figure 3(a). In order to achieve fast metrological calibration for multi-port VNA, switching matrix can also be used to realize ports from more to less, as shown in Figure 3(b). Four SPDT coaxial switches can be used to connect with the 4-port VNA, and then two SP4T coaxial switches are used for editing and switching logic. The 6-channel output of the 4-port VNA can be arbitrarily output into 2 ports, which is convenient for the online rapid measurement and calibration of multi-port VNA. Improve the calibration efficiency of VNA. [13]

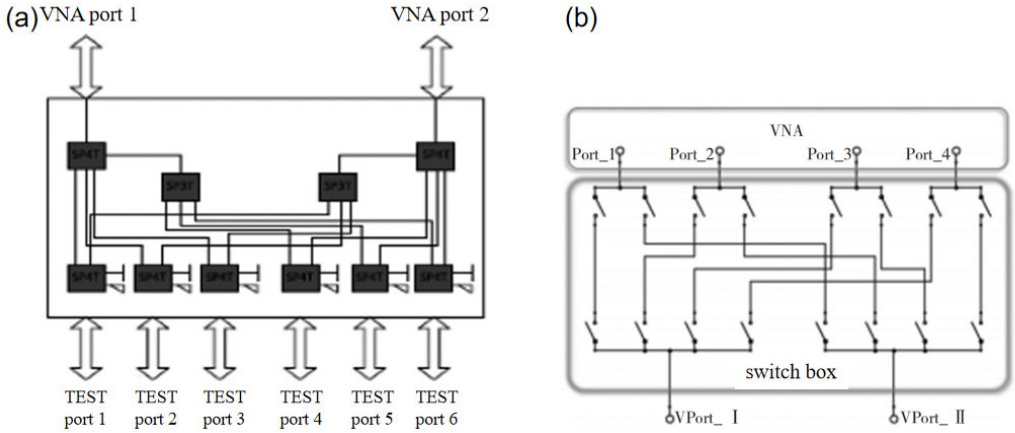


Fig 3.(a)Schematic diagram of port expansion, (b)Schematic diagram of the switching matrix

3. The process of measurement

3.1 Measurement and calibration of VNA

Figure 4. (a), (b), and(c) are the block diagrams of VNA, NVNA and LSNA, respectively. NVNA is an upgrade and modification based on VNA with the addition of additional phase reference channels, while LSNA can be regarded as a microwave absolute FFT analyzer. [8]

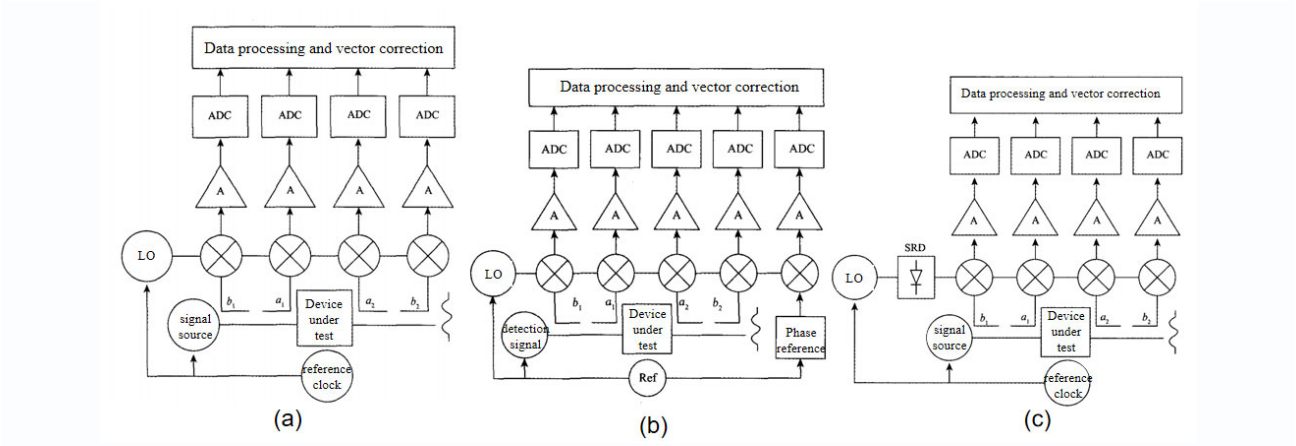


Figure 4.(a)Block diagram of VNA (b)Block diagram of NVNA (c)Block diagram of LSNA

VNA and NVNA work in the frequency sweep measurement mode to measure the measured signals at different frequency points. The difference is that VNA can directly measure the reflected and incident waves ratio. By calculating the difference between the measured reflected and incident waves and the phase reference measurements, the absolute amplitude and phase measurements of the reflected and incident waves can be obtained by NVNA. LSNA works in accordance with the principle of harmonic sampling, as shown in Figure 5, by down-converting all measured signals of different harmonic frequency points to IF, and obtaining them all through a single measurement.

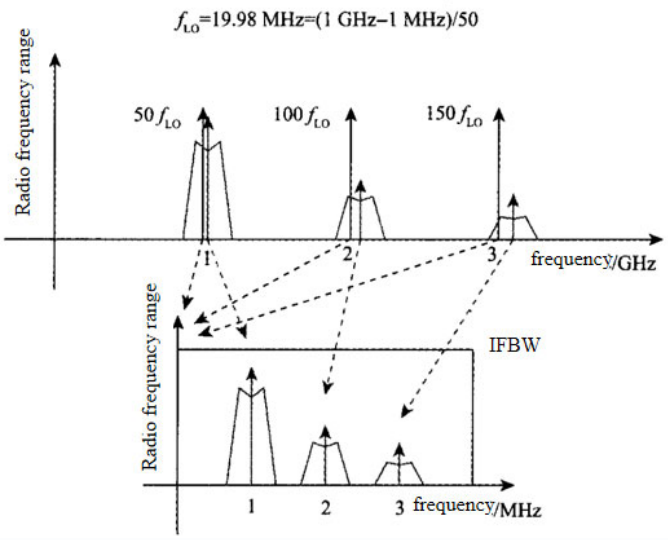


Figure 5. Harmonic sampling principle

VNA, NVNA, and LSNA all need to be calibrated before measurement to obtain the error model coefficients to complete the vector correction from the original measurement to the valid measurement. The error model describes the functional relationship between the initial measured values a_0, a_3, b_0, b_3 of the receiver and the effective measured values a_1, a_2, b_1, b_2 (representing the true values on the measured port surface). The essence of calibration is to invert the coefficient of the error model by measuring a series of known standard components. Due to the need for nonlinear measurement, both dual-port NVNA and LSNA adopt the 8-item error model [14-17]. At the same time, VNA with more mature linear measurement theory can also be calibrated according to the 10-item, L2, 15-item and other error models. However, for the convenience of discussion, this paper adopts the 8-item model for analysis.

Fig. 6(a) shows the 8-item error model, and the corresponding relationship between original and effective measured values is shown in Equation (1), where e_{00}, e_{01}, e_{10}, e_{11}, e_{22}, e_{23},

e_{32} and e_{33} are 8 error coefficients ($\Delta x = e_{00}e_{11} - e_{01}e_{10}$, $\Delta y = e_{22}e_{33} - e_{23}e_{32}$). For VNA calibration, standard Short, Open, Load, and Thru calibration can be done, while NVNA and LSNA require additional phase and power calibration steps in order to determine the absolute amplitude and phase of $e_{01}$and e_{32}. The calibration process of the eight error models is shown in Fig. 6(b), and relevant calibration theories can be referred to as references [8, 14, 17].

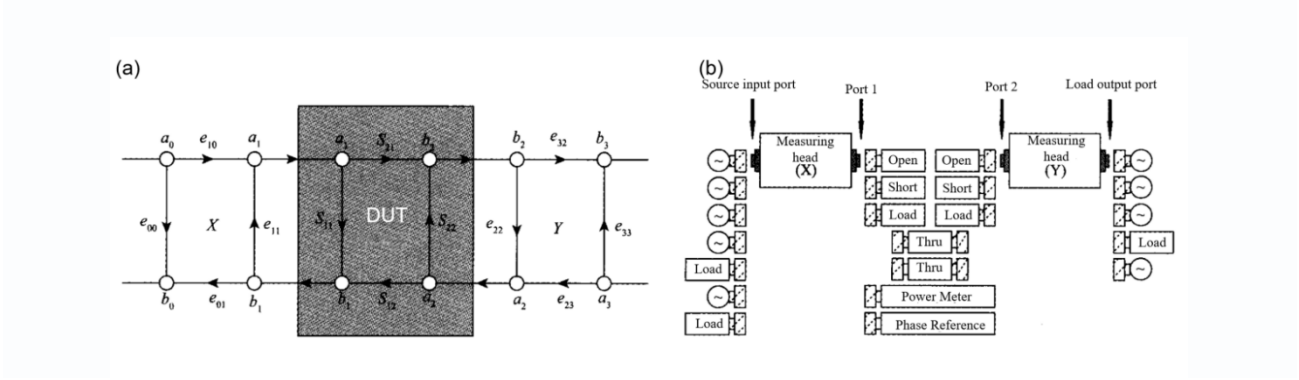


Figure 6.(a)8-term error model(b)NVNA calibration procedure

3.2 Uncertainty analysis and measurement of VNA

In order to use Agilent86100C to calibrate the micro-wave pulse signal [17], it is often necessary to obtain the mismatch of the measuring end surface (reflection coefficient Γ_s of the oscilloscope input and reflection coefficient Γ of the microwave signal output). The mismatch correction equation of Equation (1) converts the direct measurement results in the frequency domain to the "standard value" Vs corresponding to the 50ω matching load. Therefore, this modified time-domain waveform can further examine the measurement uncertainty of the S parameter by VNA.

$$\boldsymbol{V_s = \frac{V}{1 - \Gamma\Gamma_s}} \tag{1}$$

Fig. 7 shows the result of the modified time-domain waveform uncertainty. It can be seen in full consideration. In the case of the correlation between S parameters, the time-domain waveform uncertainty will increase significantly in the rising and falling edges of the pulse with sharp amplitude changes, but maintain a low level in the relatively gentle interval. Suppose the correlation between S parameters (mainly reflected in the cross-correlation of reflection coefficient measurements between different frequency points) is ignored. In that case, the time-domain waveform uncertainty does not change dramatically during the whole period. In contrast, the former will have a local uncertainty peak, which is significantly higher than the maximum global value of the latter. The latter is overall higher than the former in the rest. The above results are consistent with the experimental results of high-speed electrical pulse measurement of EOS system by NIST, which proves the necessity of fully considering the correlation information (covariance) between variables. In order to further test the validity of the method based on covariance matrix analysis, this paper also generates 10000 groups of random samples based on the cosquare difference matrix from the uncertainty degree for Monte Carlo simulation comparison. The results are in good agreement with the analysis results based on the covariance matrix, which not only confirms the importance of relevant information, but also verifies the accuracy of the proposed method. It can also be shown that ignoring the higher-order terms in Equation (2) and adopting the first-order approximate covariance matrix method is reasonable and effective in the field of measurement uncertainty analysis.

$$\boldsymbol{Y = F(X) \approx F(X_0) + J \cdot (X - X_0) + \cdots} \tag{2}$$

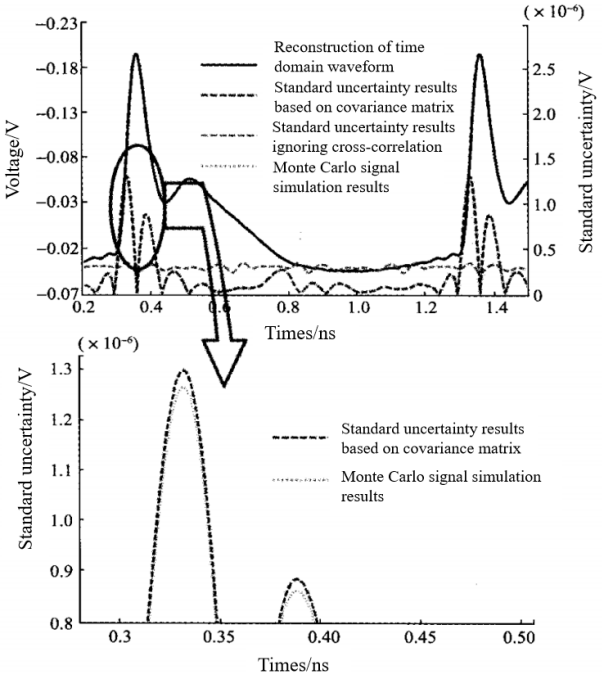


Figure 7.Experimental results of VNA

For measuring instruments, because manufacturers are more concerned about the direct measurement indexes of products rather than the subsequent needs of users, the traditional VNA uncertainty analysis is to directly give the variance of the measured values of each S parameter. Therefore, many high-precision signal characterization and device calibration studies have to treat each S parameter as an independent source of uncertainty. Taking fixed-direction coupling method for calibrating power rate meter [3] as an example, the uncertainty of the calibration factor is transmitted from four S parameters of a three-terminal power splitter: S_{22}, S_{21}, S_{31}, and S_{32}, but the correlation between them is neglected in previous analyses. Moreover, suppose the power divider's S parameter and the power meter's reflection coefficient are measured by the same VNA. In that case, the traditional analysis method of ignoring correlation also loses some other important information.

The analysis method based on the covariance matrix proposed in this paper further completes the uncertainty theory of VNA measurement. It fundamentally solves the above problems from the perspective of the final result demand. Since the cross-correlation information of all variables has been fully preserved, the correctness of subsequent analysis results can be effectively guaranteed only by carefully examining all the sources of uncertainty transmission. With the increasingly wide application of VNA and S parameters, this method will gradually replace the original analysis theory and become a universal quantitative calculation method of measurement uncertainty propagation [11].

3.3 System Error analysis of multi-port VNA expander

3.3.1 Systematic error model and uncorrected error term of VNA

VNA is a kind of broadband segment, multi-parameter, frequency/time domain amplitude phase volume measurement and control system. It uses the tuning receiver structure system, to provide high sensitivity and large dynamic range of the signal, to measure image feature, phase characteristic of microwave components and group delay characteristics, and utilizes the time domain features determine the impedance mismatch (or circuit fault) of location, etc. The VNA with the multi-port expansion is mainly composed of the VNA host and the multi-port expansion device. In order to facilitate automatic and rapid calibration and measurement, the multi-port expansion device can also be configured on the four-port VNA to a two-port VNA (see Fig. 3(b)).

For any measuring instrument, its hardware can not be completely ideal, VNA is the same. Even if the complete VNA on the hardware is used to measure the parts under test, there will be errors in the measurement results. These measurement errors must be corrected or minimized in order to obtain accurate measurement results. The system error is caused by the imperfection of VNA and multi-port expansion devices. Such errors do not vary from time to time, are reproducible, predictable, can be determined during the calibration process, and can be reduced mathematically during the measurement period. In most microwave measurements, systematic errors are considered to be the main source of uncertainty. The purpose of VNA calibration is to reduce the impact of systematic errors on the measurement results. There are 12 systematic errors in VNA's two-port measurement, and 6 errors in forward and reverse measurement. There are three systematic errors in forwarding reflection coefficient measurement: directionality, source matching and reflection tracking. There are also three systematic errors in forwarding transmission measurement: load matching, transmission tracking and crosstalk. The signal flow diagram and error term are shown in Fig. 8. The errors in reverse measurement are similar to those in forwarding measurement, only in the opposite direction [13].

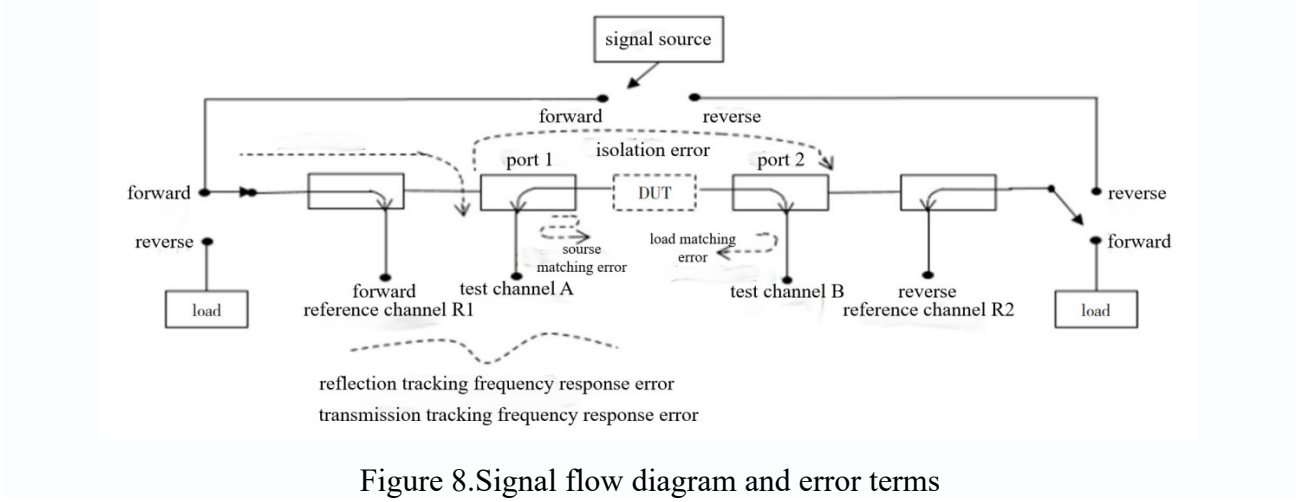


Figure 8.Signal flow diagram and error terms

All VNAs use directional couplers or directional Bridges when performing reflection measurements. Only the signal reflected back from the tested part is available for an ideal coupler. However, due to the fact that the coupler is not ideal, part of the incident signal will leak into the reflected signal, which is the directional error in reflection measurement, as shown in Fig. 9, $e_{00}$and$e_{33}{}'$. In an ideal reflection measurement, all the signals reflected back from the part under test should be measured. However, due to the mismatch between the source port and the system impedance, the signals reflected back from the part under test are reflected back to the source again, which is the source matching error in the reflection measurement, as shown in Figure 4, $e_{11}$and$e_{22}{}'$. Similarly, in reflectance measurements, the frequency responses of the reference and reflected signals should ideally be equal. However, in practice, due to the frequency response changes of amplitude and phase of devices, cables, connectors, etc. , this is the reflection tracking error in reflection measurement, as shown in Figure 4 for $e_{10}e_{01}$ and$e_{23}{}'e_{32}{}'$. Similar to the frequency response error of reflection tracking, the frequency response error of the amplitude and phase of each variable in the system is inconsistent between the transmission channel and the reference channel, which is the transmission tracking frequency response error in transmission measurement, as shown in Fig. 9, $e_{10}e_{32}$and$e_{23}{}'e_{01}{}'$. In the actual transmission measurement, due to the mismatch between the load test port and the system impedance, part of the transmitted signal is reflected back to port 2, which is the load matching error term in the transmission measurement, as shown in Figure 4, $e_{22}$and$e_{22}{}'$. Ideally, the transmission channel should be completely transmitted through the signal from the part under test, but in practice some signal leaks into the transmission channel through various paths, which is the crosstalk and isolation error in the transmission measurement, as shown in e_{32} and $e_{23}{}'$ in Fig. 9.

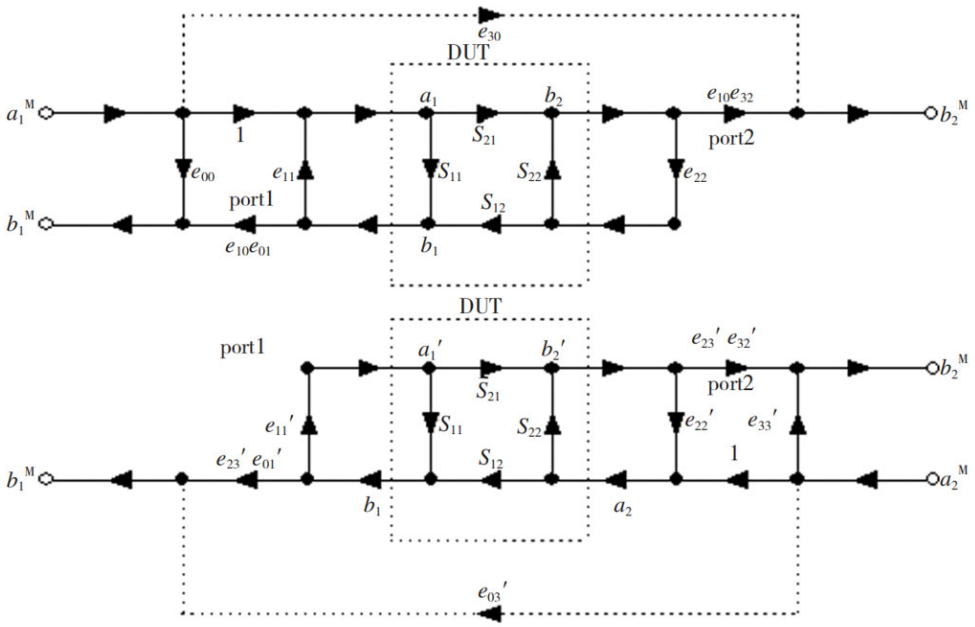


Figure 9.Two-port 12 error model and error terms

According to the error model in Fig. 9, the uncorrected system error term can be obtained by connecting the open-circuit (Γ=1), short-circuit (Γ=-1), load (Γ=0) and pass-through ($S_{11} = S_{22} = 0$, $S_{12} = S_{21} = 1$) at ports 1 and 2 respectively, combined with Equations (3) to (6).

$$S_{11M} = \frac{b_0}{a_0} = e_{00} + (e_{10}e_{01})\frac{S_{11} - e_{22}\Delta S}{1 - e_{11}S_{11} - e_{22}S_{22} + e_{11}e_{22}\Delta S} \tag{3}$$

$$S_{11M} = \frac{b_3}{a_0} = e_{30} + (e_{10}e_{32})\frac{S_{21}}{1 - e_{11}S_{11} - e_{22}S_{22} + e_{11}e_{22}\Delta S} \tag{4}$$

$$S_{22M} = \frac{b'_3}{a'_3} = e'_{33} + (e'_{23}e'_{32})\frac{S_{22} - e'_{11}\Delta S}{1 - e'_{11}S_{11} - e'_{22}S_{22} + e'_{11}e'_{22}\Delta S} \tag{5}$$

$$S_{12M} = \frac{b'_0}{a'_3} = e'_{03} + (e'_{23}e'_{01})\frac{S_{12}}{1 - e'_{11}S_{11} - e'_{22}S_{22} + e'_{11}e'_{22}\Delta S} \tag{6}$$

3.3.2 Analysis of uncorrected error terms for VNA and VNA with extended ports1.

Analyze the uncorrected error terms of VNA and VNA with expansion ports

Using R&S vector network analyzer ZVA40 and Ecal ZV Z54, according to the type (1) ~ (4) to calculate the VNA is not repair the error term.

R&S VNA ZVA40, multi-port expansion device and Ecal ZV-Z54 were adopted. According to Equations (3) ~ (6), the uncorrected error term of VNA was calculated, . The switch matrix of the expansion port is CCR-53S-SPDT of TELEDYNE and EPX SP3T-0E-26A. In the full frequency segment from DC to 26. 5GHz, the main indicators' standing wave ratio is less than 2. 00 and the insertion loss is less than 1. 5dB. The isolation was greater than 50dB.

2. Analysis of valid system errors of VNA and VNA with extended ports

The 2. 92mm precision calibration sheath (Model: P292CK40) of a company was used to calibrate VNA through TRL/ LRL calibration and calibration based on coaxial air transmission line. The effective error term was calculated according to Equations (7) to (10).

The coaxial 2. 92mm precision air calibrator is used to calibrate the VNA of the expansion port through TRL/LRL calibration and calibration based on the coaxial air medium transmission line. The effective error term is calculated according to Equations (7) ~ (10).

$$\begin{bmatrix} b_1^M \\ a_1^M \end{bmatrix} = M \begin{bmatrix} a_2^M \\ b_2^M \end{bmatrix} \tag{7}$$

$$M = \frac{1}{S_{21}}\begin{bmatrix}(S_{12}S_{21} - S_{11}S_{22}) & S_{11}\\ -S_{22} & 1\end{bmatrix} \tag{8}$$

$$' = X'\bar{Y} \tag{9}$$

$$X = R_1\begin{bmatrix}A_1 & B_1\\ C & 1\end{bmatrix} = \frac{1}{e_{10}}\begin{bmatrix}-(e_{00}e_{11} - e_{01}e_{10}) & e_0\\ -e_{11} & 1\end{bmatrix} \tag{10}$$

$$Y = R_2\begin{bmatrix}A_2 & c_2\\ B_2 & 1\end{bmatrix} = \frac{1}{e_{32}}\begin{bmatrix}-(e_{22}e_{33} - e_{32}e_{23}) & -e_{22}\\ -e_{33} & 1\end{bmatrix} \tag{11}$$

Where $\delta = e_{00}$, $\mu_1 = e_{11}$,$1 + \tau_1 = e_{10}e_{01}$,$\mu_2 = e_{22}$, $1 + \tau_2 = e_{10}e_{32}$.

3. Impact of port expansion device on VNA system error

The system error of VNA is not corrected by VNA port expansion device, as shown in Table 1. The influence of the network division expansion device on the effective system error of VNA is shown in Table 2. As can be seen from Table 1, the influence of VNA expansion device on VNA uncorrected system error mainly lies in reflection tracking and transmission tracking, because the expansion device increases the loss of reflection and transmission links. As can be seen from Table 2, the impact of VNA expansion device on VNA effective system errors is mainly in source matching and load matching, and the reason is that the expansion device deteriorates the matching characteristics due to the increase of reflection and transmission links.

Table 1 Impact of expansion device on uncorrected system error

error term	10MHz~10GHz	10GHz~18GHz	18GHz~20GHz	20GHz~26.5GHz
directivity	–3dB	–3dB	–3dB	–3dB
source match	0dB	0dB	1dB	0dB
load match	1dB	1dB	2dB	1dB
reflection trace	–0.6dB	–6.8dB	–9.6dB	–10.1dB
transmission track	–0.6dB	–6dB	–8.3dB	–8.7dB

Table 2 Effect of expansion device on effective system error

error term	10MHz~10GHz	10GHz~18GHz	18GHz~20GHz	20GHz~26.5GHz
directivity	2dB	–4dB	–7dB	–10dB
source match	–7dB	–8dB	–11dB	–14dB
load match	–7dB	–9dB	–9dB	–12dB
reflection trace	0.11dB	0.38dB	0.57dB	1.25dB
transmission track	0.01dB	0.08dB	0.13dB	0.12dB

4. Conclusion

At the beginning of this paper, the basic theoretical concept of vector network analyzer is introduced, and then several common measurement principles of vector network analyzer are given. Finally, three analysis methods of vector network analyzer are listed and introduced. Firstly, the measurement and calibration of VNA, NVNA and LSNA, VNA uncertainty analysis and VNA multi-port expansion device system error analysis are briefly introduced. Then the three methods are evaluated and analyzed, and their rationality is demonstrated through data combination. The advantages and disadvantages of different vector network analyzers are analyzed.

Vector Network Analyzers, from mobile phone networks to Wi-Fi networks to computer networks and the cloud, all of today's most common technology networks are implemented using VNA, invented more than 60 years ago. VNA is used to test component specifications and validate design simulations to ensure that the system and its components work properly. R&d engineers and manufacturing test engineers typically use VNA at all stages of product development. [18] Component designers need to verify the performance of their components, such as amplifiers, filters, antennas, cables, mixers, and so on. System designers must validate their component specifications to ensure that the system performance they rely on meets their subsystems and system specifications. The production line uses VNA to ensure that all products meet specifications before they are shipped for customer use. In some cases, VNA is even used in field operations to verify and troubleshoot deployed RF and microwave systems. As the most commonly used and important instrument in the microwave field, it has been widely deployed in various research institutes, universities and even research groups. However, its application value and test accuracy are rarely developed. [19] At the same time, the main suppliers of the vector network are very limited, and the equipment standards they produce are not uniform. When measuring the same equipment, the small signal parameters are basically the same, and the nonlinear results are different, especially in the intermodulation test. The difference can reach a considerable degree. So the precision calibration of vector network analyzer and the unity of measurement standards will be the direction of future development. [20]

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