Determination of the Complex Residual Errors of a Calibrated One-Port Vector Network Analyzer Using the Ripple Test

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Abstract — This article presents a new method of accuracy verification of calibrated one-port vector network analyzers based on the least mean square algorithm. The method is of particular interest for significantly limited frequency ranges as well as for cost-effective S-parameter measurement systems where the use of conventional ripple test may be impractical and/or relatively expensive. Experimental studies were conducted for few frequency ranges in coaxial measurement environment.

Index Terms — accuracy verification; S-parameters; residual error-box; ripple test; least mean square (LMS) algorithm; vector network analyzer.

I. INTRODUCTION

The vector network analyzer (VNA) measurement uncertainty depends on the calibration method applied. Verification of VNA is a very important issue for ensuring accurate measurements. The basic idea of verification is testing of standards with known or designed frequency properties. Several methods of verification are known [1]–[5]. These methods use precision transmission air lines or use the calibration comparison method. Reference [6] presents a new residual errors verification algorithm for one-port VNA. The practical application example of this algorithm is shown in [7]. The paper [7] considers the situation where a reference verification kit is not available and measurement conditions are such that the resolution in the time domain is low.

This paper considers the situation when the resolution in the time domain is lower. Some applications do not require the use of broadband VNA. The proposed algorithm is a good candidate for a wide range of practical applications especially for measurement uncertainty estimation of cost-effective vector network analyzers.

II. SYSTEM ERROR MODEL AND OBSERVED SIGNAL

The residual error model of one-port VNA consists of three components. Denote the residual directivity by $D$, the residual source match by $S$, and the residual reflection tracking by $R$. Determination of three residual factors simultaneously is possible only with the help of a transmission line terminated with a short or open and separation in the time domain. Fig. 1 shows a calibrated one-port VNA and error-box when performing verification.

$$M_k = D + R \cdot \delta_k \cdot \Gamma_k + S \cdot \delta_k^2 \cdot \Gamma_k^2,$$  \hspace{1cm} (1)

where $\delta_k = \exp(-\gamma_k \cdot 2l)$, and $S = S \cdot R$. Product $S$ and $R$ allows to find $S$ when $R$ is known.

Using the model (1) is acceptable if the variations of the residual factors are negligible. Minimum bandwidth defined by the length of line. Consider the proposed algorithm and perform experimental studies to determine its characteristics.
III. VERIFICATION ALGORITHM

The total number of unknown variables is 3. The vector of unknown constant variables is defined as:
\[ x = [D \ R \ S]^T. \]  (2)

Measurements of shorted air line are used to calculate the estimates of unknown variables. On the k-th step of verification (frequency point \( f_k \)) dependence of \( z \) observations from vector \( x \) can be written as:
\[ z_k = C_k \cdot x + n_k. \]  (3)

The observed signals are interrelated by complex linear expression with the vector \( x \) from (1). Thus the vector \( C_k \) is defined as:
\[ C_k = \begin{bmatrix} \delta_k \cdot \Gamma_k & \delta_k^2 \cdot \Gamma_k \end{bmatrix}. \]  (4)

Reflection coefficient sampling measurement inaccuracies are represented by noise \( n_k \). As the verification measurements arrive, i.e. for \( k=1,2,\ldots,K \), \( z \) combined into a vector:
\[ z = [z_1 \ z_2 \ldots z_K]^T. \]  (5)

Matrix \( C \) has the form:
\[ C = [C_1 \ C_2 \ldots C_K]^T. \]  (6)

As a result we can write:
\[ z = C \cdot x + n, \]  (7)
where \( n \) is the vector of noise. The solution of the equation (7) for the vector \( x \) with the least mean squares method is:
\[ \hat{x} = (C^H \cdot C)^{-1} \cdot C^H \cdot z, \]  (8)
where \( H \) is the operator of Hermitian transpose.

When processing measurements at frequencies \( f_k \) for \( k=1,2,\ldots,K \), estimates correspond to the range from \( f_1 \) to \( f_K \). The parameters of the line and of the short must be known and should not affect the estimate of residual factors.

IV. EXPERIMENTAL RESULTS

Experimental studies of the algorithm (5)-(8) were performed for verification of a calibrated VNA. Measurements have been performed with a VNA Agilent E8364B for the frequency range from 10 MHz to 32 GHz with 3200 data points (in frequency steps of 10 MHz) using 3.5mm connectors, and using a 75 mm air line. The intermediate frequency filter band was configured at 1 kHz, with a signal level of -15 dBm, with length of short being 9.5 mm. One-port Short-Open-Load calibration was performed before the measurements (using model 85052D calibration kit) [8]. The measured frequency response of an air line terminated with a short is shown in Fig. 3.

Fig. 3. Measured magnitude of reflection coefficient of a coaxial short-circuited air line.

The reference estimates of the parameters of the error-box received after processing of all the 3200 frequency samples (band 0.01-32 GHz) using special time domain technique [6] were compared to estimates received after processing of 200 samples (bands: 0.01-2; 2-4; 4-6; 6-8; 8-10 GHz; etc.) using the algorithm (5)-(8). The measured frequency response in the range from \( f_{\text{start}} \) to \( (f_{\text{start}} + 2 \text{ GHz}) \) is shown in Fig. 4.

Fig. 4. Measured magnitude of reflection coefficient of a coaxial short-circuited air line in the 2 GHz band. For example, frequency \( f_{\text{start}} \) is 10 MHz, 8 GHz, 12 GHz, 24 GHz, and 30 GHz.

In the case of the 2 GHz band, the resolution in the time domain is low. Fig. 5-7 shows the results of comparisons.

Fig. 5. Comparison for the magnitude (top figure) and the phase (bottom figure) of the residual directivity \( D \) (in 2 GHz bandwidths). The dotted lines on both figures show the reference estimates.
Fig. 6. Comparison for the magnitude (top figure) and the phase (bottom figure) of the residual reflection tracking \( R \) (in 2 GHz bandwidths). The dotted lines on both figures show the reference estimates.

Fig. 7. Comparison for the magnitude (top figure) and the phase (bottom figure) of the residual source match \( S \) (in 2 GHz bandwidths). The dotted lines on both figures show the reference estimates.

As shown in Fig. 5, the deviation of the residual directivity estimates is negligible. Similar conclusion can be drawn for other residual factors.

V. CONCLUSION

Summarizing this work, a new method was introduced and verified for estimation of the residual errors of an S-parameter calibrated measurement system. The method is based on the least mean square algorithm.

The algorithm produces qualitative estimates. One ripple should be in the frequency band to generate accurate estimates. Assumption of constant of the residual factors is accepted in a narrow frequency band only. These remarks should be considered when choosing the length of the line to verify the VNA within operational range of specific radio systems.

Relative to the other algorithm, software using the least mean square algorithm is much simpler to develop. Also, the proposed method can be used for verification in a narrow band of operational frequencies. Consequently, this new method can be of a special interest for cost-effective vector reflectometers and VNAs.

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