Residual Errors Determination for Vector Network Analyzer at a Low Resolution in the Time Domain

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Abstract — A method is introduced for determination of a vector network analyzer’s calibration residual errors for measurement of the reflection coefficient. The method utilizes unscented Kalman filtering and spline interpolation time domain techniques. All three residual errors are calculated by processing the measured reflection coefficient of a single verification device, such as an air line terminated with a short or open network. The proposed method shows particular advantages when the use of a long verification line is impractical (e.g. at the wafer-level), or for measurements at low frequency ranges or similar cases when the resolution of conventional time domain methods is low.

Experimental studies were conducted for two frequency ranges and in coaxial and on-wafer measurement environment. 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.

I. INTRODUCTION

Vector network analyzer (VNA) verification is a very important issue for ensuring accurate measurements. The basic idea of verification is testing of standards (other than calibration standards) with known (or designed) frequency properties [1]–[3]. Several methods of verification are known. In [3] the author performed a comparison of several methods. These methods use precision transmission lines and may be applied in the absence of a reference calibration kit. Otherwise, we can use the calibration comparison method [4].

This paper 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 occurs, for example, when working in a coaxial transmission line with a relatively low maximum frequency or on-wafer measurements in a wide frequency band. A long line segment with precision metrological parameters is difficult to fabricate, especially on-wafer. Nevertheless, verification should be carried out. To solve this challenge the developed method of verification a VNA has been investigated in such conditions.

II. ALGORITHM

The residual error model of one-port (reflection) measurements consists of three components. Therefore, verification of such a VNA requires several devices. Determination of three effective factors simultaneously is possible only with the help of a short or open transmission line and filtering in the time domain. Denote the line length by \( l \), the propagation constant by \( \gamma \) and the reflection coefficient of a short or open by \( \Gamma \). Fig. 1 shows an ideal VNA, an error-box when performing calibration and a residual error-box when performing verification. In verification, the input signal can be described as the sum of three components:

\[
\Gamma_M \approx D + R \cdot \Gamma_d + S \cdot R \cdot \Gamma_d^2.
\] (1)

The measured and actual reflection coefficients are denoted as \( \Gamma_M \) and \( \Gamma_d \), respectively.

Fig. 1. Representation of the one-port measurement system for calibration (top) and verification (bottom) measurements.

\( \Gamma_d \) is the known reflection coefficient of the verification device defined at the measurement reference plane. The residual error-box parameters are residual directivity \( D \), residual reflection tracking \( R \), and residual source match \( S \).

We described the calibration residual error model of the VNA in the time domain over a set of three networks, so-called “reflectors”. Each reflector has a known distance (time delay) and unknown frequency characteristics. Fig. 2 shows the set of samples in the distance-frequency plane. In Fig. 1, \( f_1 \) denotes start frequency while \( f_2 \) denotes stop frequency, \( \Delta f \) denotes frequency step between samples. To interpolate the frequency characteristics of the reflectors, we used cubic splines.

The estimation algorithm synthesis of the frequency characteristics of two or more reflectors with closely spaced delays was performed using the Markov theory of nonlinear filtering [5], [6]. A numerical algorithm was employed which applied the unscented transformation, leading to an algorithm known as UKF (Unscented Kalman Filter) [7]–[10]. This
algorithm is discussed in [11]. It should be noted that the parameters of the transmission line and of the reflection of the short or open ($\Gamma_A$) must be known and should not affect the estimate of residual factors. The number of frequency points for each reflector depends on the frequency range and frequency step $\Delta f$.

![Distance-frequency model](image)

Fig. 2. Distance-frequency model of the line terminated with the short or open network.

To obtain an accurate solution, the value of $\Delta f$ was selected so as to provide a phase step of $2\pi$ for a double line length, i.e.

$$\Delta f = c/(2 \cdot l), \quad c = 3 \cdot 10^8 \text{ m/s}. \quad (2)$$

### III. Experimental Results

Experimental studies of the algorithm were performed for verification of a VNA after one-port calibration. Studies were conducted in coaxial waveguide with 3.5mm connector coaxial environment, for the frequency range from 10 MHz to 8 GHz and to 32 GHz (in frequency steps of 10 MHz) and using a 75 mm air line ($\Delta f = 2$ GHz). The maximum frequency of 32 GHz was chosen to obtain a high resolution in the time domain. Measurements were taken using an Agilent Technologies E8364B VNA. The intermediate frequency filter 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 had been performed before the measurements (using model 85052D calibration kit) [12]. Artificial constraint of the maximum frequency allowed for performing a detailed analysis of the proposed method. An example of the measured frequency response is shown in Fig. 3.

![Reflection coefficient](image)

Fig. 3. Typical reflection coefficient of a coaxial line terminated with the short.

Transformation into the time domain was performed. The results are shown in Fig. 4 (separately for the 8 GHz and 32 GHz bands). There are three local reflectors present. Frequency parameters of the reflections contain information about the parameters of the VNA residual error-box.

![Time domain diagram](image)

Fig. 4. Time domain diagram (coaxial line).

However, in the case of the 8 GHz band, the resolution in the time domain is very low. The reflections cannot be separated.

Application was made of an algorithm [11] for processing the measured reflection coefficient (Fig. 3) and the main results of the algorithm operation were examined. The estimates of the parameters of the error-boxes in filters received after processing of all the 3200 frequency samples (band 32 GHz, thin line) were compared to the estimates received after processing of 800 samples (band 8GHz, thick line). Fig. 5-7 shows the results of comparisons.

![Comparison of residual directivity](image)

Fig. 5. Comparison for the residual directivity $D$ (top figure) extracted from 8 GHz (thick line) and 32 GHz (thin line) measured data as well as its absolute difference for two data sets (bottom figure). The dotted line on top figure show the value of directivity (the right Y axis).
source match errors. At the bottom of the graphs, the absolute difference between the estimates is shown.

Comparative analysis of the estimates reveals several important observations. In the overlapping frequency range (from 10 MHz to 8 GHz) the estimates of residual parameters were practically identical (with a difference of less than -70 dB).

When the algorithm processes the measurements near a certain frequency point, the estimates are produced mainly in the vicinity of this frequency. In the frequency range up to 32 GHz, the total number of complex unknowns is 51. In the range up to 8 GHz, the total number of complex unknowns is 15.

The proposed algorithm was also evaluated using an on-wafer measurement system in the frequency range up to 40 GHz. We used a 5.25 mm line (electrical length was 12 mm, time delay 40 ps, $\Delta f = 13.4$ GHz) opened at its second end (an open-stub) as the verification element.

Measurements were taken using a Rohde & Schwarz ZVA40 VNA, with SUMMIT probe station platform model 11000B-M. The VNA intermediate frequency filter bandwidth was 100 Hz, the output signal power level -10 dBm, and the frequency range from 10 MHz to 40 GHz (frequency step of 10 MHz). Two-port TRL calibration had been performed before the measurements. A Cascade Microtech Impedance Standard Substrate 101-190 C [13] was used. The measured frequency response is shown in Fig. 8. Processing of the measurements could be carried out as in the previous example. In this experiment, qualitative verification of our algorithm for wafer-level measurements was the focus. For this reason, and for simplicity, it was assumed that the radiation loss of the verification open stub element was negligible and that the characteristic impedance of the line was matched with the system reference impedance. However, the quantitative verification may require an extra step of the impedance transformation, as demonstrated in [14].

Transformation into the time domain was performed. The results are shown in Fig. 9. A number of window functions was applied: none (without window), Hamming window, and Nuttall window. Observe that the resolution in the time domain is very low. The pulses cannot be separated. Filtration in the time domain is not possible.
Fig. 9. Time domain diagram of the measured wafer-level open stub verification element.

An algorithm [11] for processing the measured reflection coefficient (Fig. 8) was applied and the results of the algorithm analyzed. Also when processing the measurements in the coaxial transmission line, a model of the line with losses was applied. Fig. 10 shows the residual directivity \((D)\) and residual source match \((S)\) errors. Fig. 11 shows the residual reflection tracking \((R)\).

The process results in values which accurately characterize the residual factors. Also note that the selected interpolation method requires three or more samples. In the given case four samples were used.

IV. CONCLUSION

In this paper an algorithm was presented which produces estimates of the frequency characteristics of individual reflectors at a low resolution in the time domain.

The effectiveness of the algorithm was shown, including analysis of experimental data applied to the problem of residual error verification in a VNA. Analysis of the experimental data in a coaxial transmission line compared the estimates of the residual parameters of a VNA in the respective frequency ranges at various resolutions (with various maximum frequencies for verification within the same VNA).

The effectiveness of the algorithm for solving the problem of on-wafer verification was also shown.

The algorithm can be used for verification in a narrow band of operating frequencies. The frequency range may be significantly limited. For example, this situation occurs when measuring a waveguide transmission line. In this case, a convenient verification standard is a short-circuited waveguide.

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REFERENCES


