A new TRL/TRM PCB-based Calibration Method for On-Board Devices Under Test (DUTs)

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***Abstract*— In this paper, a new TRL/TRM calibration method is described and compared to an electronic calibration module (ECal) method which is widely used in industry. This method needs a specifically made de-embedding board but does not require an expensive ECal or any special precision board-level calibration devices. The method is applied to an automotive sensor interface IC showing the new calibration method enables us to conduct accurate on-board S-parameter measurements up to 4 GHz whereas the other method becomes inaccurate above 500 MHz.**

***Keywords*— VNA, S-parameter measurements, calibration, thru-reflect-line (TRL), short-open-load-thru (SOLT)**

I. Introduction

Characterization of electromagnetic systems by their scattering parameters is the most suitable tool for full wave analysis and EMC problem simulations [1]. By using a Vector Network Analyzer (VNA), scattering parameters (S-parameters) can be measured over frequency. However, as in reality making perfect hardware is not possible, it is necessary to do a measurement calibration before S-parameter measurement.

Among a variety of calibration methods, the most commonly known are SOLT [2] and TRL [3] which are based on 8-term or 12-term error models. SOLT is an abbreviation for Short, Open, Load and Thru. It measures one transmission standard (T) and three reflection ones (SOL). TRL is an abbreviation for Thru, Reflect, and Line and it measures two transmission (T and L) and one reflection (R) standards to determine the error coefficients. Different calibration techniques such as TRM (Thru, Reflect, Match), LRL (Line, Reflect, Line), LRM (Line, Reflect, Match) belong to the TRL family. An overview is given in [4].

Each of these calibration techniques has its advantages and disadvantages depending on frequency range and application. While the math behind SOLT is simpler than the TRL, the latter has a better accuracy. That's because SOLT needs well-defined standards whereas a limited knowledge of the calibration standards does not impact the accuracy of the TRL method [5]. TRL standards only need to be representative and repeatable without being precisely known [6].

The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 812.790 (MSCA-ETN PETER). This publication reflects only the authors' view, exempting the European Union from any liability. Project website: http://etn-peter.eu/.

This paper presents a new on-board calibration method which is based on the TRM and TRL methods. In comparison to an ECal method which basically is an automatic SOLT calibration technique that enables to calibrate at the PCB connector level, this is a manual method that enables to calibrate at the level of the device under test (DUT) pins resulting in more accuracy at higher frequencies. This method is mainly useful for testing on-board DUTs such as SMD components and PCB circuits. In this paper we used both calibration techniques and did S-parameter measurements on a DUT to compare the two methods. The measurement result shows that the new calibration method is accurate up to 4 GHz whereas the ECal result becomes inaccurate above 500 MHz.

On the other hand, a disadvantage of this method is that it is a manual calibration and needs more time compared to the electronic module. While there may be other TRL calibration structures which can be as accurate as this one, this method has proven to be very convenient in practice.

The structure of the paper is the following: in section II, a description of the method and the theory behind it are presented. In section III, the method is verified by measuring the S-parameters of a test chip that was produced in a previous R&D project (i.e. an automotive sensor interface chip that was called TOLERAN TC1 [7]). Finally, in section IV we offer some concluding remarks.

II. Theory

A. ECal Calibration

The calibration of a VNA has a double function: setting the reference planes of the test ports, and correcting the systematic measurement errors of the test setup. Typically, the VNA will be calibrated using either a traditional mechanical calibration kit (Calkit) or an ECal module. When using a Calkit, different connections to the test ports need to be made for a single calibration, while a full calibration can be done with a single connection to the ECal module. Therefore, an ECal calibration is not only faster but also less susceptible to operator errors [8].

The ECal operation is based on a SOLT calibration, which can determine the error coefficients of a full 12 term error model [9]. This device sets the reference planes at the end of the test cables where they connect to the test board on which the DUT is mounted. Hence the effect of the coaxial-to-PCB transitions and the PCB itself are not taken into account and will affect the measurements. Hence, we only correct for transmission loss and phase errors of the cables but not for PCB traces and mismatch at the SMA connectors. Moreover, as the frequency increases, this error increases too. Therefore, there is a need for de-embedment of the PCB effects but no simple and good solution is available [10]. Using the port extension feature of the VNA can correct for the electrical length between the SMA connectors and the pins of the DUT when we use ECal for calibration, but there is still inaccuracy in measurement results due to mismatch errors of the SMA connectors and miscrostrip lines.

B. *Proposed Calibration Method*

The proposed method is a combination of the TRM and TRL calibration techniques and is based on True, Reflect, Match and Line calibration standards. It fully corrects 10 error coefficients of 12-term error model [9], two other error terms are due to leakage that we did not consider in this study. At higher frequencies, TRL calibration is used which is the more accurate approach since it does not need lumped models and precise calibration standards. But at lower frequencies, using TRL is impractical because of the long length of lines [11,12]. The alternative approach at lower frequencies is TRM, which applies a match standard instead of the line standard used in TRL. This perfect match can be considered as an infinitely long line, which is also the limitation of the TRM method as determining accurately the load impedance is very difficult at higher frequencies [13,14]. In this study, we use the advantages of both methods where we use the TRM method for lower frequencies up to 500 MHz, and the TRL calibration at higher frequencies. This calibration requires a specially made de-embedding board called calibration board which will be explained in detail in the next section.

This new calibration method is a manual technique and takes more time than using an ECal. The advantage is that it is more accurate as it sets the reference planes at the component terminals and additional de-embedment is not required. This technique is also convenient to accurately measure an SMD component or an on-board structure. Then the reference planes can be located at the on-board terminals of the component-under-test.

III. METHODOLOGY & MEASUREMENT RESULTS

Measurements were performed using an advanced four-port Keysight E5080A, with frequency range from 9 kHz to 9 GHz and a set of short precision test cables with guaranteed phase and amplitude stability. A four-port ECal N4431B, 9kHz to 13.5GHz was also used. On the calibration board, 8 SMA through-hole PCB-mounting connectors were used and FR4 with the dielectric constant of 4.3 was the material of the PCB. The calibration quality is validated for both TRL/TRM method and ECal. This evaluation of the two methods was performed before the TOLERAN TC1 measurements.

For TRL/TRM calibration board, the primary length which is the length of traces from the SMA connector to the reference plane was set to 37mm, the trace impedance was around the targeted reference impedance of 50 Ω and all tracks on the surface layer are microstrip lines. To cover the frequency up to 6 GHz, on the calibration board one thru, one open (Reflect), 2 lines (called 1 and 2) and one load were considered. See Fig.1.

Thru length is twice the primary length and it has connectors

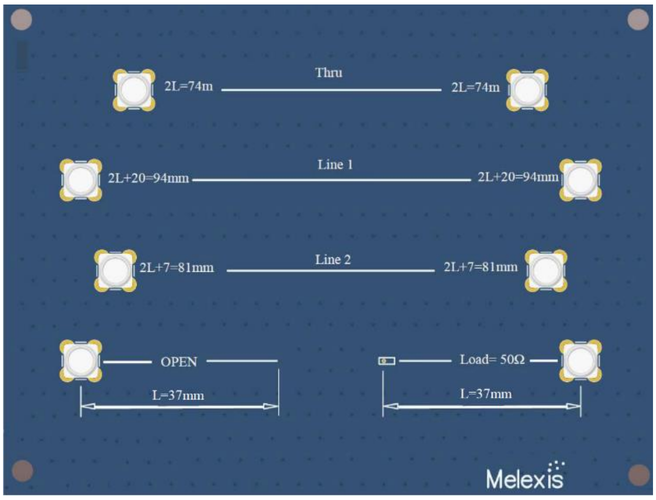

Fig. 1. TRL/TRM calibration board

at both ends. For the Reflect standard, an open is used. Each trace of line1 and 2 has a specific offset length compared to thru. The offset length of two lines is controlled at least 20 - 30 degree phase margin at the determined boundary frequencies. Thru and open can cover the whole frequency range 0-6 GHz, line 1 with an offset length of 20mm referenced to thru is used for frequency range of 0.5 GHz to 3 GHz and line 2 with an offset length of 7 mm compared to thru can cover frequencies between 3 to 6 GHz. The Load covers the low frequency region below 500 MHz which behaves as an infinitely long Line. For the Load, one precision 50 Ω 0603 size resistor is connected towards the end of the primary length for termination.

A. *Evaluation of TRL/TRM Method*

For comparison purposes, we performed both ECal and TRL/TRM calibrations and measured S-parameters for a test board similar to the calibration one which had two extra traces, one short and one line with 20 mm shorter length compared to thru called line 3.

Thru measurement data which were acquired after TRL/TRM method and ECal calibrations are shown in Fig. 2.a. For S12 magnitude, deviation from 0dB for the calibration board is -0.0105dB up to 6GHz and phase deviation from 0 degree is within 0.3 degree up to 4.5GHz, at the worst case it reaches to 5.1618 degree for frequencies near 6GHz. But for ECal S12 magnitude deviation is -11.6733dB and phase diagram shows different oscillations between -180 and +180 degrees. Also for the calibration board figures show nearly perfect phase linearity for frequencies up to 6GHz while for ECal some nonlinearities can be seen at different frequency sections.

Fig.2. (b, c) show measurement results for line 1 and 3. As the length offset for two lines referenced to thru is the same, we expect to have symmetrical phase and magnitude for S12. Plots prove perfect symmetry in phases and magnitude for 2 lines when we used calibration board. In contrast, there is no symmetry in phase or magnitude when calibration was done by ECal.

In Fig. 2.d, the measurement result for short is shown. Here also the difference between 2 methods are clear. While the deviation from 0 dB is -0.1919dB by calibration board it is -10.5801 dB for ECal one. Also in phase, the nearly perfect short circuit can be seen up to 4GHz, but for ECal an obvious

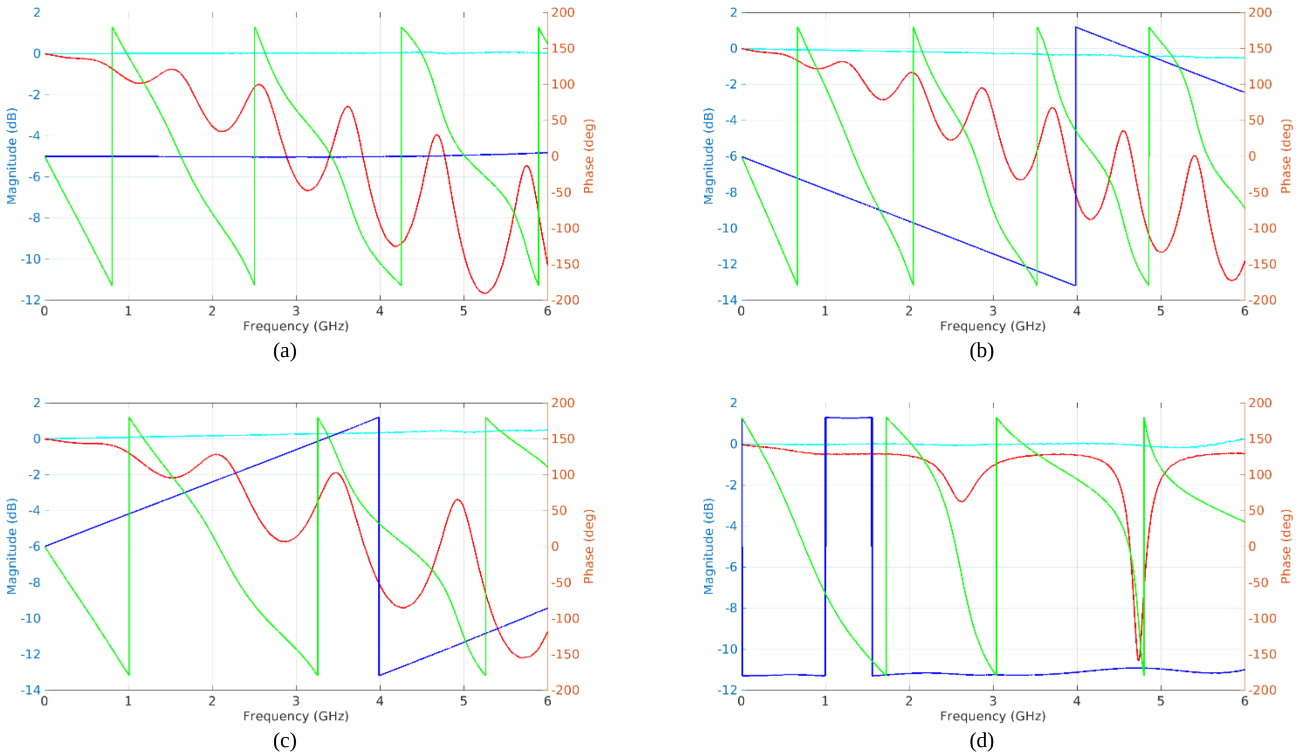

Fig. 2. S-parameter measurement results versus frequency for the test board calibrated by TRL/TRM calibration method and ECal. S12 magnitude calibrated by TRL/TRM method — , S12 magnitude calibrated by ECal — , S12 phase calibrated by TRL/TRM method —, S12 phase calibrated by ECal — (a) Thru (b) line 1 (c) line 3 d) short

nonlinearity can be seen at different frequency sections, even though we can see short circuit behavior in the phase plot.

B. Measurement Comparison

TOLERAN TC1 which is a sensor interface IC used in the TOLERAN project [7] was measured using the two different calibration methods. In this case, there was a need for designing an additional board to measure S-parameters. In fabrication, we used the same PCB purchase order as calibration board and the same 4-layer SMA connectors. No on-board supply and monitoring networks were used, supply and monitoring were done via the integrated bias tees of the VNA.

On S-parameter test board, all injection lines have the same length as the primary length of the calibration board. Here it is 37mm. This length is measured between the center of each SMA connector and the corresponding center of the solder pad of the IC pin-under test. Fig. 3 shows TOLERAN TC1 schematic and external components for applying this IC in S-parameter measurement. This device is a mixed signal sensor interface IC which converts small changes in resistive Wheatstone bridge to large output voltage variations.

According to application information of this IC, four 3.9kΩ resistors were used as bridge resistors which provided a basic protection but no decoupling capacitors were used in this measurement. Nominal supply voltage and current were 5V and 9.1mA during this test. Also, nominal voltage of Vbrg and output pins were 3.083v and 2.434v respectively, as well. The injected power was set to 10dBm at the VNA to have linear S-parameters. It was also possible to increase the power to 15dBm where the S-parameter results are still in linear region and did not change during the measurement.

As it is shown in the picture, port 1, 2, 3 referred to supply, output and bridge voltage called Vbrg, respectively. Fig. 4 (a, b, c, d) clearly proves using different calibration methods affects the result of S-parameter measurements. Comparison between S11, S22 and S33 measurement calibrated by TRL/TRM method shows that most of the incident RF energy is reflected from the output pin. However, the Vbrg pin is the most susceptible one and chip can be disturbed by it very much. This means that more protection for this pin may be needed when an application PCB is designed.

On the other hand, by applying ECal calibration the magnitudes and phases of the reflection parameters, S11, S22 and S33 are different from the former ones. While it was clear Pin3 is the most susceptible one with the TRL/TRM calibration method, it is not obvious which pin has the worst case by ECal calibration. In this case measurement results show the weakest reflection parameter is S22 with the magnitude equal to -26.4284dB at 4.136GHz while the weakest one by the TRL/TRM calibration method is S33 at 3.322GHZ with -18.07 dB magnitude. Fig. 4.c also shows a big difference in phase of S33 between two methods and specially at higher frequencies.

Looking at the Fig. 4.d again confirms the importance of using this method in our calibrations which shows the results for the transmission parameter between bridge pin and supply one.

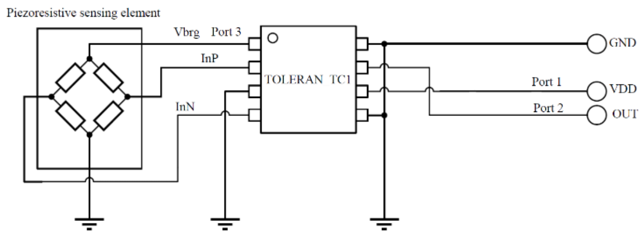

Fig. 3. Application schematic for TOLERAN TC1 in S-parameter measurements

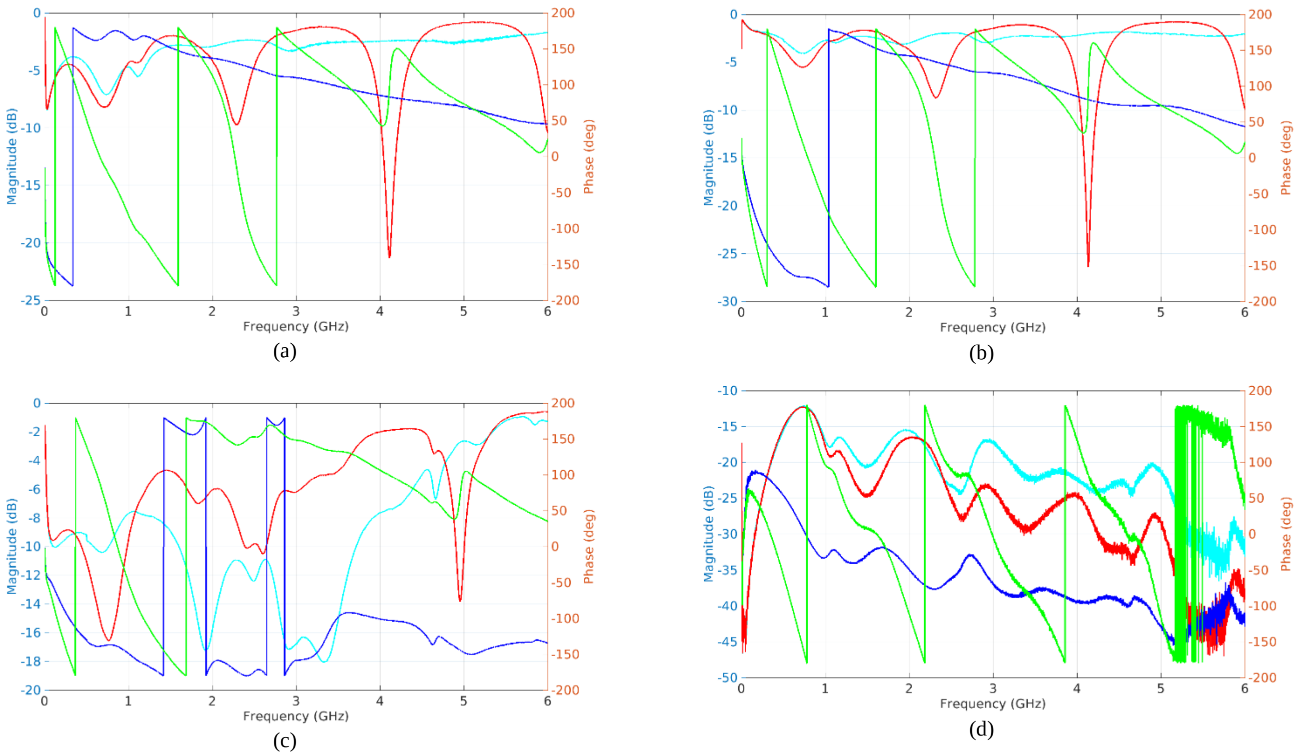

Fig. 4. S-parameter measurement results versus frequency for TOLERAN_TC calibrated by TRL/TRM calibration method and ECal. S-parameter magnitude calibrated by TRL/TRM method —, S-parameter magnitude calibrated by ECal —, S-parameter phase calibrated by TRL/TRM method —, S-parameter phase calibrated by ECal—, (a) S11 (b) S22 (c) S33 d) S13

Here more important than magnitude is the difference between phase measurement result. While by ECal we can see different frequency sections resonance between 180 degree and -180 degree, by the calibration board S13 phase is between 89 degree and -153 degree. As the transmission parameter can show the unintentional parasitic effects, the importance of this inaccuracy is obvious although part of the inaccuracy may be due to the difference in electrical length as no port extension was applied to the reference planes set by the ECal.

We also repeated the calibrations and measurements after one month and the obtained results perfectly matched with the first ones, which shows the repeatability of TRL/TRM calibration method.

IV. Conclusion

Even though the ECal method is much more convenient than the TRL/TRM calibration method, the accuracy should not be sacrificed by the simplicity. In this paper, we first evaluate this method by comparing the S-parameter results calibrated using this method and ECal which clearly shows the accuracy of TRL/TRM calibration approach. In another experiment, the S-parameters of an automotive sensor interface called TOLERAN TC1 measurement reveals the importance of using an accurate calibration method. This method is also cost effective compared to ECal which is an expensive device.
The accuracy of the proposed method was nearly perfect for frequencies up to 4GHz while ECal was only accurate up to 500MHz. To design this calibration kit for frequencies above 4GHz we need to take some other approaches which is not in the scope of this paper.

Looking at Fig. 4. a, b we observed that the impedance of the supply and output pins become inductive at higher frequencies which can be due to package effects.
Also Fig. 4. C shows the bridge pin is no longer high impedance at higher frequencies. These results show the need for behavioral EMC models of ICs to accurately model the scattering parameters of a device.
Therefore, because the value of the calibration board has been demonstrated, the authors will apply this methodology to behavioral IC models in further work.
This calibration approach should also be interesting for the validation of EMC simulations, the characterization of the EMC behavior of SMD passive components, the RF characterization of other passive PCB structures, and the development of new technologies which need to be characterized.

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