Advanced TRL Method for Differential Devices

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***Abstract*— A stringent calibration of Vector Network Analyzers (VNA) is necessary for an accurate measurement of RF and microwave devices, especially when differential connections are brought onto a highly integrated measurement substrate, resulting in improving the accuracy that is important in sensitive applications, such as human health and education quality. We present an improved Thru-Reflect-Line (TRL) calibration technique for components such as receivers with differential inputs and single-ended outputs. The proposed method generalizes the previous two-port TRL measurement to an asymmetric three port system, using either simulated or on-wafer characterized standards, which is made up of three sequential calibration routines based on an impedance-bridging procedure that allows for all the elements of the impedance (Z) matrix to be obtained, even those which are in principle inaccessible. Validation by simulation using Agilent ADS shows good agreement between the reconstructed and ideal parameters. The results demonstrate that the proposed method is scalable, accurate and applicable for measurement of embedded devices, such as transition in differential structures where standard calibration kits are restricted or limited by geometry or access to connector.**

Keywords— ***Calibration, TRL, Differential, Test board, DUT.***

I. INTRODUCTION

Traditional calibration techniques often do not provide the accuracy and versatility required by the new high frequency, fast speed electronic platforms. Because of smaller, multi-chip and possibly multilayer packages with often-differential interconnects implemented inside the printed circuit board (PCB), RF measurement is made more difficult. These challenges are primarily due to restricted port access and the asymmetry of differential transmission paths. In this context, the Thru-Reflect-Line (TRL) method has emerged as a reliable alternative to classical Short-Open-Load-Thru (SOLT) technique. While SOLT relies on standard impedance standards, TRL uses a transmission-line reference plane which makes it more suitable for non-coax and on-board measurements.

Relying on a previously validated two-port TRL calibration technique [1] this procedure is also extended to devices with differential inputs and single-ended outputs. Generic AI-ML approaches are being increasingly utilized in BB transceivers, integrated baluns and analog front-end ICs. This calibration method has the advantage that it requires only custom-made standards, which can either be simulated using electromagnetic simulation tools or derived from direct on-wafer measurements, making its practical realization in realistic test environments feasible. An unique point that the present technique is the combination of an impedance-bridging process, by means of which a full reconstruction of () matrix (containing the element) is obtained that cannot be achieved using conventional TRL methods.

This paper presents the structure of the proposed calibration method, analytical expression of -parameter extraction and confirmation of reliability by simulation.Results. One overall goal is for the calibration to be efficient and repeatable, for easy porting to different embedded differential systems.

For clarity, the rest of the paper is structured as follows. Section II reviews the state of art on TRL calibration scale applied to complex system RF. The proposed dual-TRL method and its theory are described in Section III. Section IV explains the simulation settings and how they were validated. Section V presents and discusses the results, followed by concluding remarks in section VI and outlook to future work.

II. RELATED WORKS

The advance of RF and microwave technology has led to the development of more advanced calibration techniques in order to be compatible with differential signaling or multi-port operation. The original TRL method, of which I~present a slightly modified version based here on the I:3-plane VNA scanning technique, was optimized for coaxial scenarios but is now in a state-of-aw process that familiarizes it with complex and cabled-in environments.

In 2022, Ehsan et al. [6] presented a multiline TRL technique for de-embedding differential multi-port devices considering the effects of asymmetric transmission lines and impedance mismatch between ports. They demonstrated the correctness of our reference standard customization and optimized de-embedding procedures, which are capable of effectively improving S-parameter accuracy for non-standard network topologies.

One year later, Wang and Lee [7] introduced a mixed-mode TRL that could measure both balanced and unbalanced transmission and reflectance of a single calibration structure. The scheme also focuses on the conversion of common- to differential-mode signals, which is a problem which occurs frequently in high-speed interconnects and monolithic integrated RF modules.

Martinez-Gonzalez et al. [8] expanded the concept of TRL-based calibration to millimeter-wave circuits by incorporating the standards into a device-under-test (DUT) layout so that extraction uncertainties in connectors and cable transits are minimized. Meanwhile, Hu and Zhang [9] used a hybrid co-simulation approach combined with circuit-level simulation and electromagnetic analysis to more accurately take account of the coupling and discontinuity effects. Similarly, Li et al. [10], TRL has been modified to support flexible microwave substrates, and results were favorable for wearable and reconfigurable electronics.

To address the remaining TRL limitations, adaptive and learning-based methods have been recently introduced. Zhang et al. [11] used an AI-based self-tuning TRL scheme that dynamically adjusts calibration parameters with respect to different board states. Kim and Yoon [12] pursued a similar route, by designing distributed TRL network equipped with embedded sensors and ML-based error correction to maintain accuracy under deformable RF stages.

In sum, those previous publications highlight a clear shift toward smart integrated flexible TRL methods. Although effective, the majority of these methods still rely on complex physical setups or idealized port accessibility. On the other hand, what is introduced in this work is a methods to fully extract the () matrix of differential devices with minimum hardware overhead and simulation-assisted calibration standards.

III. DOUBLE TRL CALIBRATION PROCESS

The Thru-Reflect-Line (TRL) procedure introduced in [1] is implemented in two consecutive configurations. The first configuration connects the calibration standard between Ports P1 and P3, while Port P2 remains unterminated to decouple its influence.

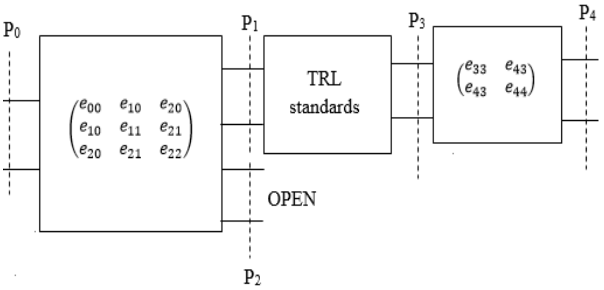

Fig.1. First TRL step: The TRL standards are connected between P1 and P3; P2 remains open.

Accesses 0 and 4 represent the external reference points of the calibration environment. The first measurement yields the following matrix relationships for the sub-networks:

$$\text{For A:} \quad \begin{pmatrix} e_{00}^{(1)} & e_{10}^{(1)} \\ e_{10}^{(1)} & e_{11}^{(1)} \end{pmatrix} \tag{1}$$

$$\text{For B:} \quad \begin{pmatrix} e_{33} & e_{43} \\ e_{43} & e_{44} \end{pmatrix} \tag{2}$$

These matrices are subsequently converted to their de-normalized impedance form. Because Port 2 is left open in this setup, the resulting impedance matrix of the three-port network can be expressed as:

$$\begin{pmatrix} Z_{00} & Z_{10} \\ Z_{10} & Z_{11} \end{pmatrix} \tag{3}$$

The second configuration follows the same logic, except that Ports P2 and P3 are now interconnected through the line standard, and Port P1 is left open. Combining the outcomes of the two measurements provides all Z-matrix elements except Z_{21}. To obtain this remaining term, a supplementary measurement is introduced.

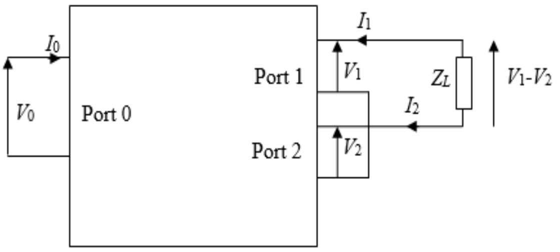

Fig.2. Third step: Determination of Z_{21}: Ports P1 and P2 are connected by a wire of impedance Z_L.

The input reflection coefficient $S_{00}$is related to the input impedance Z_{in}. The missing parameter $Z_{21}$is computed as:

$$Z_{21} = \frac{Z_{11}-Z_{22}-Z_L}{2} - \frac{(Z_{20}-Z_{10})^2}{2(Z_{00}-Z_{IN})} \qquad (4)$$

where Z_L represents the impedance of the interconnection between P1 and P2, determined either from electromagnetic simulations or by on-wafer characterization. This final configuration completes the extraction of all impedance-matrix elements and establishes full three-port calibration for the differential device under test..

IV. MEASUREMENT SIMULATION

The calibration process was simulated using an ideal balun, following the configuration outlined in [3]. In the first TRL setup (Fig. 3), Ports 1 and 3 are interconnected, while Port 2 remains unterminated to isolate its effect on the system response. The second configuration follows the same approach, except that Ports 2 and 3 are connected and Port 1 is left open.

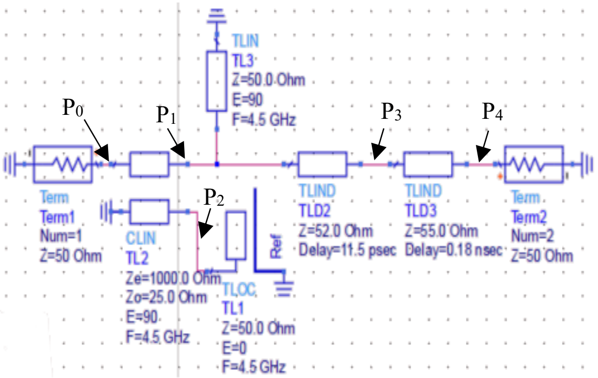

Fig.3. Calibration between P_1 and P_3

In both arrangements, the thru and line standards are implemented as transmission lines with characteristic impedances distinct from the nominal 50 Ω reference, whereas the reflect standard is modeled by a π-type equivalent circuit. From the initial TRL stage, the S-matrix of block B and the impedance components Z_{00}, Z_{10}, and Z_{11} of block A are derived. Repeating the procedure with the second configuration provides the same S-matrix of block B and the impedance terms Z_{00}, Z_{20}, and $Z_{22}$of block A.

The third configuration, illustrated in Fig. 4, focuses on extracting the element Z_{21}. In this setup, Ports 1 and 2 are connected through a transmission line having impedance Z_L. This link enables computation of the remaining impedance parameter necessary to complete the full Z -matrix representation of the three-port network.

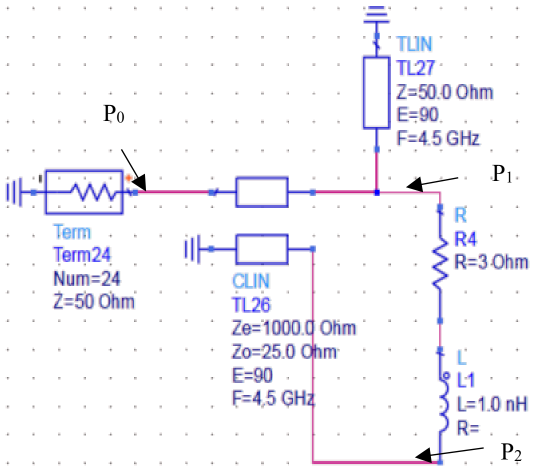

Fig.4. Third step to determine Z_{21}

Once all measurements are finalized, every component of the impedance matrix is obtained and normalized to a 50 Ω reference. The resulting data for networks A and B are then compared to their original simulated counterparts, confirming the accuracy and repeatability of the proposed calibration methodology.

V. SIMULATION RESULTS

The proposed calibration procedure involves seven sequential measurements: two thru, two line, two reflect, and one link configuration. From these simulations, the impedance characteristics of both the three-port network A and the two-port network B were obtained. A detailed comparison between simulated and reconstructed data reveals a strong correspondence, especially in the imaginary components of the impedance parameters Z_{B11} and Z_{B21} . Comparable agreement was also observed across the other matrix elements, confirming the robustness of the extraction process.

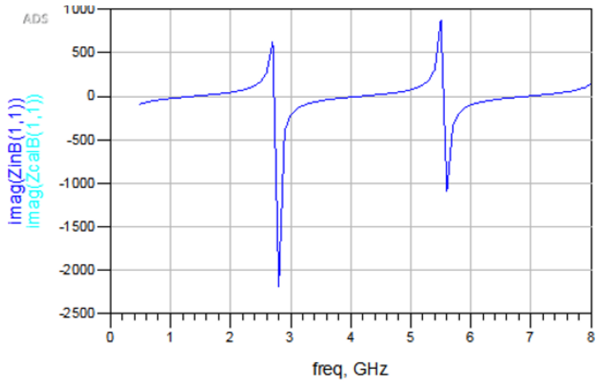

Fig.5. Imaginary part of Z_{B11}

The results demonstrate that the developed calibration effectively eliminates fixture and transition artifacts, providing impedance responses that mirror those of the reference simulations. This close correspondence confirms that the implemented TRL model accurately compensates for phase and magnitude variations introduced by the measurement setup.

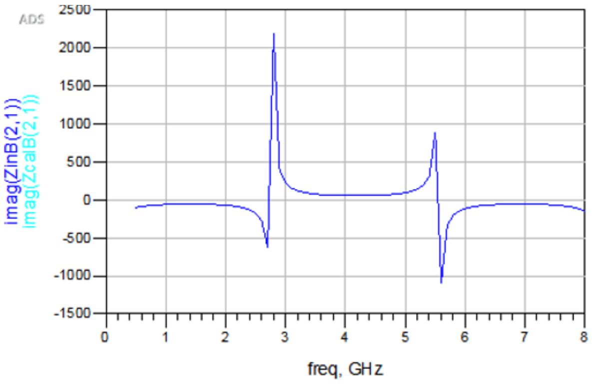

Fig.6. Imaginary part of Z_{B21}

The close alignment between simulated and reconstructed Z_{B21} values—representing the transmission between the differential input and the single-ended output—validates the inclusion of the impedance-bridging configuration. This additional step enables precise recovery of the previously inaccessible parameter and ensures full reconstruction of the impedance matrix.

Collectively, these outcomes verify that the enhanced TRL approach yields reliable and high-fidelity impedance extraction for asymmetric differential structures, confirming its suitability for accurate calibration of embedded RF devices.

VI. CONCLUSION

One of the major problems in high-frequency metrology is to calibrate Vector Network Analysers (VNAs) accurately for a non-standard device, especially for that with differential inputs and single- ended outputs. With traditional calibration kits, connector geometry, restricted port access and asymmetric signal paths frequently limit the ability to achieve an accurate measurement.

In this paper, an improved Thru-Reflect-Line (TRL) calibration mechanism is presented to generalize a previously proposed two-port procedure for unbalanced three-port structures. The proposed method, consisting of two separate TRLs followed by a bridging step process for the impedance properties, allows full retrieval of the impedance matrix including the element which otherwise cannot be recovered in conventional TRL methods. Comparisons between the extracted and reference data in simulations showed good consistency and further verified its accuracy for practical use.

The method provides a highly scalable and integrated solution for PCB-differential systems with severe spatial and connectivity constraints. Although the current validation was performed on a simulation level, our results indicate excellent experimental feasibility. Future work will involve hardware realization, optimization of the error-correction algorithms, and generalization to higher frequency and multi-port situations.

Further research directions will be to design a dedicated verification board for experimental measurement, to study the effect of parasitic coupling and interconnect discontinuities and to extended the technique for millimeter-wave by using advanced fabrication methods. The additional integration of the presented model within automated measurement systems would facilitate real-time high-throughput calibration procedures.

In the scope of flexible and wearable RF and microwave techniques shaping up, precise calibration of bending or/and non-planar elements is more important for their future applications. Integrating simulation-led TRL as well as machine-learning-driven drift compensation might finally result in a next-generation intelligent and adaptive calibration system. The work presented here thus not only alleviates existing drawbacks of differential measurement but additionally lays the groundwork for new developments in on-chip microwave metrology.

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