Comparison of TRL Calibration vs. 2x Thru De-embedding Methods

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Abstract— In this paper, TRL (Through-Reflect-Multiple Lines) and 2x thru de-embedding schemes of AFR (Automatic Fixture Removal) and SFD (Smart Fixture De-embedding) are compared from various perspectives: calibration fixture design, calibration / de-embedding procedure, and the measurement accuracy. Especially for the accuracy comparison, one of our test boards which support TRL calibration up to 40 GHz was used. In order to derive a valid conclusion, the calibration / de-embedding standards were thoroughly examined and calibration stability and de-embedding accuracy were tested. The comparison showed excellent correlation in IL, RL, NEXT and FEXT over the full frequency range of measurement, while the 2x thru de-embedding method significantly simplifies the de-embedding procedures.

I. INTRODUCTION

Accurate electrical characterization of high speed interconnects, such as connectors, vias, cables, and traces on a package or on a PCB (Printed Circuit Board), over the wide region of frequency is critical in successful high speed bus design. As the data rates increase, the characterization gets more difficult and challenging.

Electrical characterization of high-speed interconnects is usually done in the frequency domain using a VNA (Vector Network Analyser). A DUT (Device Under Test) is typically mounted on a PCB (Printed Circuit Board), which provides connection of the DUT to the VNA, the complete removal of test fixture artifacts is very important as the test fixture manifests its own characteristics over high frequency region. The removal is done by calibration or a de-embedding process and the quality determines the accuracy of measurement [1].

Although TRL (Through-Reflect-Multiple Lines) has been known to be one of most accurate calibration methods, the complexity and difficulties in design and measurement limit its usage. For this reason, various simplified de-embedding techniques have been reported. Among those various de-embedding techniques, 2x thru de-embedding scheme such as AFR (Automatic Fixture Removal) [2, 3], SFD (Smart Fixture De-embedding) [4], ISD (In-Situ De-embedding) [5, 6], etc. stands out due to its simplicity. Even AFR claimed its accuracy was comparable or equivalent to the one of TRL [7].

In this paper, we validate the accuracy of AFR and SFD compared to TRL. For proper evaluation, we used our test board which was designed to support TRL calibration up to 40 GHz with high measurement stability and accuracy [8]. As 2x thru de-embedding needs only one structure of Primary thru from TRL standards, the test board was reused for the 2x thru de-embedding methods.

This paper is organized as follows: First, the comparison between TRL and 2x thru de-embedding methods is summarized in terms of complexity in a test fixture design and calibration / de-embedding procedure. Second, fundamentals of TRL calibration / de-embedding structure design and the evaluation procedures are presented. Third, measurement data of TRL, AFR and SFD are compared.

II. TRL VS. 2X THRU DE-EMBEDDING, COMPARISON OF TEST FIXTURE DESIGN AND MEASUREMENT PROCEDURE

The differences between TRL versus 2x thru de-embedding methods are summarized in Table 1 considering typical design and measurement procedure in our lab.

<table>
<thead>
<tr>
<th>TRL</th>
<th>2x Thru De-embedding</th>
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<tr>
<td>• Design Calibration standards (thru, multiple secondary lines, short, load)</td>
<td>• E-Cal to Launch Connector; one step automatic calibration with no need to define calibration standards.</td>
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<tr>
<td>• Define calibration standard characteristics in VNA Calibration Setup</td>
<td>• Measure 2x Thru</td>
</tr>
<tr>
<td>• Many steps in calibration procedure. More room for error involvement and difficult in root causing.</td>
<td>• Measure DUT</td>
</tr>
<tr>
<td>• Direct measurement of DUT</td>
<td>• De-embed to get results</td>
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Table 1. TRL vs. 2x Thru De-embedding

TRL calibration kit has four fundamental elements: Primary thru (2x thru), Reflect, Multiple lines and Load. On the other hand, 2x thru de-embedding needs only one element, a Primary thru for de-embedding. Hence a test board area covering de-embedding structures can be reduced by as much as 80%, when 2x thru de-embedding is adopted.

Also each TRL calibration standard needs to be designed in a way to follow its own design rule. However, designing the TRL standards properly satisfying its own design rule is not a trivial task. So the 2x thru de-embedding methods can save time and effort in the test board design.

Once a test board is designed and the board is fabricated, all the components of TRL calibration standards should be evaluated before making measurements. Typical TRL calibration starts with setting up a calibration Kit for each element, by providing various customized information and
options. While performing many steps for a complete TRL calibration, users face various options and questions, which is not trivial. As human error can involve in any operational step, troubleshooting is difficult when calibration does not work properly.

For 2x thru de-embedding methods, when the test board is evaluated after manufacturing, only Primary thru needs to be evaluated before de-embedding. We use ECal (Electronic Calibration) before AFR/SFD in order to set the reference planes (the virtual points where measurement begins and ends) at VNA cable ends. ECal is rather straightforward with fewer steps, which reduces chances of human error involved in the process. Once the measurement is done after ECal, the de-embedding is applied as a post process in order to get DUT-only data by removing all the rest of test fixture artefacts and moving the reference plane close to DUT from the cable ends.

III. CALIBRATION/DE-EMBEDDING FIXTURE DESIGN

Calibration fixture / standard design plays a critical role in accurate measurements. In the design, impedance discontinuity should be minimized and any resonance should be avoided within the frequency region under test. Also, the loss should be minimized in order to increase the dynamic range of the DUT measurement and the measurement accuracy.

In this section, our TRL calibration design, which supports VNA measurement up to 40 GHz, is introduced and the calibration quality is validated for both TRL and AFR/SFD. The calibration quality evaluation is presented before DUT measurement comparison.

A. TRL Calibration Standards and Quality Verification

![Figure 1. TRL Calibration Kit](image)

For TRL calibration standards, one Primary thru, one Short (Reflect), three Lines (called Secondary 1, 2 and 3) and one Load were used. Detailed information of length and offset delay time for lines is shown in Figure 1. The Half Primary thru in Figure 1 is not used for the calibration.

In the test board/standard design, trace impedance was tightly controlled within 5% (2.13 Ω) around the targeted reference impedance of 42.5 Ω. In order to provide extended frequency range up to 40 GHz, 2.4 mm launch connectors were used. The Footprint of the 2.4mm launch connector on the PCB was optimized for improving impedance continuity, minimizing reflections and preventing any resonance. Low loss PCB material was used and the distance between the DUT and the launch connector was minimized to extend the dynamic range of the measurement and to enhance the measurement accuracy. The traces which connect the launch connectors and DUT were all length matched within 0.5mil difference. All the calibration standards are routed on the surface layer using microstrip routing. A thru via is located on the bottom of each launch connector as the launch connector does not allow the surface routing on the same side with the connector.

Primary thru length is twice the length of traces from the launch connectors to reference planes. Primary thru has launch connectors on both ends. Its design should be optimized so that IL (Insertion Loss) is larger than RL (Return Loss) over the full frequency region of measurement. The frequency where IL and RL cross tends to indicate the stop frequency of the de-embedding capability. For the Reflect standard, Short is used. The trace of each Secondary line has its own specific offset length referenced to the Primary thru. The offset length of a Secondary line is precisely controlled to provide at least 20 - 30 degree phase margin at boundary frequencies of its corresponding calibration section. The Load covers the low frequency region below 400 MHz and precludes the need of an infinitely long Line. For the Load, two 85 Ω 0201 size resistors are connected in parallel at one end, creating a 42.5 Ω termination, and the other end is connected to a launch connector.

Before TRL calibration, manufactured TRL calibration standards were evaluated up to 40 GHz. For this verification, ECal was performed and the standards were measured and the measured data are plotted in Figure 2.

Figure 2 (a) plots IL and RL of the Primary thru. No cross frequency of IL and RL is found up to 40 GHz. No resonance or abnormality is observed. The Primary thru was designed and manufactured acceptably.

![Figure 2. (a) IL and RL of Primary thru, (b) phase offset of Secondary Line 1](image)
Phase offsets of Secondary Lines to the Primary thru are plotted in Figure 2 (b)-(d). The phases of Secondary line 1, 2 and 3 are fairly linear and no discontinuity ($\pi/2\pi$ jump) is observed. At the frequency boundaries of each Secondary line, phases show ~30° or more phase margin, and the phases are reasonably linear over each frequency section. We can conclude that TRL calibration standards are fairly well fabricated as designed.

For TRL calibration verification, Primary thru was measured after TRL calibration. Primary thru measurement data which were acquired after TRL calibration are shown in Figure 3; IL, magnitude of $S_{12}$ in (a), phase of $S_{12}$ in (b) and RL, magnitude of $S_{11}$ in (c) [1]. IL deviation from 0 dB is within 0.01 dB up to 40 GHz, phase deviation from 0 degree is within 0.2 degree and RL is less than -45 dB over the whole frequency region of measurement, which shows excellent repeatability and measurement stability of TRL calibration.

For AFR/SFD, no additional de-embedding fixture was designed and the Primary thru among the TRL calibration standards was used. As shown in Figure 2(a), IL of the Primary thru is larger than RL over the frequency region of interest, which verifies the goodness of the de-embedding structure for AFR/SFD.

Once the measurement was done using ECal, AFR was applied to the measured data as a post-process. Figure 4 shows the Primary thru measurement data which were acquired after de-embedding via AFR. IL deviation from 0 dB is less than 0.015, phase deviation of transfer S-parameter from 0 degree is less than 2 degree and RL is less than -68 dB up to 40 GHz. Plots in Figure 4 shows how AFR algorithm works well and how well Primary thru is de-embedded with its own structure via AFR.
The IL of 1x Thru which was obtained from AFR is compared to IL of 2x Thru in Figure 5. They are fairly linear and the slope of 2x Thru IL is about double the slope of 1x Thru IL.

IV. TRL VS. AFR/SFD, THE MEASUREMENT COMPARISON

A high-speed interconnect component was measured using three different calibration or de-embedding methods: TRL calibration, AFR and SFD. Three sets of measured data are compared in Figure 6 for IL, RL, FEXT (Far End Crosstalk) and NEXT (Near End Crosstalk). Since the ECal reference impedance was 50 Ω, the de-embedded data via AFR and SFD were compared to TRL results that are re-normalized to 42.5 Ω. Pictures in Figure 6 show excellent correlation between TRL and 2x thru de-embedding methods. It is worthy to note that although the DUT has repeatability issues as internal connections in DUT are not soldered on the test fixture, three sets of data match tightly.

Plots in Figure 6 clearly prove that AFR and SFD of a 2x thru de-embedding schemes are equally accurate as TRL calibration for high-speed interconnect measurement.

Often engineers face situations to make trade-offs between the accuracy and efficiency, but the high-speed interconnect characterization has not been the case as the accurate characterization is critical in the high-speed bus design. Hence, even though TRL calibration is not a trivial task, TRL calibration has been widely used with additional caution and effort from the test board design to measurement in the laboratory.

However, with the 2x thru de-embedding of AFR and SFD, we do not sacrifice the accuracy for efficiency and still we achieve the high accuracy as TRL calibration is used. In addition to the benefits of simplified procedures and reduced board area/cost described in the second section, we can even keep better consistency among launch connectors as 2x thru de-embedding methods need only 2 connectors for calibration/de-embedding, while TRL needs 10 connectors (for a 3-line TRL calibration kit).
V. CONCLUSION

AFR and SFD 2x thru de-embedding methods have been compared to TRL calibration method in terms of design, calibration / de-embedding procedure, and accuracy. AFR and SFD significantly reduces complexity in de-embedding fixture design and simplifies high-speed interconnect measurement. Also for accuracy verification, three different sets of measurement data were compared for a high-speed interconnect, using TRL calibration and 2x thru de-embedding (AFR and SFD) for frequencies up to 40 GHz. The comparison showed excellent correlation in IL, RL, NEXT and FEXT over the full frequency range of measurement. This comparison result proves that 2x thru de-embedding methods of AFR and SFD are as accurate as TRL calibration for the high-speed interconnect characterization.

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