Accurate Characterization of PCB Transmission Lines for High Speed Interconnect

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Abstract — **Accurate PCB transmission-line characterization can be challenging due to the effect of test fixtures and launching vias, etc. In this paper, VNA measurements with innovative de-embedding approaches, including those that utilize only one "2X-Thru" calibration standard are studied. The 2X-Thru de-embedding method is first shown to be correlated to existing TRL calibration method. Test boards built with varying lengths of transmission lines routed on different layers were then characterized with the new de-embedding method. Excellent de-embedded results are achieved for frequencies up to 30 GHz.**

I. Introduction

High speed differential serial links have been used widely in modern computer systems for most input/output (I/O) interfaces. The data rate of differential serial links has grown exponentially over the last two decades to meet ever increasing bandwidth requirements. When USB1.1 was introduced at 1998, it was running at 12Mbps. Fast-forward to today, PCIE gen 4 is expected to run at 16Gbps [1]. The 802.3bj standard was approved in 2014, and specifies 100 Gbit/s 4x25G PHYs for backplane and twin-ax cable, where the data rate for an individual lane is 25Gbps [2], over 2000x faster than USB1.1. With increasing data rates, characterization of the printed-circuit-board (PCB) has become a critical factor in high speed interconnect design. The non-ideal effects of PCB transmission lines, such as copper surface roughness, the fiber-weave effect, dielectric dispersion, environmental effects, etc., are no-longer negligible at the frequencies in the tens of Gbps data spectrum, yet it is challenging to accurately capture these effects through simulation models. Therefore, characterization of PCB structures at high frequencies has become a critical task.

Traditional PCB test methods are hard pressed to keep up with the demanding requirements for high data rates. For example, most of the IPC test methods are based on TDR/TDT measurements, and the test fixtures and PCB via artifacts are not properly addressed for accurate PCB transmission line characterization. On the other hand, the vector network analyzer (VNA) has been the de-facto standard for passive interconnects characterization including on the printed circuit board, connector, cables, etc., but not without some challenges.

Making high quality VNA measurement can be straight-forward with standard coaxial connectors and precision SOLT (short, open, load, through) calibration kits, as mentioned earlier. In a typical calibration/de-embedding exercise, specialized calibration standards that are inserted at the end of the test fixtures are used, and a calibration process to move the reference plane to the end of the test fixtures is performed [3]. The accuracy of the measurement relies highly on the quality of the physical calibration standards, especially for SOLT type of calibration standards, where the parasitics of the SOLT calibration standard must be known a priori. However, for PCB structures, it is not feasible to build an accurate broadband SOL structure right after the test fixtures. Hence the on-PCB SOLT calibration process does not generally work well for frequencies above a few gigahertz.

The TRL (and its variants such as LRM) method solved the above issue and has become a mainstream approach to move the calibration reference plane from the coaxial connector to PCB interfaces [4]. However, there are still challenges with TRL calibrations. For example, there are many calibration standards to handle. This takes a large area on the PCB, and the calibration procedure can be a tedious process in the lab and prone to operator error. In addition, manufacturing variations make it difficult to achieve identical test patterns for the calibration structures and DUT, and the de-embedded results are often un-satisfactory without careful test fixtures design. Further, in certain cases, the complex arithmetic in the de-embedding calculations can be highly sensitive to numerical and measurement error, resulting in a failure of the de-embedding approach.

In this paper, de-embedding using a straight-forward approach, where only one calibration structure (a 2X-thru) is needed, is studied. Two types of 2X-thru de-embedding tools are used to remove the test fixtures and via effects from the measurement. Test boards were built with several lengths of transmission lines, and on different routing layers. Excellent de-embedded results are achieved up to 30 GHz.

II. 2X-Thru De-embedding

Recently, a new type of de-embedding methodology is being proposed and gaining acceptance due to its simplicity of test fixtures design and de-embedding procedures [5-7]. For this new type of de-embedding approach, only one 2X-Thru structure is needed, as compared to six structures needed for a typical broad-band TRL calibration, which includes a Thru, Reflective, Load (for low frequency), and three lines with different lengths to cover all frequency ranges.

The basic idea of the 2X-Thru de-embedding approach is as follows: The S-parameters of the 2X-thru structure are measured first; Assuming the 2X-Thru structure is symmetric, the S-parameters of a 1X structure can be calculated directly from the 2X-Thru measurement. Once the S-parameters of the 1X structure on both sides on the DUT are obtained, the S-parameters of the DUT can be readily calculated. This significantly simplifies calibration/de-embedding procedures as compared to a traditional TRL calibration where six calibration structures are typically needed.

There are commercially available tools for 2X-Thru de-embedding such as KeySight's AFR (Automatic Fixtures Removal). Alternatively, the SFD (Smart Fixtures De-embedding) tool developed at the Missouri University of Science and Technology, based on a waveform peeling algorithm, can be used to perform the same task.

III. Comparison of TRL vs SFD de-embedding

In this section, 2X-Thru de-embedding with SFD and classical error correction scheme with TRL are compared in measurement environments. The first example is demonstrated on a 28 layers Megtron 6 TRL test coupon with 2.4 mm precision compression-mount test connectors. The designed test board and measurement setups are shown in Fig. 1 and Fig. 2 respectively. The short black lines on test board the 2X-Thru measurement standards for SFD.

Fig. 1 28-Layer Megtron 6 test coupon

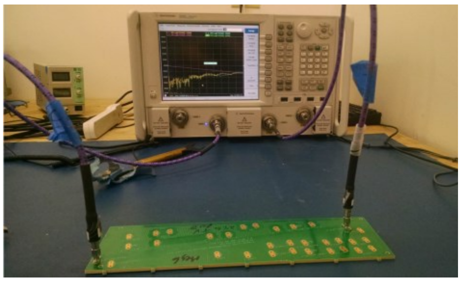
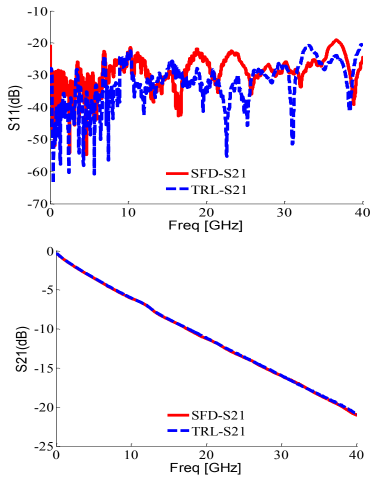


Fig. 2 Measurement setup

The scattering parameter of TRL calibration and SFD results are compared in Fig. 3. Time domain characteristic impedance (TDR impedance) of de-embedded results (not shown herein due to paper length limitation) confirms discontinuities are removed through both methods. As observed from measurement results, the insertion losses of TRL and SFD agree with each other very well.

The second example is demonstrated by single-ended micro-probe measurement as shown in Fig. 4. A pair of GSG probes with 1mm pitches size were used in both TRL calibration and SFD de-embedding.



(a) (b)

Fig. 3 De-embedded results on 28 Layer Megtron 6 test coupon (a) $|S_{11}|$, (b) $|S_{21}|$

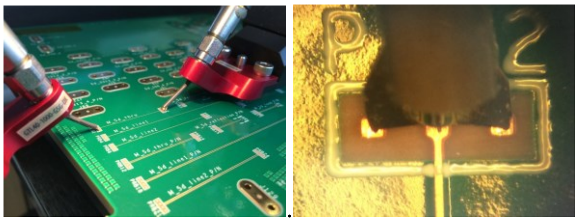
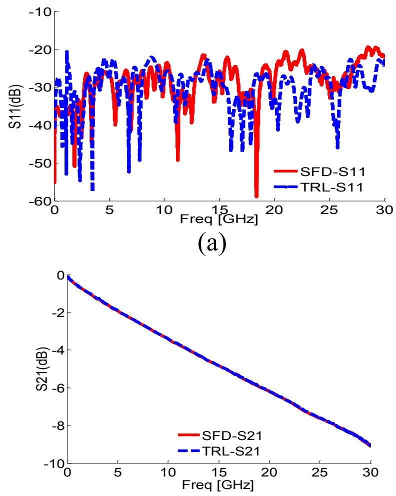


Fig. 4 GSG micro probe and close-up view

The results are shown in Fig. 5. Excellent agreement is achieved in insertion losses, and the discrepancy between return losses are generated from 1) manufacturing variation of test fixtures for DUT and 2X-Thru; 2) uncertainties introduced during micro-probe landing.



(b)

Fig. 5. De-embedded result on micro probe measurement (a) $|S_{11}|$, (b) $|S_{21}|$

IV. PCB Differential Line Characterization

Test boards of differential interconnect were built with different routing lengths on different layers (microstrip, and striplines with different via stub lengths), and used to further evaluate the de-embedding approaches for high speed interconnect characterization. The test board is a six-layer standard FR4 board with a board thickness of 62 mil. The signal traces are routed on Layer 1, 3, and 4. Four different routing lengths were studied, 2.5", 5.5", 10.5", and 0.5".

A picture of the 4-port microwave probing is shown in Fig. 6. All the measurements were done using an Agilent NA, with standard SOLT calibration done at the probe tip, from 10MHz to 30GHz.

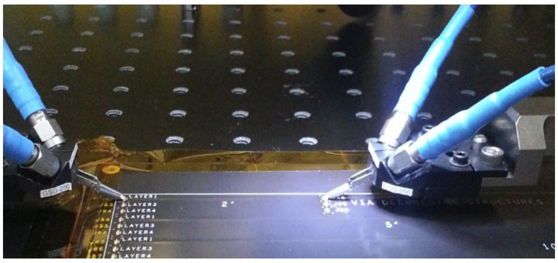


Fig. 6 Microwave probing of the test board

Fig. 7 shows the measured $|S_{DD21}|$ of the 10.5" lines on the three different layers. The 51 mil via stub results in a resonance at approximately 19.6 GHz, while the 59 mil via stub for Layer 1 routing results in a resonance at a slightly lower frequency, approximately 18.6 GHz. For routing on Layer 4 with a 10 mil via stub, the resonance frequency is beyond 30 GHz.

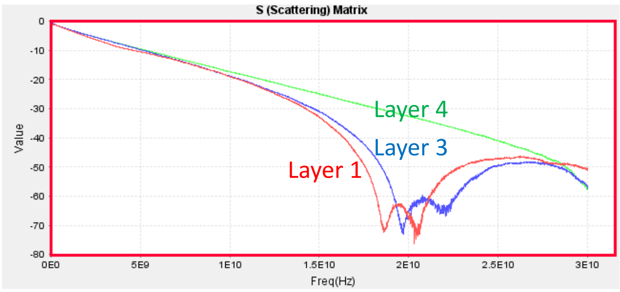


Fig. 7 Measured $|S_{DD21}|$ of the three 10 in transmission line patterns on three layers within the test PCB

The first de-embedding study was performed on the Layer 4 traces, in which via stub length is only 10mils. Three types of de-embedding approaches are studied for this case:

- AFR (automatic fixtures removal) from KeySight®,
- SFD (smart fixtures de-embedding) from the Missouri University of Science and Technology, and,
- Delta-L approach proposed by engineers from Intel [7].

Both AFR and SFD utilize a 2X-thru structure as the calibration structure, but with different de-embedding algorithms, while the Delta-L approach utilizes two different routing lengths and calculates the differences directly.

For 2X-thru de-embedding, it is preferable to use the 0.5" length as the test-fixtures, and the measured $|S_{DD21}|$ of the 2X-Thru and calculated 1X-Thru (using SFD as an example) are shown in Fig. 8. The calculated S parameter of 1X-Thru is then used to de-embed the measured S parameter of DUT with test fixtures, to derive the S parameter of DUT (i.e., the transmission line only, without via and probe launch).

Fig. 9 shows the de-embedded results of a 10.5" trace routed on Layer 4. Note that after de-embedding with the 0.5" of 2X-thru structure, the de-embedded results have a net length of 10". The correlation of de-embedded $|S_{DD21}|$ between AFR and SFD is good, with some slight deviation at around 30GHz probably due to algorithm difference of the two tools. The de-embedded $|S_{DD11}|$ results (not shown herein) agree with each other as well.

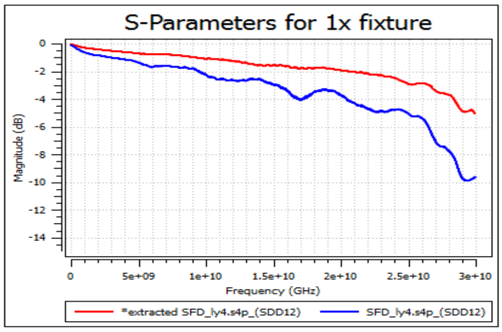


Fig. 8 Measured $|S_{DD21}|$ of the 0.5" 2X-Thru (blue curve) and the calculated $|S_{DD21}|$ of the 1X-Thru (red curve)

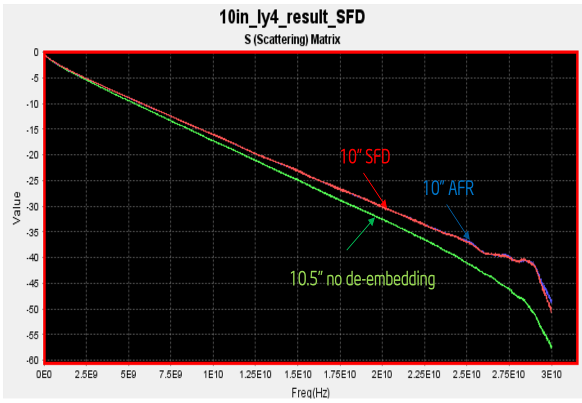


Fig. 9 De-embedded $|S_{DD21}|$ results for a 10" transmission-line trace routed in Layer 4

To further validate the de-embedding procedures, another set of de-embedding results were performed:

- 10.5" line was de-embedded with 0.5" line, with both AFR and SFD methods, the resulting $|S_{DD21}|$ of 10" line was divided by 10 for plotting.
- 5.5" line was de-embedded with 0.5" line, with both AFR and SFD methods, and the resulting $|S_{DD21}|$ of 5" line was divided by 5 for plotting.
- The $|S_{DD21}|$ of the 10.5" line was divided by the $|S_{DD21}|$ of the 5.5" line directly, and this result divided by 5 for plotting. This is the "Delta-L" approach mentioned previously.

All the results above yield the de-embedded insertion loss normalized to 1 inch of routing. The comparison is shown in Fig. 10. Excellent agreement is achieved using different de-embedding algorithms, with the two different routing lengths. The agreement is a strong indicator of the accuracy of the de-embedding approaches of both AFR and SFD. The results of a 2.5" line de-embedded using a 0.5" line yields some small ripples in the results (not shown herein), and may not be best suited for transmission line characterization. Another interesting observation in Fig. 10 is that the Delta-L approach yields excellent results on the de-embedded insertion loss for these longer transmission-line patterns with the associated loss, yet the calculation is straightforward without complicated de-embedding algorithms in AFR or SFD.

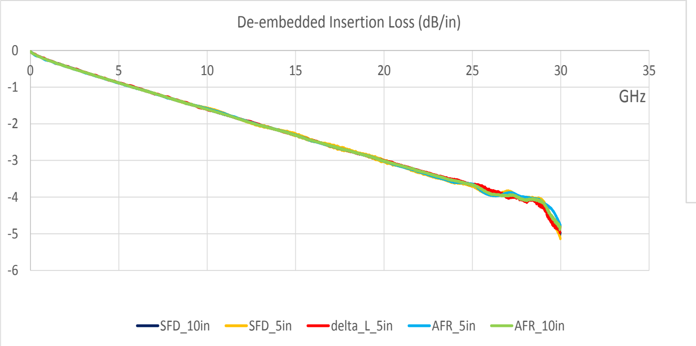


Fig. 10 Comparison of de-embedded |S_{DD21}| (per inch) for 5" and 10" transmission-line lengths

It is also important to note there are design consideration differences between the 2X-thru de-embedding and the Delta-L approach. The 2X-thru de-embedding requires a short routing length as the test fixtures, such as the 0.5" routing used in this case, while the Delta-L approach works better with two longer routing lengths, such as 10.5" and 5.5". A more detailed study of the Delta-L methodology is reported in [7].

The same de-embedding studies were performed on the transmission lines routed on Layer 3 with a 51mil via stub. Same kind of agreements were observed except for that the 51mil via stub has a prominent effect on the measured insertion loss, where the resonances are around 20GHz. There is good agreement between the AFR and SFD results, but both de-embedding method begin to fail at around 17GHz. This is due to the fact that there is not much energy passing through the 51mil via stub, and the signal to noise ratio is too low for any de-embedding method to work well.

V. The Importance of De-embedding in Transmission Line Characterization

As mentioned previously, although TRL-type de-embedding is ubiquitous in interconnect characterization, commercially available transmission-line characterization techniques within the PCB industry often fail in de-embedding of launching vias due to a lack of an effective de-embedding methodology constrained to low-cost application considerations. However, it is important to understand the consequences if de-embedding is not performed for whatever reason.

Fig. 11 shows the comparison of normalized insertion Loss (dB/in) for routing on Layer 3 and Layer 4 with a 5" length. When the via stub is short as for routing on Layer 4, the calculated insertion loss has a slight error of 5% at 10GHz (comparing the orange curve to blue curve), while for the case when the via stub is longer as for Layer 3 routing, the error is 25% at 10GHz (comparing the green curve to red curve). Note that due to symmetry of the PCB stackup construction, the transmission line on Layer 3 is expected to have the same loss as that on Layer 4.

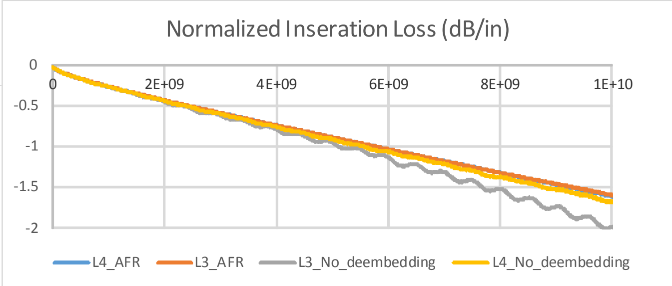


Fig. 11 Normalized|S_{DD21}|, with and without de-embedding (5" line)

VI. Summary

De-embedding techniques utilizing 2X-Thru structures for PCB transmission line characterization are reported herein. Test boards were built with various lengths of transmission lines routed on different layers, and consequently having different via stub lengths. Multiple de-embedding tools are compared, and a series of data consistency analysis were performed to demonstrate the accuracy of the de-embedded results.

The 2X-Through de-embedding approach, including AFR, and SFD, significantly simplifies the de-embedding procedures compared to a traditional TRL type approach to move reference planes from co-axial connectors to PCB interconnects, yet proven accurate for PCB transmission line characterization. The approaches shown herein are applicable to not only transmission lines, but also any type of interconnects such as cable assemblies, connectors, and PCB structures, which will be published in the future.

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