Assessment of 2x Thru De-embedding Accuracy for Package Transmission Line DUTs

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***Abstract*—This paper examines 2x Thru de-embedding accuracy for uniform package transmission line devices under test (DUTs). Accuracy is first assessed using 3D modeled data, with and without 2x Thru impedance mismatch. The learnings from this analysis are then applied to improve the match between de-embedded measurement data and modeled data.**

Keywords—De-embedding; 2x Thru; TDR

I. Introduction

2x Thru de-embedding is a broadband, time-domain-based de-embedding method that is gaining popularity in the industry as a convenient alternative to Thru-Reflect-Line (TRL) de-embedding, offering a similar level of accuracy with reduced design complexity [1]. In the case of symmetric fixtures, 2x Thru de-embedding requires a single characterization fixture (called the 2x Thru) to determine the test fixture response. This approach utilizes both the frequency-domain and time-domain responses of the characterization fixture; the calculation is described in detail in [2]. Several commercially available tools implement 2x Thru de-embedding, as well as open-source code developed as part of the IEEE P370 standard [3].

The success of a de-embedding method depends upon several factors: complexity of design, complexity of the measurement process, accuracy (including resilience to mismatch between the calibration structure and test fixture), effective bandwidth, and applicability to a wide range of DUTs. The simplicity of the 2x Thru design and calibration process, as well as its broad applicability, are widely recognized benefits. Further, various means of evaluating the accuracy have been proposed in the literature: analytical [2], [4], comparison to TRL [1], use of synthesized S-parameters [5], and use of NIST-traceable test coupons [6].

However, some gaps remain. Most of the papers addressing accuracy use complex or poorly matched DUTs, thereby masking more subtle de-embedding effects [1]; and few address the impact of impedance mismatch between the 2x Thru and test fixture [5]. This work is intended to address these gaps by examining the accuracy of 2x Thru de-embedding for a uniform package transmission line DUT across a wider range of metrics and in the presence of 2x Thru impedance mismatch. The accuracy is first evaluated using simulated data as in [5]; the learnings from this analysis are then applied to a fabricated package transmission line. All de-embedded results are obtained using a commercially available 2x Thru algorithm.

II. De-embedding Accuracy for Ideal Simulated Data

To establish the baseline accuracy of the de-embedding algorithm for package transmission lines, data for the 2x Thru, fixtured DUT, and true DUT were generated through 3D full-wave electromagnetic (EM) simulation; the fixtured DUT was then de-embedded and compared with the true DUT. The DUT comprises a 5 mm, 50 Ω single-ended stripline structure. The fixture comprises a transmission line segment terminating in surface-layer probe pads at one end. The fixture length is varied between 2.5 mm and 7.5 mm. The 2x Thru structures mirror the test fixture geometry and vary between 5 mm and 15 mm in length. Fig. 1 illustrates the general model geometry.

Fig. 2 shows the insertion loss of the true DUT overlaid by the de-embedded result. The maximum $\Delta S_{21} < 0.003$ from DC to 110 GHz for all fixture lengths. Since this is significantly below the convergence criterion of the field solver ($\Delta S < 0.01$ at 110 GHz), we conclude that de-embedding of insertion loss magnitude is highly accurate, conditioned upon the equivalence of 1x fixture and DUT test fixture loss. Similarly, the de-embedded insertion phase (not shown) is within 2° (0.4%) of the true value for all cases; we conclude that insertion phase de-embedding is also highly accurate, conditioned upon the equivalence of 1x fixture and DUT test fixture insertion phase.

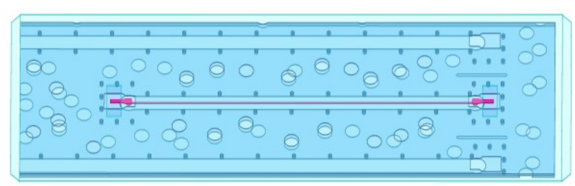

Figure 1. 3D model of the 5 mm 2x Thru structure.

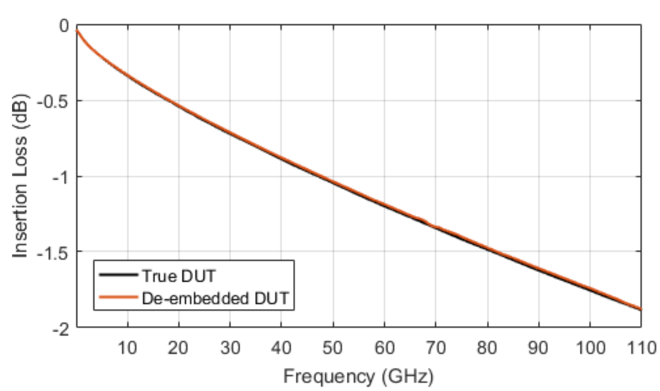

Figure 2. Insertion loss comparison between de-embedded and true DUT.

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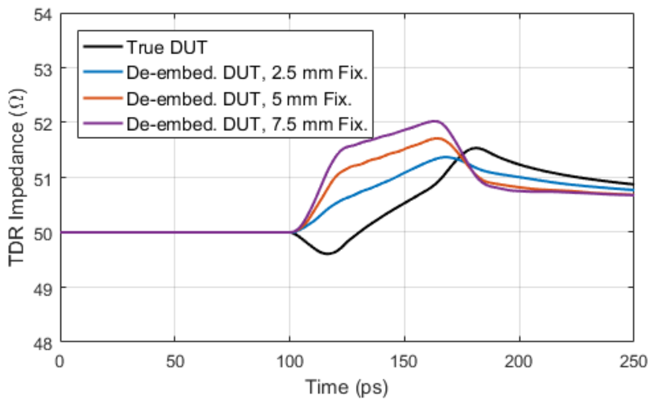

Figure 3. TDR profiles of the 5 mm true DUT and de-embedded DUTs with varying lengths of fixture removed: 2.5 mm, 5 mm, and 7.5 mm.

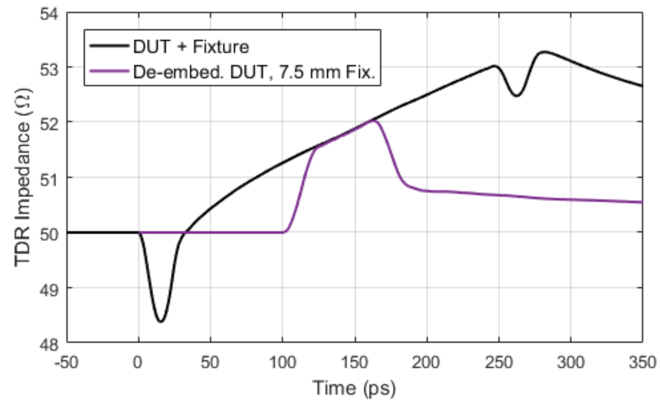

Figure 4. TDR profile of fixtured DUT (20 mm) and de-embedded DUT (5 mm). The de-embedded DUT is shifted to align in time with the fixtured DUT.

Examining time-domain reflectometry (TDR) impedance, however, reveals an unintuitive result: there is a systematic offset between the de-embedded TDR impedance and true DUT impedance, proportional to the fixture length. Fig. 3 shows the impedance gap growing from 0.6 Ω for the 2.5 mm fixture case, to 1.5 Ω for the 7.5 mm fixture case. The source of this discrepancy is evident in Fig. 4. Despite a uniform cross-section, there is an apparent increase in impedance along the line, owing to attenuation of the TDR pulse. When the de-embedded DUT response is shifted to align in time with the fixtured DUT, it is evident that the two impedance profiles agree very well. It can be concluded that 2x Thru de-embedding successfully removes the fixture portions of the embedded DUT but does not remove the artificial impedance shift induced by the fixture loss.

The gap in TDR impedance leads to a gap in return loss as well. The discrepancy is roughly proportional to the fixture loss, and can cause the de-embedded return loss to be either better or worse than the true DUT result, depending on whether the true impedance is lower or higher than the reference impedance, respectively. The magnitude of the discrepancy is probably small enough to be ignored for most applications, but must be taken into account for optimal model-to-measurement correlation of transmission lines or other very well-matched DUTs.

III. De-embedding Accuracy for Non-Ideal Data

De-embedding theory rests on the assumption that the test fixture and characterization fixture are identical. However, this assumption is never perfectly true in the real world due to dimensional variation in any fabricated structure. Therefore, to build confidence in the de-embedding algorithm for real-world applications, one must assess the sensitivity of the de-embedded result to 2x Thru–test fixture mismatch.

The conventional 2x Thru algorithm calculates the fixture model S_{11} term by time-gating the first half of the time-domain 2x Thru S_{11} term, and converting back to the frequency domain. The impedance-corrected algorithm, however, calculates the fixture model S_{11} by time-gating the DUT test fixture response itself. This method significantly reduces the sensitivity of the return loss result to 2x Thru impedance mismatch. The extent of improvement is illustrated in Fig. 5.

For the results in Fig. 5, the fixtured DUT is a 10 mm single-ended stripline with 50 Ω impedance, while the 2x Thru is a 5 mm stripline with trace width adjusted to achieve 53 Ω impedance (6% mismatch). Without impedance correction, the de-embedded return loss is much worse than would be expected from a simple impedance discontinuity. De-embedding with a 53 Ω 2x Thru yields return loss peaks around –18 dB, whereas a 53 Ω – 50 Ω discontinuity gives a return loss of –30.7 dB.

Impedance-corrected return loss is significantly improved, but does not perfectly agree with the true DUT behavior. While the fixture model S_{11} term is now independent of 2x Thru mismatch, the S_{21} and S_{11} terms of the mismatched 2x Thru are still used to calculate the other fixture model parameters, and thus contribute to inaccuracy in the final result. 2x Thru impedance mismatch imposes a kind of noise floor on the de-embedded return loss, that can be calculated similarly to a simple reflection coefficient:

$$RL_{\text{floor}} \approx -20\log_{10}\left|\frac{Z_0^{2x} - Z_0^{fix}}{Z_0^{2x} + Z_0^{fix}}\right|, \quad (1)$$

where Z_0^{2x} and Z_0^{fix} are the characteristic impedance of the 2x Thru and test fixture, respectively, and RL_{floor} is the value of the return loss peaks induced by 2x Thru impedance mismatch. If the DUT is matched to below this value, the de-embedding process cannot recover the DUT behavior.

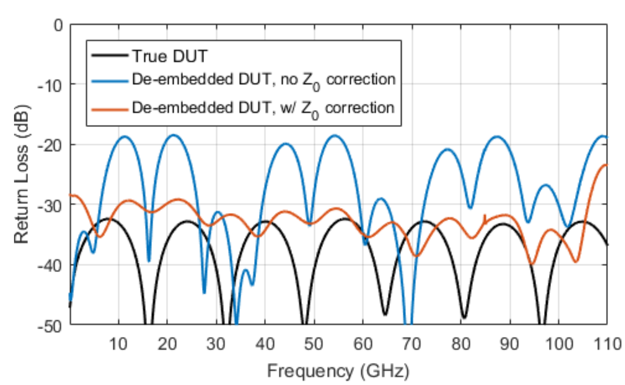

Figure 5. Return loss comparison between true DUT and DUT de-embedded with and without impedance correction.

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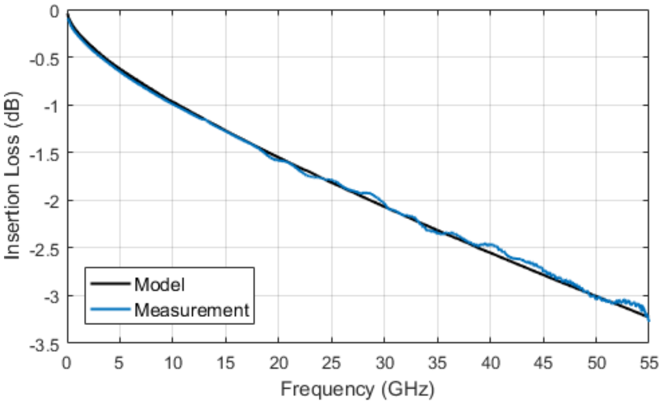

Figure 6. Insertion loss correlation for de-embedded model and measurement.

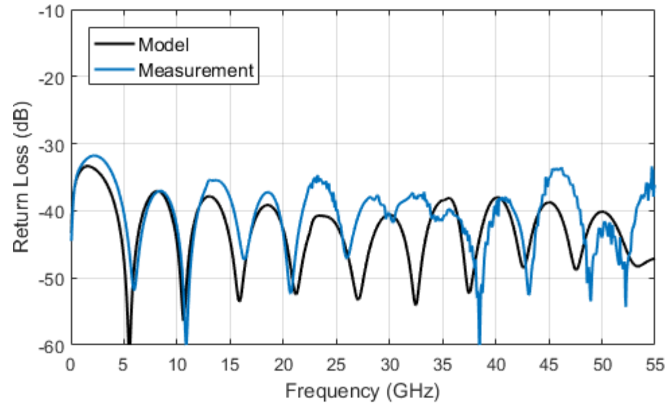

Figure 7. Return loss correlation for de-embedded model and measurement.

In sum, by removing one source of error in the 2x Thru algorithm, impedance correction can significantly improve the de-embedded return loss accuracy in the presence of 2x Thru impedance mismatch, and therefore improves the reliability of the 2x Thru method. The insertion loss is also somewhat improved when mismatch loss becomes appreciable. It is therefore recommended that impedance correction should always be used. But it is no panacea. Mismatch still limits the accuracy of the de-embedded result, and reasonable efforts should not be spared to ensure the 2x Thru is as well-matched to the fixture as possible. The fixture electrical requirements in the IEEE P370 standard include reasonable limits for mismatch along with the resulting data quality that can be expected [3].

IV. De-embedding Accuracy for Measured Data

By accounting for the limitations already discussed, one can consistently achieve very good model-to-measurement correlation for package transmission line DUTs, which serves to confirm the accuracy of the de-embedded result.

The achievable post-de-embedding correlation quality is illustrated in Fig. 6 and Fig. 7 for 50 Ω single-ended stripline structures fabricated on a test package. The fixtured DUT is 20 mm long, while the 2x Thru is 5 mm long. These structures were measured with VNA up to 67 GHz at controlled temperature and humidity, and de-embedded using the impedance-corrected algorithm. In post-processing, the data were truncated at 55 GHz and macromodeled to suppress trace noise amplified during the de-embedding process.

The model is constructed using cross-sectional dimensions taken from the measured unit, and measurement-based dielectric material models using the metrology described in [7]. Both fixtured DUT and 2x Thru are modeled, and the DUT is de-embedded using the modeled 2x Thru. Using de-embedded model data for comparison with measurement circumvents the TDR offset issue described in Section II, since both datasets include the impedance increase induced by the fixture loss.

Fig. 6 and Fig. 7 show the overlaid insertion loss and return loss results, respectively. The insertion loss agrees to within $\Delta S < 0.009$ up to 55 GHz, while the return loss agrees to within $\Delta S < 0.012$, neglecting a noisy spike near 55 GHz. These results are encouraging, as the level of agreement approaches the convergence standard for the EM simulation, and is within the error bounds of the dimensional and material measurements used to construct the model. Further, the level of agreement after de-embedding is noticeably better than the agreement before de-embedding, because the de-embedded DUT geometry is simpler and lacks elements such as vias that are difficult to cross-section. Note that the non-impedance-corrected de-embedded data are not shown, as the fabricated structures are very well-matched and the data are therefore qualitatively very similar to those shown.

V. Conclusion

The accuracy of 2x Thru de-embedding for package transmission line DUTs has been evaluated through simulation and confirmed through measurement. A small systematic offset in TDR impedance leading to return loss inaccuracy has been highlighted and addressed. The impact of 2x Thru–fixture mismatch on de-embedding accuracy has been assessed and impedance correction has been recommended as a satisfactory, though not perfect, solution. By accounting for these effects, excellent model-to-measurement correlation has been achieved for a de-embedded package transmission line, confirming the expected accuracy of the method.

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