Drawbacks and Possible Improvements of Short Pulse Propagation Technique

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Abstract—**Short Pulse Propagation (SPP) technique for characterisation of PCB and packaging interconnect losses and dispersion was introduced in early 90-s and standardized by the Institute of Printed Circuits or IPC [IPC-TM-650]. It was successfully used to build broadband models for dielectrics and conductor roughness up to 30 GHz. Though, it is not widely used and multiple new material characterisation techniques were recently proposed. Is SPP useful for 30 Gbps interconnect design and manufacturing? This paper analyses advantages and drawbacks of the original SPP technique and suggests some simplifications and improvements. It is shown that the number of characterisation steps can be substantially reduced without loss of accuracy. To reduce the sensitivity to the connector and launch reflections and improve accuracy, it is also suggested to use S-parameters instead of TDT pulse responses.**

I. INTRODUCTION

To correlate with the measurements, analysis of PCB and packaging interconnects operation at 30 Gbps requires frequency-continuous dielectric and conductor roughness models with the bandwidth from about 1 MHz up to 50 GHz – this is the most important element of design success [1]. Using such models and compliance metrics, the interconnect designer can provide the loss and dispersion limits for PCB and package manufacturers. **To avoid ambiguities, the same procedure should be used for the material model identification at the beginning of design cycle and the material loss and dispersion validation at the fabrication stage.** What techniques can be used both to build material models for EDA software and to validate the losses at the production floor? It turns out that the only technique suitable for both material model building and validation and standardized by IPC is the Short Pulse Propagation (SPP) technique [2]. The technique was introduced in early 90-s by researchers from IBM [3] for characterisation of PCB and packaging interconnect losses and dispersion and was successfully used to build broadband models for dielectrics and conductor roughness up to 30 GHz [2]. Though, the standardized technique has nine steps and, until recently, implementation of the technique was available only in IBM's software that is not available now. Because of that, the model identification part of SPP standard is practically abandoned - only the Gamma extraction part is usually used. Is SPP still relevant and useful for 30 Gbps interconnect design and manufacturing? This paper analyses SPP advantages and drawbacks and suggest some modifications and improvements to extend the frequency range up to 50 GHz.

Considering the alternatives to SPP, there is an industry trend to use de-embedding techniques such as TRL (Trough-Reflect-Line) or similar, AFR (Adaptive Fixture Removal), ISD (In Situ De-embedding) for the material characterisation. Even a new task group was recently organized by IPC D-24 committee under TM-650 to address the issue of "deficiency" in SPP and the other material characterisation standards. How the de-embedding "alternatives" stand up against SPP? A complete de-embedding is very difficult for PCB applications due to large manufacturing variations. Extraction of multiport parameters of test fixture in de-embedding techniques is the most sensitive and error-prone part of any de-embedding technique. But, it is not needed because of only complex propagation constant is required for the material characterization. Also, the complete de-embedding techniques may remove the test fixture effects successfully, but the de-embedded S-parameters of a line segment still have reflections due to the mismatch in the segment S-parameters normalization and the frequency-dependent characteristic impedance of the transmission line. The material characterisation results will depend on this reflection. An opposite to the use of complete de-embedding is characterisation without de-embedding at all suggested by engineers from Intel [5]. Attenuation and phases of two line segments in Delta-L technique are simply subtracted and divided by length difference to have per unit length parameters. The technique has strong dependency on the reflections from connectors, probes, launches and transmission lines. Design of transparent launches for any stackup is very challenging and may not be realistic in the production environment. In addition, it requires S-parameter measurements for two line segments – a modified version of SPP suggested here can be used in this case, that is more accurate and much less sensitive to the reflections.

SPP can be divided into two parts – extraction of complex propagation constant or Gamma (attenuation and phase constant) and fitting it with the t-line model to extract material parameters. The extraction of Gamma can be simplified and improved as suggested here. Only the Gamma extraction may be needed at the production floor. The IPC standard and the original SPP papers suggest to use TDT pulse measurements, window the response and compute Gamma through Fourier

transform. The windowing actually de-embeds the effect of the multiple reflections. Though, as will be shown in this paper, such removal of the reflections has some consequences. An improvement in the first part is to use measured S-parameters instead of TDT response (it is actually a part of any TRL-type de-embedding techniques. The second part of SPP is the material model identification with t-line Gamma computed in a field solver and fitted to the measured Gamma – this part is not discussed here and is covered in detail at [4].

II. ORIGINAL SPP DRAWBACKS

The original SPP technique has nine steps listed below and depends on the IBM's custom software Gamma-Z and CZ2D. Nine steps may be already confusing and not suitable for the PCB production floor. Let's go through the recommended steps and see how the technique can be simplified or improved.

Step 1: Select samples for the identification with TDR screening. **–** Samples evaluation is definitely needed. Sensitivity of the technique to the impedance variation should be investigated to provide clear rules on impedance deviations.

Step 2: Measure resistance of a t-line segment and capacitance of large disk at DC. – The disk test can be eliminated. First, because of it measures the out of plane component of the dielectric constant. Second, a dielectric model with the low-frequency asymptote can be used (such as Wideband Debye, aka Djordjevic-Sarkar). The resistance measurement is needed only in cases if manufacturing process increases the conductor resistivity. It can be .replaced by tuning resistivity to match the attenuation at lower frequencies.

Step 3: Measure TDT step response, identify delay and construct preliminary transmission line model. – This step is simply not needed.

Step 4: Measure short pulse TDT for two line segments with about three to one ratio of the lengths. – TDT step should be allowed at this step to simplify the process – the numerical post processing and differentiation eliminates need in additional equipment. It can be combined with step 1.

Step 5: Convert short pulse TDT responses into complex propagation constant (Gamma) with windowing, Fourier transform and simple formula [2]. – It can be improved by allowing Gamma extraction from S-parameters.

Step 6: Cross-section test board and take measurements of the test structures. – This is the most important step if the accuracy is a concern. Sensitivity of the Gamma extraction to the incorrect values of the cross section should be investigated to provide clear guidelines.

Step 7: With the measured dimensions, compute dielectric constant from the disk capacitance and resistivity of conductor from resistance, both measured at DC in step 2. – Not needed, see comment to step 2.

Step 8: Create transmission line model with multipole Debye dielectric model and tune parameters in dielectric model to match the measured attenuation and phase constant (real and imaginary parts of Gamma). – This is the main material model extraction step that requires an accurate field solver and extension of the possible material models (see comments in section III).

Step 9: Compute effective dielectric constant and loss tangent (includes roughness). – Needed only in case if the roughness model in the field solver is not reusable and has to be converted into the effective loss tangent for other EDA tools.

III. SPP LIGHT WITH TDT

Considering all that, here is a simplified 4-step version of SPP (SPP Light with TDT):

Step a: Measure TDR and TDT step responses of line segments – select TDT responses of two segments with the close TDR impedances (strict guidance is needed).

Step b: Convert TDT into short pulse response, window it and extract Gamma following the original technique.

Step c: Optionally, cross-section the board traces and measure the dimensions, to improve accuracy. Additional test fixtures can be considered as the alternative to the cross-sectioning.

Step d: Use field solver to build cross-section model matching Gamma extracted in step b) following either the original procedure or simpler one described in [4]. The parameters of material models that produce the matching Gamma is the end result of the material model identification. Such models can be either converted from formulas into tabulated form or just directly used in EDA software.

Steps a) and b) and optionally c) are common for the model identification and validation at the production floor. Step d) is the main material model building step. The Gamma matching process in step d) can be further broken into matching at different frequency bands to separate the loss and dispersion contributors – match resistivity at lowest frequency, dielectric model parameters at medium frequencies and conductor roughness at high frequencies as suggested by Scott McMorrow in [6]. The process allows separation of the dielectric and conductor effects without additional resistivity measurement or use of flat conductor board as suggested in the original SPP. Note that the field solver used at step d) should support reusable broadband dielectric models such as multipole or wideband Debye and conductor roughness models such as modified Hammerstad or Huray's snowball models [4]. The solver used for the extraction must be validated, to produce the reusable models. Otherwise, if a solver has systematic error, the models may be not usable in the other solvers. Besides CZ2D, there are multiple commercial field solvers that support the broadband material modelling and are validated. Simbeor THz for instance, supports Gamma extraction from TDT in step b), automates the matching process in step d) and produces dielectric and conductor roughness models that are usable in HFSS and some other electromagnetic solvers [6].

IV. SPP LIGHT WITH S-PARAMETERS

There are two problems with steps a) and b): noise in TDT causes oscillations in Gamma at high frequencies and elimination of the double reflections from launches causes defects at lower frequencies. To improve the Gamma extraction and extend frequency range, S-parameters of the transmission line segments can be measured with VNA, instead of TDT/TDR. Considering this, steps a) and b) of the

SPP light can be replaced with the following steps (**SPP Light with S-parameters**):

Step a: Measure S-parameters of line segments, estimate quality and compute TDR and select two segments with the close TDR impedances (similar to GSM-parameters).

Step b: Convert S-parameters into the reflection-less GMS-parameters and extract Gamma – see details at [4].

Steps c) and d) are the same as in the SPP Light.

The quality and selection step a) is the same as in the material identification with GMS-parameters. Sensitivity to the test fixture variation and guidance are provided at [7]. Gammas of two modes can be easily extracted from s4p parameters measured for differential pairs. The Gamma extraction in step b) can be further eliminated with the direct use of GMS-parameters in the material identification [4]. Only the diagonalization of the product of two matrices is required in this case that is actually a part of any TRL-type de-embedding (no test fixture extraction is needed). It produces the reflection-less multiport parameters (normalized to unknown characteristic impedance) of the line segment difference that is already sufficient for the material characterisation – it is the simplest approach (minimal number of steps) and gives both attenuation and phase or group delay of a line segment.

V. EXAMPLES

Three pairs of 2 and 6 inch segments of strip line with three different launches were used to test the effect of reflections in test fixture on the SPP Light technique with numerical experiment. Extracted Gamma is shown in Fig. 1 together with the matching Gamma computed with Simbeor field solver.
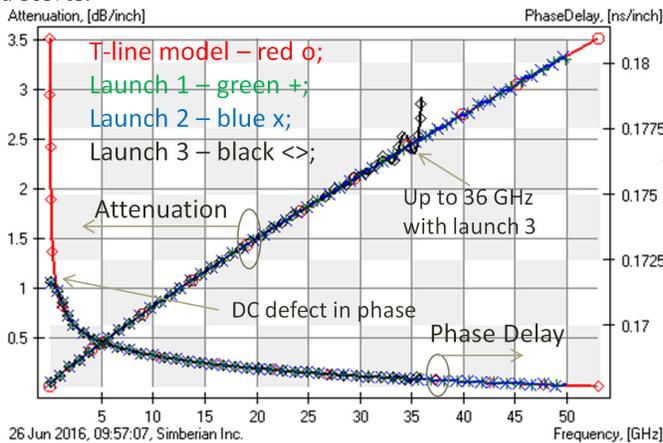
Fig. 1. Attenuation and phase delay extracted with SPP Light with 20 ps TDT for 3 pairs of strip line segments with 3 launches.

First pair has good launch 1, second one has average launch 2, and the third one has bad launch 3 with the stub resonating at about 38 GHz. Gammas with launches 1 and 2 are extracted up to 50 GHz and have just small defects at DC. The worst case pair produced Gamma with acceptable accuracy only up to 36 GHz if TDT step response is used. SPP Light with S-parameters improves the bandwidth for the worst case and produces Gamma matching the model from 0.01 to

50 GHz with minor numerical noise in this numerical experiment. The 50 GHz bandwidth of the SPP light with S-parameters was earlier demonstrated with the experimental data in [4] (extraction of Gamma from GMS-parameters is technically the SPP light with S-parameters technique).

Another test case was 3 and 14 inch strip line segments with SMA connectors. TDT and S-parameters measurements were used to extract Gamma and to identify the dielectric and conductor roughness models as shown in Fig. 2. Gamma extracted with TDT has more noise, but is acceptable for the frequency-continuous models identification. Wideband Debye and modified Hammerstad models were used to overcome the DC and oscillations defects. Gamma extracted with S-parameters shows less oscillations and no DC defect as expected for the test fixtures with over 2 Ohm variations on TDR.
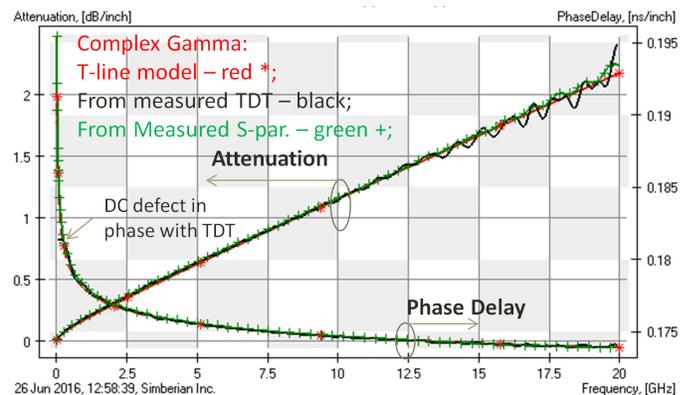
Fig. 2. Gamma extracted from TDT and S-parameter measurements and fitted with the field solver model.

VI. CONCLUSION

It is shown that SPP technique has some advantages and cannot be simply discarded in favor of more complicated de-embedding techniques. It is suggested to simplify SPP technique by allowing use of TDT step response and by reducing the number of steps from 9 to 4 (SPP Light). It is shown that use of S-parameters in SPP Light technique reduces sensitivity to the reflections and can extend the frequency range of SPP up to 50 GHz for PCB applications.

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