Measurement-assisted extraction of PCB interconnect model parameters with fabrication variations

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***Abstract*— Measured S-parameters and cross-sections of PCB interconnects are used in this paper to identify parameters of electrical models suitable for statistical analysis of interconnects with manufacturing variations. The constructed models reproduce observed effects of geometry and material properties variations on the loss, delay and impedance, and are suitable for yield analysis of interconnects with up to 56 Gbps signals. This is the first attempt to build such models for PCB interconnects.**

I. INTRODUCTION

The design of predictable PCB interconnects for 56 Gbps PAM-4 links requires an analysis to measurement correlation from 1-10 MHz up to at least 40-50 GHz. There are three necessary conditions to achieve such correlation [1]. First, we need to know the actual PCB interconnect geometry – PCBs are not manufactured as designed. Second, broadband dielectric and conductor roughness models are needed – such models are not available from the material or PCB manufacturers. Third, the accuracy of the analysis software must be systematically validated for this bandwidth. Theoretically, if all three conditions are satisfied, the models should correlate with the measurements. However, the manufacturing variations may prevent such correlation in case of mass production and even for the same PCB [1]. Statistical models are needed, but no data are available from PCB manufacturers to build such models. Statistical geometry variations and effect on the characteristic impedance were investigated by Gary Brist at Intel over 10 years ago [2]. Statistical distribution of losses was investigated at Intel with the standardized SET2DIL methodology [3], with Delta-L and different de-embedding techniques [4]. In this paper we try to account for the geometrical variations on the material model parameters, with the goal to build transmission line models with observed variations of loss, delay and impedance. The results are the statistical distributions of the strip geometry as well as of parameters of dielectric and conductor roughness models suitable for yield or corner-case analysis of 56 Gbps links. It is not just the observation of the geometrical or electrical properties, but an attempt to build interconnect models suitable for the design of 56 Gbps data links on PCB.

II. TEST COUPON DESIGN AND MEASUREMENTS

Very low loss dielectric Megtron 7 and smooth HVLP copper were used, to meet 56 Gbps channel performance requirements. Short and long segments of striplines with length difference 1.5 inch were placed on a coupon attached to production boards as shown in Fig. 1. S-parameters of the segments can be used to extract reflection-less GMS-parameters [5] as well as the complex propagation constant or Gamma from measured S-parameters for the SPP Light technique [6]. All segments are equipped with snap-on connectors suitable for measurements up to 67 GHz. Three batches of the same board were manufactured with some modifications of the launches. 5 boards were manufactured in the first batch (Rev1), 20 boards in the second batch (Rev2) and 30 in the third batch (Rev3).

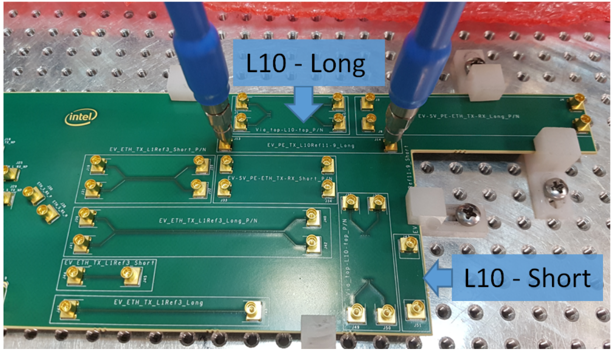

Fig. 1. Test coupon view during measurements – only single-ended strip line segments in layer L10 are used in this investigation.

Network Analyzer with 67 GHz bandwidth and mechanical 1.85mm Standard Calibration Kit were selected for all measurements. Two adaptors from the snap-on MMPX connectors to 1.85f and to 2.92m are used for each structure. The calibration was done up to the coaxial side of the adaptors. The measurement setup is shown in Fig. 1. S-parameters for the three batches of the test structures were measured. Insertion losses for the short single-ended line segments for all three batches are plotted in Fig. 2.

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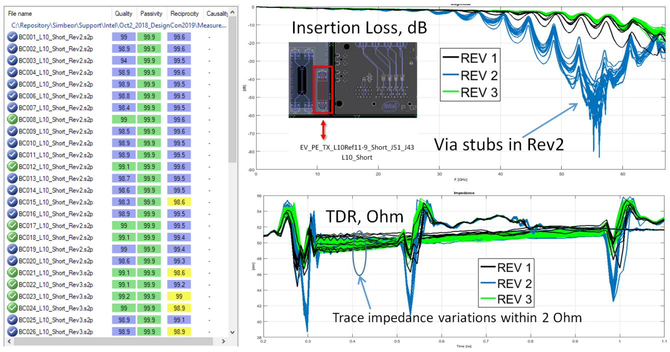

File name	Quality	Passivity	Reciprocity	Causality
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✓ BC015_L10_Short_Rev2.s2p	98.3	99.9	98.6	-
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✓ BC020_L10_Short_Rev2.s2p	98.6	99.9	99.3	-
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✓ BC024_L10_Short_Rev3.s2p	99	99.9	98.9	-
✓ BC025_L10_Short_Rev3.s2p	98.9	99.9	99.1	-
✓ BC026_L10_Short_Rev3.s2p	98.9	99.9	98.9	-

Fig. 2. Quality of measured S-parameters (left) and insertion (right top) for short segments and TDR (right bottom) for all segments.

The quality of the S-parameters was evaluated with IEEE standardized metrics of passivity, reciprocity and overall quality with the rational approximation (first columns in table of Fig. 2). Practically all metrics came out as either good (highlighted in green) or acceptable (highlighted in blue). Structures in Rev2 batch have stubs on the connector launch vias, whose resonance is visible in the insertion loss plots in Fig. 2. It restricted the bandwidth of GMS-parameters. The insertion loss in structures of Rev3 was the best - the via-holes at the launch were back-drilled in that batch. TDRs for all segments were computed from S-parameters and are shown in Fig. 2. We observed an about 2 Ohm variation in the trace impedances and over 5 Ohm variations in the connectors to launches transitions due to inconsistencies in connector soldering. It further restricted the bandwidth and distorted the GMS-parameters to about 40 GHz. Also, there was an about 1 Ohm systematic offset between impedances of the short and long transmission line segments. It was due to the orthogonal orientation of t-lines on the test coupon and the fibre-weave effect (glass fibre was spread more in one direction).

After the measurements of S-parameters, all test boards were cross-sectioned and geometry variations were observed. Both short and long segments were cross-sectioned, but measurements from the short segments only are used for the material model identification. All measurements of the same dimension are taken at two or three locations as illustrated in Fig. 3 and averaged. Min, max, mean and standard deviation values for all samples are shown in Table 1. The major contributor to the conductor losses at lower frequencies and impedance variations is the trace width and thickness. As we can see from the trace width and thickness shown in Table 1, the trace cross-section area can vary between samples by as much as 30%! Most of the variations are in the thickness of the trace. Substantial variations of the trace thickness were confirmed by multiple measurements along the trace on the same board – data for one of the samples are in the last row of Table 1. It is caused by variations in the foil thickness or, more likely, by foil processing by PCB manufacturer [2]. It contributes to the impedance and loss variations and introduces uncertainties into the identification process, especially at lower frequencies.

Considering the thickness of the laminate above and below the strip, the variations are not so large. The dielectric thickness affects mostly the characteristic impedance and not the losses. The material parameters will be not very sensitive to the variations of these parameters. From Fig. 3 we can also observe differences in spreading of the fibre bundles. The fibre bundles across the short line cross-section look wider than across the long line cross-section. It was also confirmed by additional cross-sectioning. That difference can explain systematic offset in TDR impedance between long and short segments.

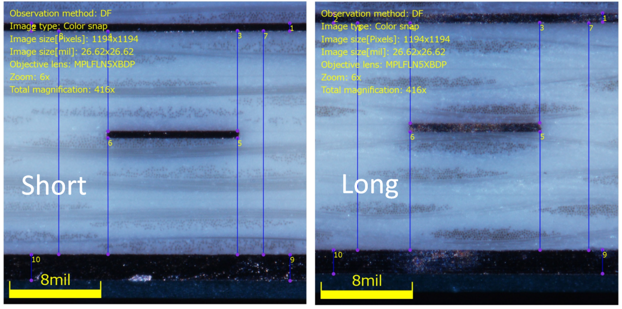

Fig. 3. Cross-section measurement points.

Table 1. Short strip line cross-section measurements.

Meas. Value [mil]	Min	Average	Max	Sdt. Dev.
Top Ref. plane thickness	0.658	0.751	0.889	0.069
Trace to top plane distance	8.546	8.845	9.037	0.097
Trace to bot. plane distance	10.146	10.349	10.592	0.112
Trace width	11.74	11.905	12.019	0.074
Trace thickness	0.614	0.677	0.864	0.049
Trace thickness along one trace	0.61	0.665	0.709	0.028

III. MATERIAL MODEL IDENTIFICATION

One broadband model for dielectrics and one broadband model for conductor roughness are selected as being the simplest, suitable for PCB characterization, and available in multiple EDA tools.

The Wideband Debye model (aka Djordjevic-Sarkar or Swensson-Dermer, see references in [1], [5]) is the dielectric model often used for broadband analysis of PCB and packaging interconnects – it is simple, causal and easy to identify. The model can be uniquely defined with dielectric constant (Dk) and loss tangent (LT) at one frequency point [1]. Default values are used to define model bandwidth ($m1=4$, $m2=12$).

To simulate the effect of conductor roughness, we use the unified roughness correction coefficient with the causal Huray-Bracken transition function [7]. It is applied to the complex transmission line impedance per unit length. The model is uniquely defined by two parameters – surface roughness (SR) and roughness factor (RF). Metric parameter SR defines onset frequency of the skin-effect on a rough surface and unit-less parameter RF defines maximal increase in conductor losses due to roughness effect.

Identification of Dk, LT, copper relative resistivity (RR, normalized to 1.724e-8 Ohm*m), SR and RF can be done either with generalized modal S-parameters (GMS-parameters) [5], or with the equivalent SPP Light methods [6]. Both methods are based on S-parameter measurements for two transmission line segments and, technically, should produce

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very similar results. GMS-parameters are used here. We first tried identification algorithm with the dielectric and conductor loss separation as described in [1] by fitting parameters affecting loss over separate bandwidth (for copper resistivity at 10-20 MHz, for loss tangent over 0.05 to 1-2 GHz, and for roughness model over 3 to 40 GHz). The algorithm did not work well because of an extremely low loss dielectric and large variations of the trace cross-section – it was impossible to separate the losses. Thus, the following modified identification algorithm was used:

- *Fix all cross-section parameters to batch mean values;*
- *Identify Dk @ 1 GHz first by matching GMS phase delay from 2 to 40 GHz*
- *Identify relative resistivity (RR) with loss tangent LT @ 1 GHz simultaneously by matching GMS attenuation from 0.01 to 2 GHz;*
- *Identify roughness model parameters SR and RF by matching GMS attenuation from 2 to 25-35 GHz;*
- *Correct Dk @ 1 GHz by matching GMS phase delay from 2 to 40 GHz;*

Simbeor SDK with quasi-static field solver was used to implement and automate the identification process. The identification results for batch Rev3 are in Table 2. The identified mean value of the dielectric constant, 3.187, is within the range from 3.12 to 3.23 provided by the dielectric manufacturer and also within the range from 3.18 to 3.32 provided by the PCB manufacturer. The loss tangent 0.0011 is also within the range provided by the manufacturers.

Table 2. Identified conductor and dielectric model parameters.

	Min	Average	Max	Std. Dev.
Relative Resistivity, RR	1.12	1.36	1.8	0.2
Surface Roughness, SR [um]	0.13	0.146	0.23	0.023
Roughness Factor, RF	6.2	8.8	9.9	0.8
Dk @ 1 GHz	3.15	3.187	3.22	0.016
LT @ 1 GHz	0.0005	0.0011	0.002	2.7e-4

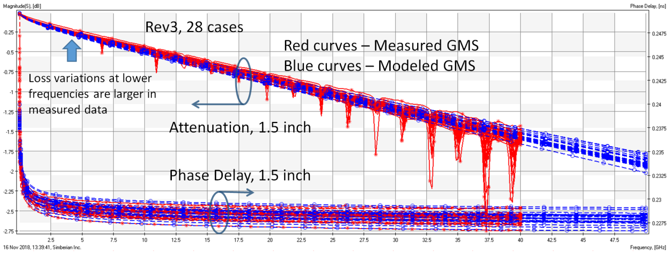

Fig. 4. Measured (red curves) and simulated (blue curves) GMS attenuation and phase delay for 28 cases from Rev3.

Correlation of the model with the measured GMS-parameters is shown in Fig. 4. The variations of the losses observed in measured GMS-parameters at lower frequencies are larger than in the model. Spikes in the measured GMS-parameters in Fig. 4 were attributed to the connector mounting problem. With a numerical experiment, we proved that this defect did not affect the identified model parameters. Variations of the transmission line characteristic impedance are computed for all 30 models for batch Rev3. The minimal impedance value was 47.45 Ohm, the maximal 48.41 Ohm, and the average 47.9 Ohm. The cross-section geometry is fixed in this case and all differences in the impedance are caused by the differences in the dielectric constant and in the roughness model (the causal Huray-Bracken model changes the internal inductance of the strip that affects the delay as well as the characteristic impedance). The model average impedance correlated well with the impedance observed on TDR for short line segment, and is about 1 Ohm lower than the impedance of the long line segments. Note that the impedance also changes along the line segments by about 1 Ohm in measured data, but not in the model – that variation is most likely due to variations of the conductor thickness and the fibre weave effect. Overall, the constructed model can be considered acceptable and suitable for statistical analysis of interconnects.

An even simpler model with an acceptable accuracy can be constructed by fixing some parameters to the average or reasonable values: LT=0.001 @ 1 GHz, SR=0.15 um, RR=1.5. Only distributions of Dk and RF are identified in this case with the following outcome: the average value for Dk is 3.188 @ 1 GHz with standard deviation 0.015, the average value of RF is 8.13 with the deviation 0.76 (both had nearly normal distribution). All variations of the losses in this case are modelled with just one parameter – the roughness factor. Both Dk and RF produced about 1 ps/inch variations in phase delay and about 1 Ohm variations in characteristic impedance, close to those observed from the measurements.

IV. CONCLUSION

The results of the investigation reported in this paper are the first step toward building simple statistical models for the design of predictable interconnects for 56 Gbps PAM4 signals. We observed variations in the geometry and investigated multiple scenarios of the material model parameters identification with statistical variations. In the simplest model, variations in interconnect impedance, losses and dispersion are reduced to just two model variables with an acceptable accuracy.

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