Measurement Uncertainty Propagation in the Validation of High-Speed Interconnects

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***Abstract*—Validating the performance of high-speed interconnect modeling against measurements of fabricated test structures requires an understanding of the robustness of the measurement methods as well as the physical variations present in an imperfectly fabricated test structure. This paper presents a methodology for evaluating the performance of interconnect modeling considering the actual metrology variation and the real-world manufacturing tolerances used to fabricate the test vehicle. By ensuring that measurement results, inclusive of operator and equipment variations, overlap the modeling inclusive of expected manufacturing variations, confidence in the high-speed interconnect modeling is established.**

***Index Terms*—measurement uncertainty, manufacturing variations, reproducibility, correlation.**

I. INTRODUCTION

Measurement-to-modeling correlation is a critical step in validating the electrical performance of high-speed interconnects [1]–[3]. A good correlation ensures that interconnect behavior can be reliably predicted for any new technology, material, or process. However, achieving a good correlation for multiple metrics is not a simple task considering the high number of factors in the correlation flow which influence the final performance [1], [4]. Furthermore, as network connectivity roadmaps target 100 Gbps and beyond [5], correlation is becoming increasingly challenging for high-speed interconnects due to increased performance sensitivity to any variation.

A measurement result is incomplete unless accompanied with an estimate of the uncertainty associated with the measurement [6]. There are many possible sources of uncertainty, not necessarily independent, including the impact of environmental conditions, personal bias in reading instruments, finite discrimination threshold, approximations and assumptions incorporated in the measurement method [7]. Considering all the challenges in high-speed interconnect validation, it is not surprising that poor correlation occurs more often than is desirable. To ascertain whether a correlation is *good* or *poor*, one needs to understand how the uncertainty propagates to the outcome, and not just focus on the outcome itself.

II. UNCERTAINTY QUANTIFICATION

Measurement uncertainty can be quantitatively determined by metrology capability analysis (MCA) [8], which comprises three parts: accuracy, repeatability, and reproducibility. In this paper, the focus is on reproducibility, which is defined as the closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement [9]. The changed conditions include repeated device under test (DUT) insertion and measurement instrument calibrations by multiple test equipment operators at different times. This process provides information on the measurement variability introduced by all temporal and spatial variations of any influence quantity. Environmental conditions, e.g., temperature and relative humidity, can have a profound adverse impact on the material properties, and loss [1], [10]. These factors should be maintained at the same intended use condition throughout the course of the experiment.

Reproducibility bounds the usefulness of any measurement and can be expressed quantitatively in terms of the dispersion characteristics of the results. Fig. 1 illustrates the factors affecting correlation quality, among which S-parameters, dielectric permittivity, and cross-section dimensional measurements are prioritized and elaborated in this section.

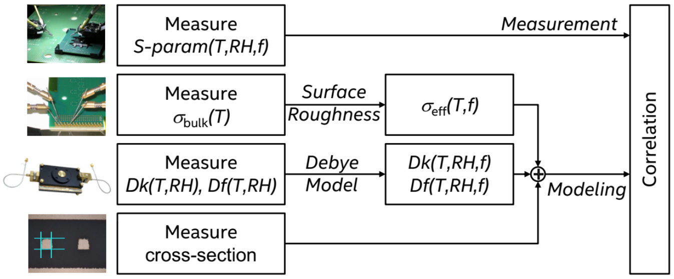

Fig. 1. Measurement-to-modeling correlation flow. T, RH and f indicate dependence to temperature, relative humidity and frequency, whereas σ_{bulk}, σ_{eff}, Dk, and Df refer to bulk and effective conductivity, dielectric constant and dissipation factor, respectively.

A. S-parameter Measurements

A state-of-the-art four-port performance network analyzer (PNA) was utilized to measure the S-parameters of a differential stripline (DSL) package test structure up to 67 GHz. To understand the impact of measurement variation, 3 different operators collected data on 3 different days, calibrating the PNA before each measurement. This yielded 9 measurements of the DUT that could be used to calculate the mean (μ) and control limits ($\mu \pm 3\sigma$), where σ is the standard deviation. Fig. 2 shows the reproducibility results for several differential performance metrics obtained by post-processing single-ended measurement results: return loss (RL), insertion loss (IL), time domain reflectometry (TDR), and phase delay (PD).

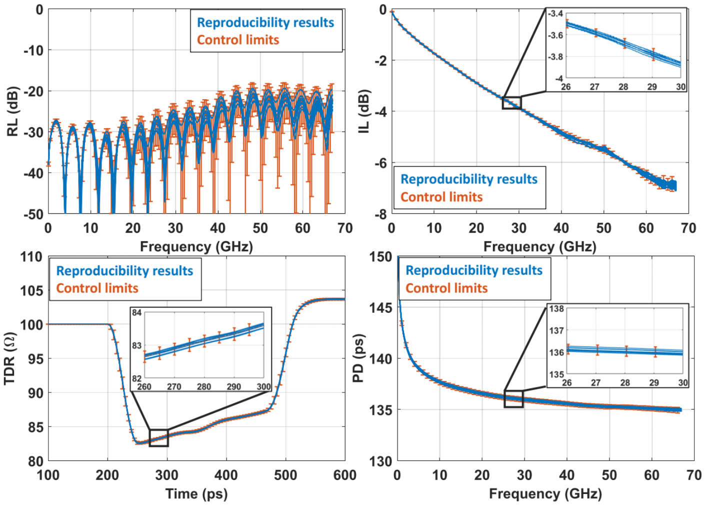

Fig. 2. Four-port PNA reproducibility results for differential metrics referenced to 85 Ω. Error bars indicate $\mu \pm 3\sigma$ control limits.

RL is observed to be very sensitive. This could be due to RL being calculated relative to a reference impedance. Therefore, for well-matched lines, any small dispersion from an already small reflection leads to high relative uncertainty. Variation in IL increases with frequency but relative standard deviation ($3\sigma/\mu$) remains under 4%. Variations in TDR and PD are very small and practically constant over time and frequency with $3\sigma/\mu$ of 0.25% and 0.15%, respectively.

B. Dielectric Permittivity Measurements

In [10], an MCA was performed on the dielectric measurement metrology, utilizing a split post dielectric resonator (SPDR). From that study, it was found that operator variation in the measurement of sample thickness (required to extract dielectric constant (Dk) from SPDR [11]) was a key limiter to reproducibility. This is because the relative errors in thickness result in an almost one-to-one relative error in Dk.

In this study, a separate MCA was performed on dielectric sample thickness measurement utilizing a micrometer. A typical dielectric sample provided by vendors is shown in Fig. 3(a). Three different operators measured two samples with different thicknesses on three different days. The variations from mean value are shown in Fig. 3(b). It appears that the thickness variation shows small dependence on the mean considering one sample is more than twice as thick. As a result, reproducibility is expressed in absolute terms, i.e., $3\sigma \approx 4$ µm. This result also means that thicker samples would yield smaller relative variation in thickness, and hence smaller relative variation in extracted Dk.

Measurement dynamics and sample thickness variation lead to a combined uncertainty of $3\sigma/\mu \approx 3\%$ in Dk. This result implies that any simulation should be performed at both the upper and lower bounds from the dielectric characterization to bound the expected impact of the measurement variability.

C. Cross-section Dimensional Measurement

High fidelity geometrical representation of a transmission line can be achieved by cross-sectioning and is essential for a good correlation. Cross-section dimensional features become more critical considering today's on-package high-speed interconnect loss is largely dominated by conductors due to thinner substrate and low loss dielectric materials [2]. Cross-section pictures of typical package traces along with dimensional features are shown in Fig. 4(a).

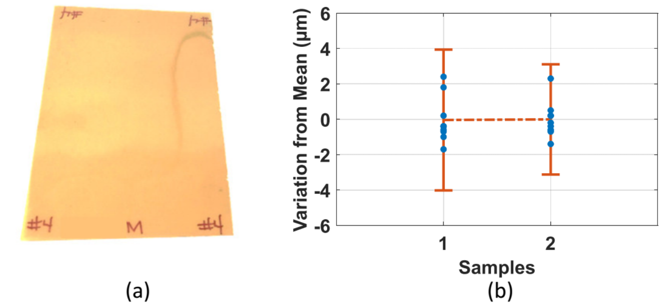

Fig. 3. (a) A typical dielectric sample received from vendors, and (b) thickness measurement reproducibility results. Error bars indicate $\pm 3\sigma$ control limits.

An MCA was performed on a cross-section dimensional measurement utilizing a visualization software. Three different operators measured four separate dimensional features on three different days. The variation of each dimensional feature from its mean value is shown in Fig. 4(b). The main source for uncertainty is the lack of clarity on where the features start and end due to manufacturing process variations and surface roughness. For larger design rules, this ambiguity might cause a relatively small uncertainty; however, for today's high-density package design rules, the resulting uncertainty is not negligible. Reproducibility results show that 3σ control limits for each dimensional feature can be as large as 0.7 µm.

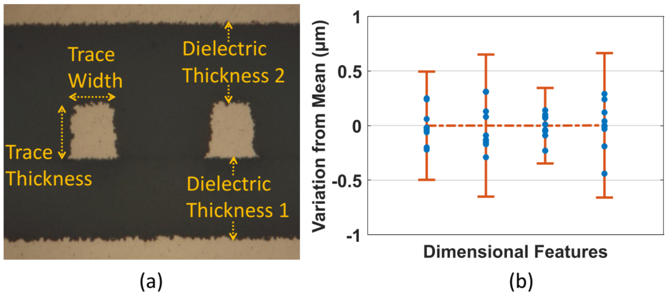

Fig. 4. (a) Cross-section pictures of typical package traces with dimensional features illustrated, and (b) cross-section dimensional measurement reproducibility results. Error bars indicate $\pm 3\sigma$ control limits.

III. MEASUREMENT-TO-MODELING CORRELATION

A package test vehicle was designed and manufactured including a DSL routed on the layer below the surface with a length of 20 mm. Measurement-to-modeling correlation is shown in Fig. 5 at typical use condition for packages, i.e., 90°C and 0% RH [1]. PNA measurement was performed after prebaking to ensure no moisture was left, and on a temperature chuck to achieve this use condition. Modeling results were generated using dielectric and conductor material properties and surface roughness characterized at the same use condition along with cross-section dimensions.

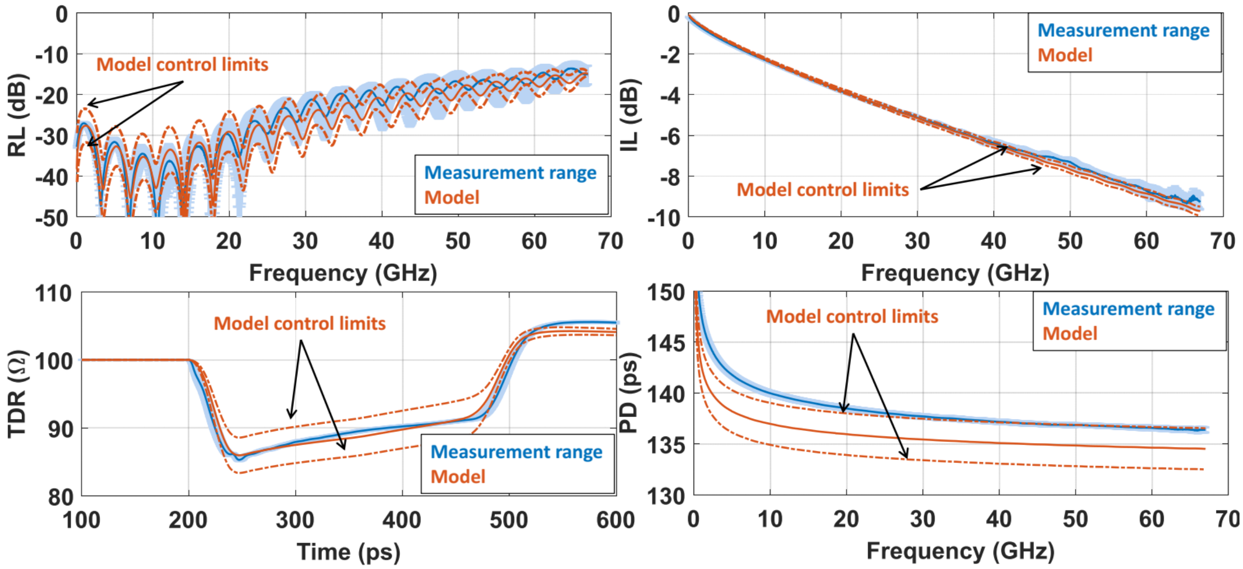

Fig. 5. Correlation at typical use condition for packages. Uncertainty incorporated into measurement (shaded) and propagated to modeling outcome (dash).

Simple visual assessment of measurement and modeling (illustrated by blue and orange solid lines, respectively) may indicate a good correlation for all performance metrics except for the phase delay. A comparison of only single measurement and model lines without any sensitivity analysis is insufficient to evaluate the correlation quality. Propagation of measurement uncertainty is required for a better judgment.

Measurement uncertainty from Section II-A was incorporated into measured S-parameter data as a shaded area, i.e., measurement range. Measurement uncertainty of Dk from Section II-B and measurement uncertainty of cross-section dimensions from Section II-C were incorporated into modeling data as model control limits. Combined uncertainty in standard deviation for each performance metric was calculated using response surface methodology and statistical design of experiments (DOE) [12]. Subsequently, Monte Carlo method was performed to understand the impact of the variabilities on the modeling results. As can be seen, when the dielectric measurement and cross-section dimensional variations are incorporated into the modeling data and compared to the measurement results including the measurement variation, most of the correlation gap in phase delay is accounted for. This result implies that the phase delay can also be considered to have a good correlation for $f > 30$ GHz. It is worth noting that the underlying surface roughness model has a nature of enveloping full spectrum of interest through ensuring better high frequency correlation.

IV. CONCLUSION

This paper presents a systematic methodology for measurement uncertainty quantification and propagation in high-speed interconnect validation. Measurement uncertainty in S-parameters, dielectric permittivity, and cross-section dimensional measurements is examined. Variability in each measurement step of the use condition-dependent correlation flow is quantitatively determined through rigorous MCAs. Combined uncertainty propagated to the performance metrics increases the confidence in correlations by identifying control limits, and helps to better interpret the correlation quality. The next steps for this work include the investigation of uncertainties introduced by various de-embedding methods.

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