Microwave Device Model Validity Assessment for Statistical Analysis

Michael C. Heimlich*, *Member, IEEE*, Venkata Gutta*, *Student Member*, *IEEE*, Anthony Edward Parker*, *Senior Member*, *IEEE*, Tony Fattorini**, *Member*, *IEEE*

*Macquarie University, Sydney 2109 Australia
**Mimix-Broadband, Houston, Texas 73303 USA

***Abstract* — model accuracy is a key consideration when using circuit simulation for microwave designs in general but normally ignored in statistical analysis. A measure of model validity against process variation, MAP, is developed from theoretical considerations. A demonstration of MAP is given for the simple case of a microstrip line and the industry-standard MLIN model. More complex cases are examined for coupled differential microstrip on module for linear design and MMIC HBT diodes for nonlinear design. The impact on MAP of both process variations and model changes is demonstrated. Limitations and extensions to the technique are discussed for other factors impacting the selection of models based on their accuracy.**

***Index Terms* — CAD, design automation, design methodology, microwave circuits, electromagnetic analysis.**

I. Introduction

Modern microwave circuits, with few exceptions, require the use of design automation software to transform design concepts into real circuits. Underpinning the use of the software are simulation models which allow the design engineer to alter key parameters, such as the width and length of a transmission line, and effect a change in the overall circuit performance. The models, to some acceptable level of accuracy, represent the essential features relevant to the design goals while sacrificing others to give a concise representation. Implicit in the use of these models is their accuracy, and the engineer, having determined that the accuracy is inadequate, seeks alternative approaches, like the use of EM analysis, to model the interconnect.

In most cases it is not clear under what quantifiable condition model accuracy is sufficient to allow the designer to predict the performance of a manufactured version of the design given the variability of the manufacturing process. Therefore, it is often desirable to perform a statistical analysis by looking at how the variations in the manufacturing process effect overall circuit performance. While better model accuracy is always desirable and sought to improve the overall capabilities of microwave design in general, manufacturing variability directly impacts the efficacy of models in their particular application to a given circuit and set of design goals. Process variations immediately remove the ability to use to a single set of parameter values for a given simulation model since the manufacturing process, to some degree, can never deliver any specific value with unlimited precision. Simulation must, therefore, always be done with some degree of statistical variation in mind. Thus, there is a balance to be struck between model accuracy and process variation when using statistical analysis as a design simulation technique.

This paper introduces a figure of merit for evaluating in model accuracy against process variability. The goal is to provide the design community with a quantifiable method of determining when model accuracy is sufficient for a given manufacturing variation and when other models or modeling means should be sought. A theoretical discussion introduces the concept and it is followed by a simple demonstration using a microstrip. More advanced examples for linear and nonlinear design are included as well as consideration of both process changes and model changes. Future directions are discussed prior to a concluding summary.

II. Theoretical Development

Consider an arbitrary circuit which has been simulated using a nodel based on no process variation and then manufactured and measured. The simulated performance, S, and the measured performance, M, will differ and an error, E can be defined,

$$E = |M - S| \quad (1)$$

The measured performance, M, can be decomposed as

$$M = M' + \epsilon \quad (2)$$

where M' is the nominal perfomance expected with no process variation and ε is the change in performance assumed to be due to the manufacturing variation. As such, ε is a statistical variable assumed to have a Gaussian distribution with mean, e, and standard deviation, σ, and given the definition of M', we take e=0. Similarly, S is decomposed into

$$S = S' + \delta \quad (3)$$

where S' is the performance predicted for the "ideal model" which exactly produces the nominal performance expected, M', and δ is the model inaccuracy or how far from M' the actual model changes E. Unlike ε, δ is not a statistical variable and is simply a scalar value.

978-1-4244-2802-1/09/$25.00 ©2009 IEEE

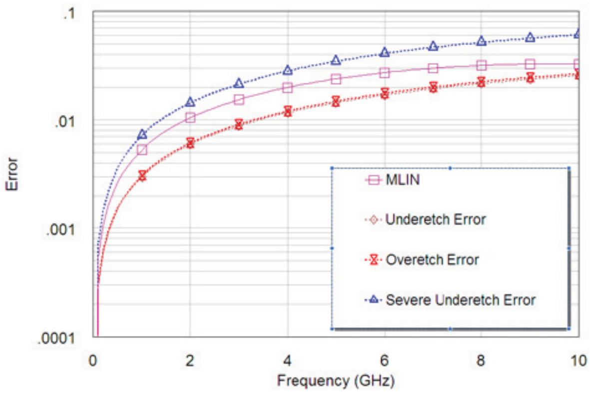

Figure 1 – MLIN, -1 mil overetch, +1 mil underetch, and +2 mil severe underetch error relative to nominal W=20 mil line

Substituting (3) and (2) into (1) and recognizing that S'=M' by the definition of S', we get

$$E = |\,\epsilon - \delta|$$

Exploring E under the variations in the relative magnitude of δ and ε, two extremes exist. If the systematic error due to the model inaccuracy is much larger than the error from the device under test (DUT) departing from a nominal device, the model inaccuracy dominates in E, or

$$E = \delta,\ for\ \frac{\epsilon}{\delta} \ll 1 \quad (4)$$

Conversely, if the random error from the process variation induces much more change on the performance than the model inaccuracy, we find

$$E = \varepsilon,\ for\ \frac{\epsilon}{\delta} \gg 1 \quad (5)$$

As such, (5) defines the most desirable conditions under which statistical analysis or yield optimization simulations should be performed.

III. Simple Microstrip Line

The microstrip-line MLIN model is used extensively across most popular microwave simulation tools and has been available for many years [1-3]. In practice, interconnects on both printed-circuit boards and integrated circuits can vary by the lines being slightly wider or narrower than intended. Over-etching or under-etching alters the characteristic impedance and other electrical properties of the microstrip line.

Here, an ideal microstrip line is constructed for 50-ohm characteristic impedance on 10 mil thick FR4 (ε_r=4) using infinitely thin perfect conductor. Using a transmission line calculating tool [4], it is found that the width of the line should be 20 mils. The length is set to 100 mils to be sufficiently short from DC to 10 GHz. The values have been chosen to remove potential inaccuracy in the MLIN itself due to conductor losses or limitations in the quasi-static nature of its representation [2].

In comparison and representing an actual microstrip line, the same geometry is solved using an EM analysis. This allows the removal of test-equipment error as a consideration. AWR's AXIEM solver [5] is used and set up for maximum accuracy. To represent manufacturing variability, the nominal case of W=20 mils is analyzed along with a presumed uniform variance of ±1 mil, allowing the width to be constrained between an over-etch and under-etch limit of 19 mils and 21 mils, respectively.

Comparing the MLIN prediction to the nominal W=20 mils EM analysis, a maximum least-squares measurement error is used to accentuate the worst-case entry in the S-parameter matrix representing the model (Fig. 1). Compared to the overetch and underetch cases, the MLIN model is found to be less accurate compared to the EM analysis for all frequencies below 10 GHz. In the extreme case of a 2 µm under-etching where W=22 mils (Fig. 1 "severe underetch"), the MLIN model is more accurate.

IV. Figure of Merit

Examination of the above results suggests that, under different manufacturing capabilities, the MLIN model may or may not be sufficiently accurate for statistical analysis. For a ±2 mil variation, MLIN provides sufficient accuracy relative to the natural S-parameter variation that would be induced by the manufacturing process itself. It would not be possible given a ±2 mil variation to know whether the MLIN model or the manufacturing process contributed to a difference between circuit performance as-designed versus as-measured. In contrast, for a manufacturing process with ±1 mil accuracy, MLIN would clearly contribute more error to any observed difference between simulated and measured circuits.

These results suggest a figure of merit to guide the designer in quantifying a model's usefulness relative to manufacturing variability. Defining the Model Accuracy Process (MAP) figure of merit as

$$MAP = \frac{\varepsilon}{\delta} \quad (6)$$

For the MLIN and the ±1 mil process, MAP= 0.59 at 2 GHz while, for the severe etching of ±2 mils, MAP= 1.43. While (5) suggest that very large values of MAP provide definitive support for a model's validity in a statistical simulation these results suggest that it is even useful at values that are only greater than unity. The analysis in section I therefore corresponds to the discussion of results in section II.

V. Linear Example

Using the approach and analysis for MAP and MLIN, a more complicated case can be examined. Two coupled microstrips are used extensively for balanced design or differential signaling, such as would be found in module design or packaging. As such, the performance of this interconnect is potentially more sensitive to process variations because the even- and odd-mode impedances can be sensitive to the microstrip line width individually and to the spacing of the two lines together. Multiple combinations of line width W and line spacing S can be chosen to give the desired impedance.

The M2CLIN model [6] is used with traces of 0.4 mil gold on 10 mil alumina (ε_r=9.8, TAND=0.0025) for a target differential impedance of 100 ohms. Using a transmission-line calculation tool [4], W=6 and S=9 are selected to keep the geometry small while providing some resilience to manufacturing variances. A similar structure is simulated using AWR's AXIEM EM solver [5].

A manufacturing variation is applied to this structure, except that this time the over/under etching is limited to ± 0.5 mil. The calculated errors are shown in Fig. 2. For all frequencies from DC to 10 GHz, the M2CLIN model has greater error than that induced by the ± 0.5 mil manufacturing variability. The MAP value calculated at 2 GHz and 8 GHz is 0.67 and 0.83, respectively.

A useful application for MAP is to seek out alternative models which could be used to provide greater simulation fidelity before having to go to EM analysis. The speed of parameter-based models and their usefulness in top-down design methodologies, like those using tuning, optimizing, and statistical analysis, are typical reasons for seeking these models despite the greater accuracy provided by EM [7]. The GFMCLIN model is a parameter-based model for an arbitrary coupled-line system of multiple lines and multiple dielectrics solved in two-dimensional cross-section using the FEM technique [8]. As such, we expect it to give better accuracy

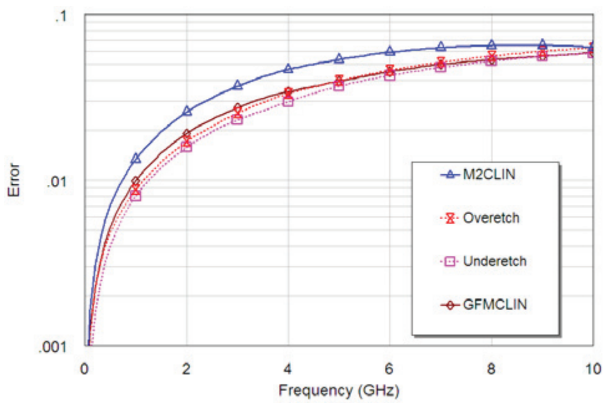

Figure 2 – M2CLIN, Overetch, Underetch, and GFMCLIN error relative to nominal W=6 S=9 coupled microstrip

than M2CLIN. Fig. 4 shows that, for all frequency values, GFMCLIN has greater accuracy than M2CLIN. MAP at 2 GHz for GFMCLIN is 0.91 which indicates that the error of the GFMCLIN model would be distinguishable from manufacturing variance in the performance of actual circuits. At 8 GHz, MAP for GFMCLIN is 1.1, suggesting that GFMCLIN accuracy is sufficient for ± 0.5 mil manufacturing variations while that of M2CLIN is not.

VII. Nonlinear Example

To demonstrate MAP for nonlinear analysis, a 49 um^2 diode is fabricated using a 1um MMIC HBT process. I-V data was taken for a larger population of data across several wafers which had passed PCM inspection and found to be within the constraints for the HBT process as a whole. A nominal model parameters I_s, N, and R_s where extracted for a SPICE diode model [5] representing the HBT process. This nominal model was than compared to measured I-V data for 30 of the diodes across a single wafer. As shown in Fig 3, a model representative of the average performance for the single wafer was also extracted. For all of the measured data, the nominal process model has nonzero δ such that the best case MAP at 0.7 V is 0.32.

While our ability to fit a SPICE diode model representing the average of the measured data vindicates the SPICE diode model itself for use with the measured diode population, the parameters selected as the nominal model for the process are inappropriate as the basis for accurate statistical modeling. Thus, the SPICE diode model itself is useful for statistical analysis for MMIC HBT diodes but the nominal model alone is inadequate. The extracted parameters for the SPICE diode model representing the nominal MMIC HBT diode may also be useful over a larger population of diodes and wafers. Clearly, the population of diodes measured here are not represented by the nominal process and careful consideration should be given as to what extracted parameter set(s) should be used for statistical analysis.

VII. Discussion and Limitations

MAP should not be applied blindly without an understanding of a model's inherent limitations and the details of the manufacturing process. The models themselves vary over all their independent variables such as frequency and/or bias, as shown here. Manufacturing variances sometimes do not manifest themselves as uniform over-etching or under-etching and may not be uniform across a complete length of line, as assumed here. The line could be continuously varying over its length. In the case of the surface mount devices, for example, the distribution is rarely uniform or Gaussian, but may be bi-modal. For nonlinear devices, metal etching as well as the dielectric and semi-conducting properties could introduce process variability.

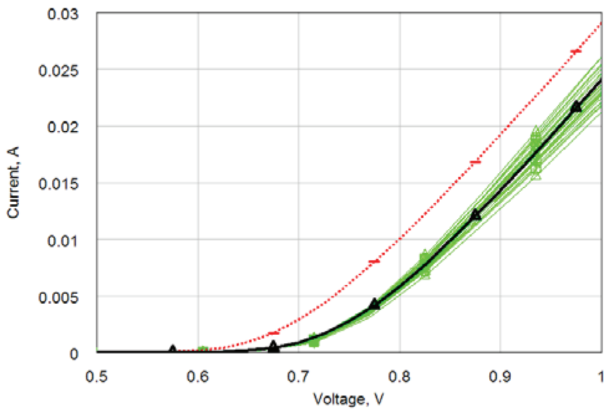

Figure 3 – I-V data for MMIC HBT diode showing nominal process model (dotted line), extracted model for average measured data (thick solid line) and measured data for 30 diodes (thin solid lines).

Other areas can impact an appropriate selection of models, and similar figures of merit could be developed for these. While we are most chiefly concerned with a model's accuracy, often it may be more important to compare this accuracy to something other than manufacturing variation itself. One example of this is when we are more concerned with the design performance limits of a given process, like minimum noise figure (NF_{min}) for a transistor. The accuracy needed for all models in a low-noise amplifier circuit design will be much greater where the design goal is very near the NF_{min} for the transistor as compared to where it is much further away.

VII. Conclusion

Model accuracy must be viewed in the context of the real-world manufacturing process into which the microwave circuit is being designed. Furthermore, attempts to simulate with manufacturing variance in mind, like statistical analysis, must be done in the context of the model's ability to represent the desired physically measurable performance goals. A quantifiable measure to assess the usefulness of a given model for a particular frequency range, application, etc. is desirable. Model Accuracy Process (MAP) as a figure of merit provides such a measure by comparing the relative error from a model to that of the error induced by variances in the relevant process parameters. Here, interconnects were allowed to vary in the printed metal width for a microstrip line and a microstrip differential-pair structure. Measured I-V data for a MMIC HBT diode population was found to differ markedly from the nominal process model. MAP can be used to show when either process or model changes could indicate a greater likelihood that the manufactured circuit will perform as designed. As such, it is a good indicator of a model's usefulness for statistical simulations. The general concept for MAP can be extended to other aspects of model accuracy.

Acknowledgement

The authors wish to acknowledge the invaluable discussions with Chris Aden and Sherry Hess during the course of this research.

References

[1] E. J. Denlinger, "A frequency dependent solution for microstrip transmission lines"; *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 30-39, Jan. 1971.

[2] T. C. Edwards, *Foundations for Microstrip Circuit Design*, New York: J. Wiley & Sons, 1981.

[3] H. A. Wheeler, "Transmission-line properties of a strip on a dielectric sheet on a plane", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 631-647, Aug. 1977.

[4] TXLine, available as shareware at www.awrcorp.com.

[5] *MWO/AO User Guide*, AWR Corp., ver. 8, November 2008.

[6] B. Bazdar, A. R. Djordjevic, R. F. Harrington, and T. K. Sarkar, "Evaluation of quasi-static matrix parameters for multiconductor transmission lines using Galerkin's method," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1223-1228, July 1994.

[7] G. G. E. Gielen and R. A. Rutenbar, "Computer-aided design of analog and mixed-signal integrated circuits," *Proc. IEEE.*, vol. 88, no. 12, pp. 1825-1849, December 2000.

[8] *MWO/AO Element Catalog*, AWR Corp., ver. 8, November 2008.