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Giuseppe Selli

Mauro Lai

Shaofeng Luan

James L. Drewniak
Missouri University of Science and Technology, drewniak@mst.edu

et. al. For a complete list of authors, see https://scholarsmine.mst.edu/ele_comeng_facwork/1323

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Validation of Equivalent Circuits Extracted from S-Parameter Data for Eye-Pattern Evaluation

Giuseppe Selli, Mauro Lai, Shaofeng Luan, James L. Drewniak, Richard E. Dubroff
EMC Laboratory
University of Missouri-Rolla
gs5xd@umr.edu

Jun Fan, James L.Knighten, Norman W. Smith
NCR Corporation
San Diego, CA USA

Giulio Antonini, Antonio Orlandi
Uaq EMC Laboratory
University of L'Aquila, Italy

Bruce Archambeault, Samuel Connor
IBM Co. Research
Triangle Park, NC USA

Abstract— **S-parameter circuit model extraction is usually characterized by a trade off between accuracy and complexity. Trading one feature for another may or may not affect the goodness of the reconstructed S-parameter data, which are obtained from frequency domain simulations of the models extracted. However, the ultimate test for the validity of these equivalent circuit representations should be left to eye-diagram simulations, which provide useful insights, from an SI point of view, about the degradation of the signal, as it travels through the system. Physics based simplication procedures can be used to tune the models and achieve less complexity, whereas the comparisons of the eye-diagrams may help to quantify the goodness of all these circuits extracted. In fact, the most accurate model is not necessary the best to be used.**

Keywords-Circuit extraction; accuracy; complexity; model order; model validation; eye-diagrams.

I. INTRODUCTION

The versatility of equivalent models for PCB interconnect discontinuities drives an increasing demand for S-parameter circuit extraction techniques [1]. Accuracy, when compared to the original set of data, and simplicity of the model are the two features usually required from the circuits extracted.

Interconnect discontinuities, e.g, via holes, are increasingly important in high speed digital applications. The impact of these elements on the degradation of the intended signal has been studied [2-10]. Spice based tools offer the advantage of analyzing more complex geometries, i.e., a complete signal path or multiple signal paths from one end to another one, by simply cascading the equivalent models for each element constituting the relevant geometry. Complexity, then, becomes the main issue if the advantage over time consuming 3-D full wave simulations is not to be lost.

Physics-based considerations can help to reduce the model order of the equivalent circuit by meaningfully processing the S-parameter data. For example, small ripples observed in frequency domain data are usually misleading, when related to the system under analysis. Removal of those features may lead to a simpler model which contains all the necessary information. The application of a Finite Impulse Response smoothing filter is an efficient way to preprocess the data, in order to implement the purpose of simplification.

Finally, the comparison of the SPICE simulated eye-patterns is the optimum means to validate the different circuit models. In fact, considerations of jitter and the opening of the eye provide the necessary information to establish the quality of a model based upon a criterion, which may depend upon the particular application.

II. THE EQUIVALENT CIRCUIT MODEL

The via geometry under analysis is pointed out in Fig. 1 and Fig. 2. The structure consists of two 50 Ohm microstrip lines connected by a via hole in a 4-layer board as shown in Fig. 2. Each microstrip line is referenced to the closest solid plane, i.e., the ground or the power plane, such that there is no DC continuity between the two ports.

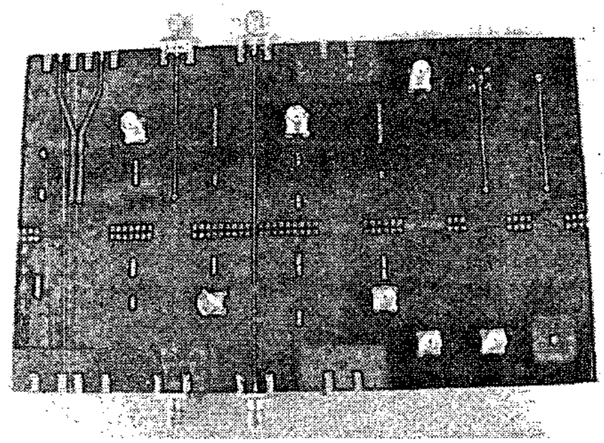

Fig. 1. 4-layer board with the geometry of interest.

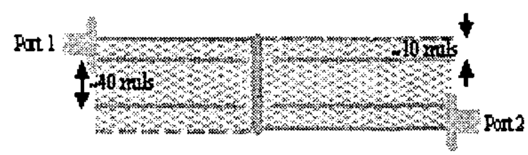

Fig. 2. Drawing of the geometry under analysis.

An equivalent model for the via geometry of Fig. 2 can be extracted from frequency domain measurements performed with a network analyzer. The circuit extraction technique is based on a vector-fitting algorithm [11]. It is implemented as it follows. The measured S-parameter data are converted into a set of Y-parameters and to realize an equivalent Pi-network between Port 1 and Port 2 [12]. Then, a vector-fitting algorithm is applied to the nodal admittances and each branch of the Pi-network is modeled in terms of poles and residues; each real pole, or each pair of complex conjugate poles with the corresponding residues, can be analytically converted into a circuit element [1]. Finally, the overall equivalent circuit can be run in a SPICE based tool, and the S-parameters can be calculated and compared with the measured values. The implementation of this extraction technique is outlined in Fig. 3.

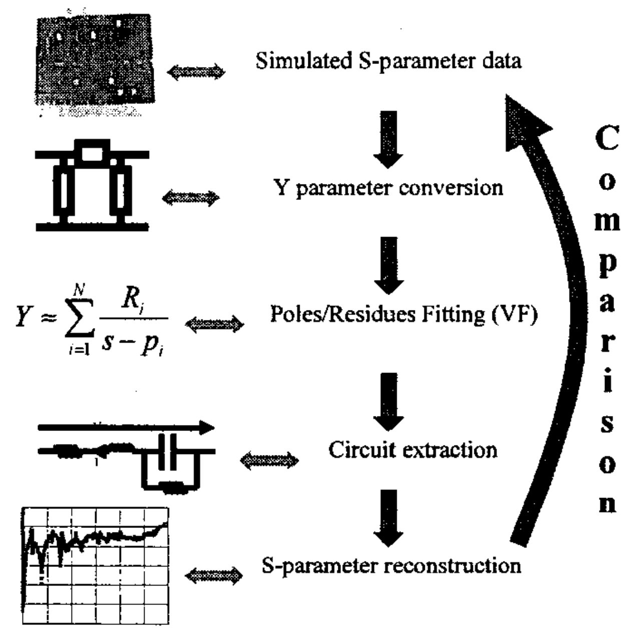

Fig. 3. Implementation diagram of the circuit extraction technique.

The choice of the number of poles represents the main degree of freedom allowed in the circuit extraction procedure outlined in Fig. 3. As a matter of fact, this number may vary over a wide range and the corresponding equivalent models characterize different compromises between accuracy and complexity. Accuracy and complexity are directly related, although the accuracy quickly saturates after a certain number of poles, whereas the complexity keeps increasing with the number of poles. The final step of the implementation diagram anticipates the comparison between the SPICE simulated S-parameter data and the original set. This comparison can be used to determine the number of poles needed to achieve the desired accuracy. In fact, the normalized squared difference between the reconstructed S-parameter data and the original data can be related to the accuracy of the reconstruction by:

$$E_{dB} = \left[\frac{|S_{11n}-S_{11}|^2 + 2|S_{21n}-S_{21}|^2 + |S_{22n}-S_{22}|^2}{|S_{11}|^2 + 2|S_{21}|^2 + |S_{22}|^2} \right]_{dB} \quad (1)$$

where the subscript "n" indicates the reconstructed S-parameter data obtained form the Spice simulation.

The relationship between accuracy, as defined in (1), and the number of poles is plotted in Fig. 4. Firstly, the error E_{dB} rapidly decreases inversely to the number of poles as this number increases from 50 to approximately 200; then, the accuracy (~ 1/E) saturates at a value of approximately -30_{dB}. On the other hand, the complexity of the model, i.e., the number of poles, keeps increasing.

Therefore, according to the functional relationship plotted in Fig. 4, the implementation of the circuit extraction technique gives a good compromise between accuracy and complexity by employing a large number of poles, i.e., 200 poles.

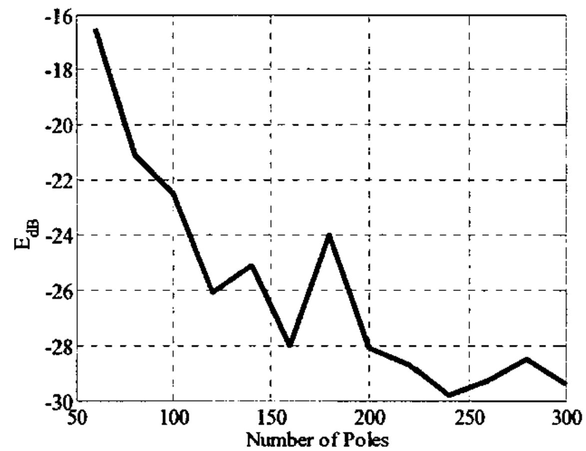

Fig. 4. Accuracy as a function of the number of poles.

III. Physics-Based Model Order Reduction

Physics-based considerations can help to further reduce the model order and achieve a lower complexity by maintaining the necessary information needed to describe the system under analysis. The implementation of a smoothing filter, as shown in Fig. 5, allows the discrimination of the features associated with the via discontinuity, with respect to the misleading information. In fact, the ripples shown in Fig. 5 are usually related to reflections that ocurr late in time, which, if not removed, usually complicate the equivalent model extracted.

An FIR filter is employed and the order is chosen in relationship to the ripple to be removed. The normalized squared difference between the smoothed S-parameter (output of the filter) and the original set (input of the filter) needs to be bounded, i.e., less than -30dB. In fact, the filter needs to smooth out the unnecessary part of the signal, i.e., the ripple; however, the distinctive features of interest needs to be preserved, since those are the main objective of the entire analysis.

Fig. 6 shows the application of (1) as a function of the order N of the smoothing filter. The normalized squared difference is kept below -30dB, if a 15^{th} order filter is chosen, such that the ripples are removed from the measured data

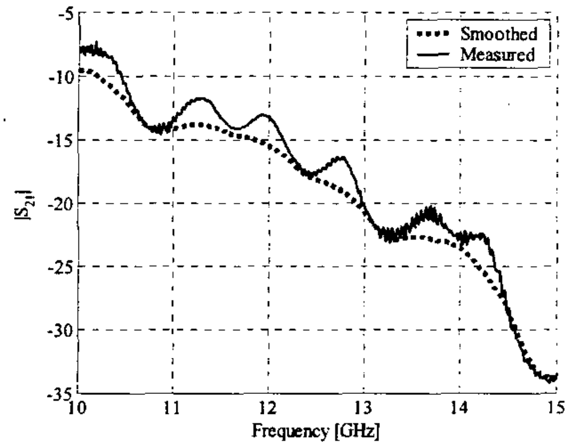

Fig. 5. Implementation of the smoothing filter.

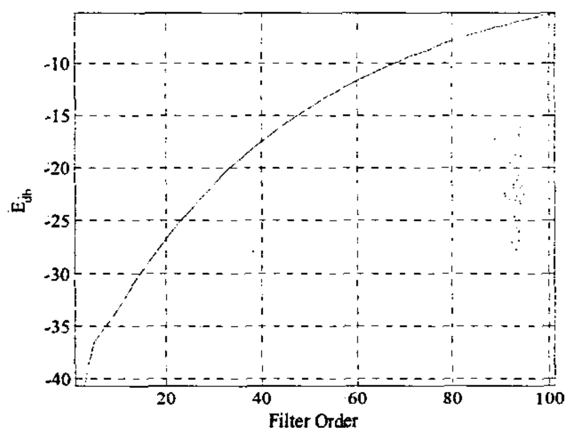

Fig. 6. Normalized squared difference [Equation 1].

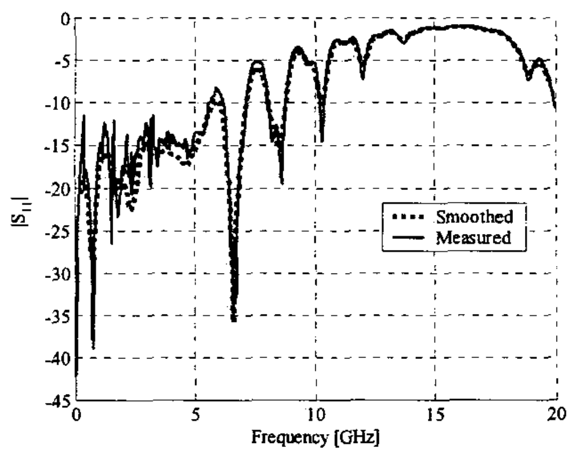

Fig. 7. S_{11} magnitude comparison.

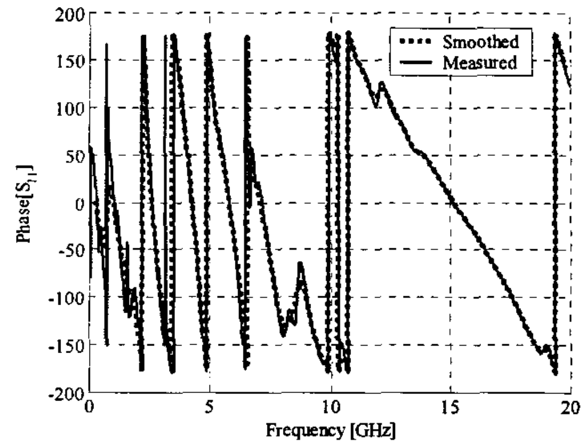

Fig. 8. S_{11} phase comparison.

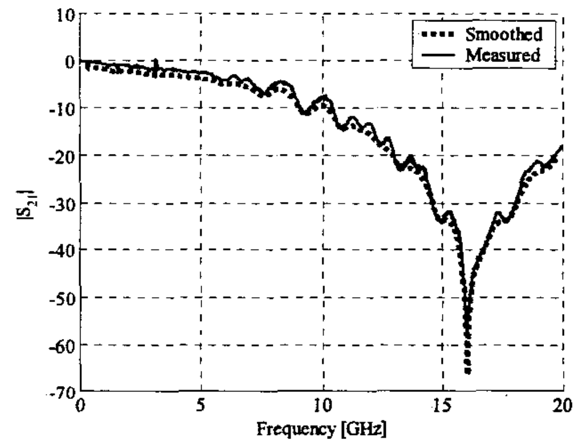

Fig. 9. S_{21} magnitude comparison.

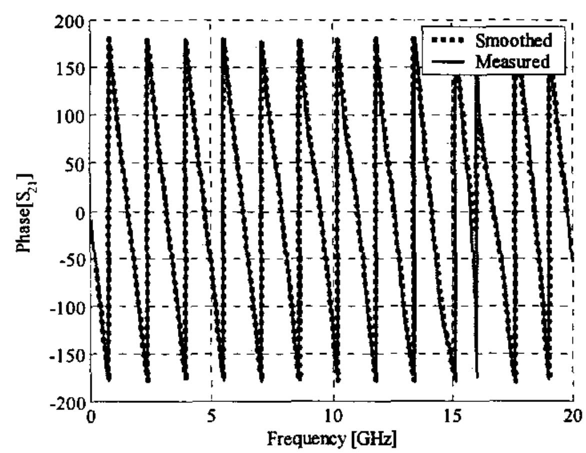

Fig. 10. S_{21} phase comparison.

as an example shown in Fig. 6, Fig. 7, Fig. 8, Fig.9 and Fig. 10.

The filters employed have only forward terms and no feedback terms (FIR). Moreover, it is centered so that the output is synchronized with the input and no lag is introduced. The first and the last (N-1)/2 samples need to be discarded from the output due to its transient response. However, the same accuracy achievable with approximately 200 poles, for example, can be accomplished with 70 poles, when a 15[th] order smoothing filter is used.

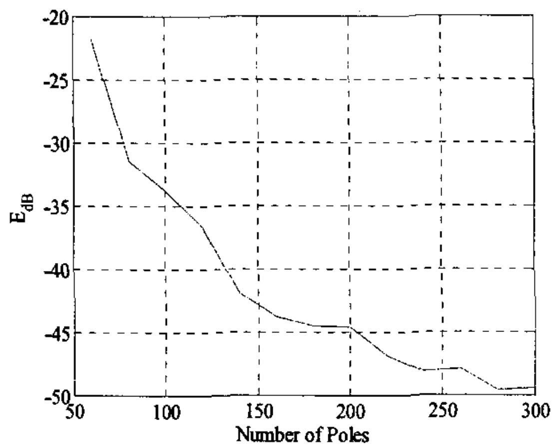

Fig. 11. Accuracy as a function of the number of poles

Fig. 11 shows the same accuracy-complexity relationship of Fig. 4 applied to the circuit models extracted from the smoothed S-parameters.

IV. EYE DIAGRAM SIMULATIONS FOR MODEL VALIDATION

Qualitative and quantitive considerations on the validity of the circuit models extracted can be drawn by comparing the SPICE simulated eye-diagrams. The pseudo-random sequence waveform employed in the different simulations consists of a 20 bit pattern, i.e., the comma (K28.5+) comma-bar (K28.5-) test sequence, at 2.5 GHz with a rise time of 250 ps.

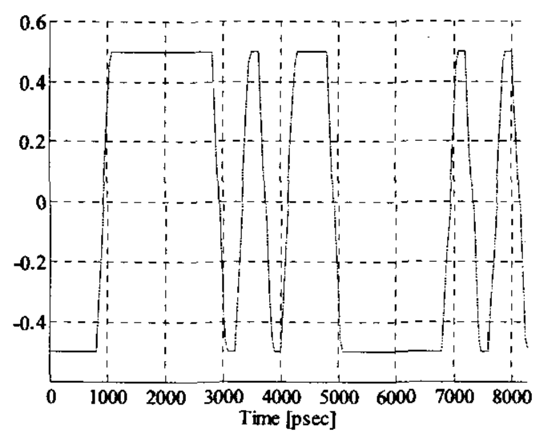

Fig. 12. Input pseudo-random sequence waveform.

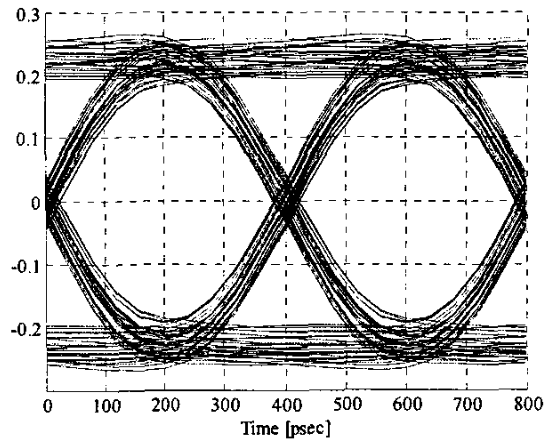

Fig. 13. Eye diagram obtained from H-SPICE simulation of the circuit extracted with 200 poles from the original S-parameter set.

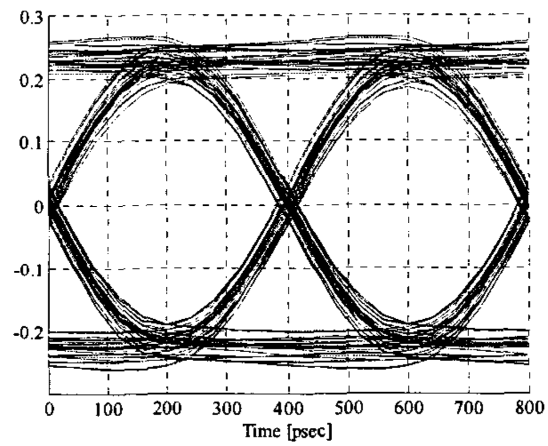

Fig. 14. Eye diagram obtained from H-SPICE simulation of the circuit extracted with 170 poles from the original S-parameter set.

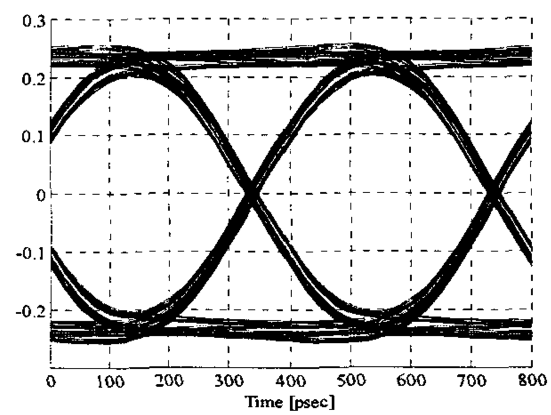

Fig. 15. Eye diagram obtained from H-SPICE simulation of the circuit extracted with 150 poles from the original S-parameter set.

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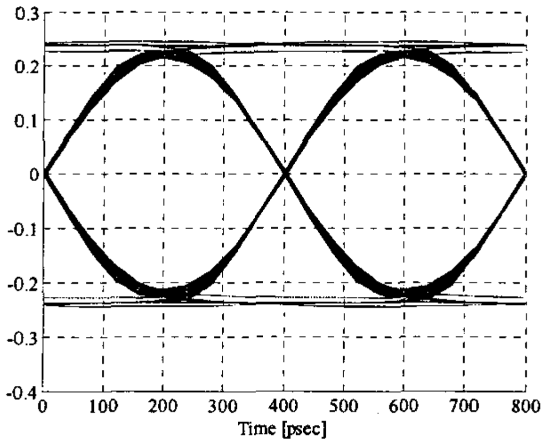

Fig. 16. Eye diagram obtained from H-SPICE simulation of the circuit extracted with 100 poles from the smoothed S-parameter data.

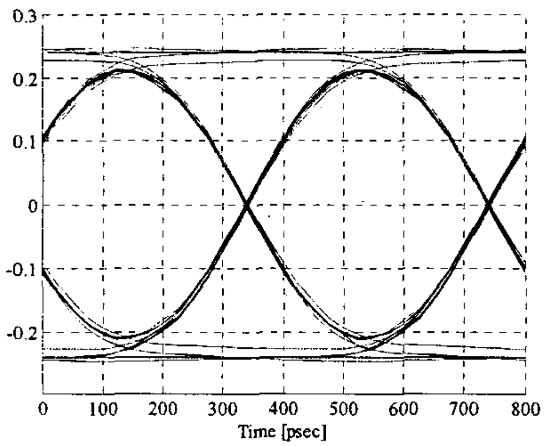

Fig. 17. Eye diagram obtained from H-SPICE simulation of the circuit extracted with 70 poles from the smoothed S-parameter data.

The simulated eye-diagrams of the models are shown from Fig.13 to Fig.17. Each model is characterized by a different complexity, i.e., number of poles employed in the extraction. The plots show the voltage observed at port 2 for a time length of 800 ps; the first three circuits are extracted from the original set of measured S-parameter data with respectively 200, 170 and 150 poles, whereas the last two are extracted from smoothed data, i.e., the extraction procedure is applied to the output of a 15^{th} order FIR filter, fed with measured data.

A distinctive trend may be observed by looking at the plots from the most to the least complex model. This trend consists of only small changes in the openings of the eye, which increse from approximately 0.38 Volts to 0.42 Volts, and a more noticeable change in the jitter, which decreases from 46 ps to approximately 10 ps. In fact, the implementation of the circuit extraction technique inherently attempts to fit the behavior of the measured data, and the larger number of poles used, the better the system is equivalently represented. This is especially true with respect to those small features, which seems to add significant spread to the jitter. On the other hand, as the system is represented with a less degree of accuracy, i.e., fewer poles, or by implementing a smoothing filter, the eye diagrams seem to show less information, although the error criterion employed (Equation 1) do not severely change. Table 1 summarizes the values of the characteristic parameters observed in the eye diagrams plotted from Fig. 13 to Fig. 16 and the errors.

TABLE I. FEATURES OBSERVED IN THE EYE DIAGRAMS.

	Eye Opening	Jitter	E_{dB}
Circuit (200 poles)	0.38 Volts	46 psec	-28
Circuit (170 poles)	0.39 Volts	40 psec	-27
Circuit (150 poles)	0.4 Volts	20 psec	-26
Circuit (100 poles)	0.43 Volts	8 psec	-30
Circuit (70 poles)	0.42 Volts	9 psec	-28

The simulations of Fig. 13 and Fig. 14 show that it is unnecessary to increase the number of poles beyond 170. In fact, a more complex circuit gives almost the same eye-pattern and the enhancement in the results is small, as Table 1 indicates. On the other hand, the simulation of the circuit extracted with 150 poles shows a big difference expecially in terms of jitter. This difference is much larger when the circuit models extracted with 100 and 70 poles from smoothed S-parameter data are simulated and the results are compared. In fact, the application of the smoothing procedure inherently decreses the accuracy by discarding the unnecessary features embedded in the measured data. However, the eye-diagram simulations of these simpler models should contain all the information needed to draw conslusions about the degradation of the signal, as it travels throug the system.

Finally, when these comparisons are performed, special attention should to be given to the bandwidth of the input pseudo random sequence with respect to the bandwidth of the S-parameter data from which the circuit models are extracted from. The use of these models can be easily extended beyond the bandwidth of the original S-parameter data. However, the values calculated outside the initial bandwidth of extraction may have nothing to do with the real behavior at those frequencies of the measured system. Therefore, the response of the system under analysis may not be realistic, if the harmonic content of the input waveform lies outside the bandwidth of the S-parameter data. However, as long as the two bandwidths are close to each other, the estimated values are correlated with the known values and the observed output response reflects the real behavior of the system.

V. CONCLUSIONS

The vector-fitting extraction technique employed provide a straightforward mean to obtain SPICE-compatible equivalent circuits. The physics-based smoothing procedure gives a meanigful way to obtain a reduction of the order model. The comparisons between the SPICE simulated eye diagrams provide the insights needed to quantify the modeling accuracy of the different extracted circuits as well as the redundancy of the information embedded in the measured S-parameters. However, further investigations regarding the model order and application of smoothing filter with respect to the eye-pattern simulations need to be carried out. In particular, a better correlation relationship needs to be found between the error criterion and the characteristic parameter of the eye diagrams, i.e., opening and jitter. This thorough analysis helps to quantify the quality of the different circuit models with respect to the trade-off between accuracy and complexity.

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