Automated Generation and Correlation of Physics-Based Via Models with Full-Wave Simulation for an SI/PI Database

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***Abstract*—A Systematic data generation and validation for signal and power integrity of printed circuit board designs to enable database creation are proposed. Efficient physics-based models and accurate full-wave simulations are used to ensure data quality.**

***Index Terms*—automation, signal integrity, power integrity, validation, physics-based, full-wave,**

I. Introduction

The development of modern high speed interconnects on printed circuit boards (PCBs) comes with challenging requirements. The finite element method (FEM) and finite integration technique (FIT) are established methods for characterizing these interconnects.

Simulation is widely used in design processes of PCBs. But conventional simulation methods reach their limitations as they need large amounts of computation time and resources. The investigation of large problems or higher frequencies immediately increases the discretization effort needed to compute meaningful results for these electromagnetic problems. Therefore alternative methods are being investigated. To tackle these challenges, machine learning (ML) receives entrance into the topic of signal integrity (SI) and power integrity (PI) [1].

Two goals can be formulated. First, the introduction of ML seeks to replace conventional simulation methods in calculating network characteristics of digital links e.g. [2]. Second, ML methods can be integrated into the design process to provide good estimates on designs given specific requirements and thereby removing slow human interaction from early design stages [3]. The application of ML requires, first, algorithms for learning and, second, data to learn from. As to the knowledge of the authors a comprehensive and publicly available database for SI and PI problems is missing, this paper focuses on providing data and works toward extending the largest existing SI/PI database introduced in [4]. A systematical analysis of the complete SI design space has not been carried out, yet, and requires an automated process to achieve the volume of trusted data, necessary for ML application.

The paper ist structured as follows. In Section II a data generation and validation framework is proposed and implemented using two specific simulation methods. Section III gives exemplary investigations using the automation scheme. Section IV concludes this paper and gives an outlook for improvement of the scheme.

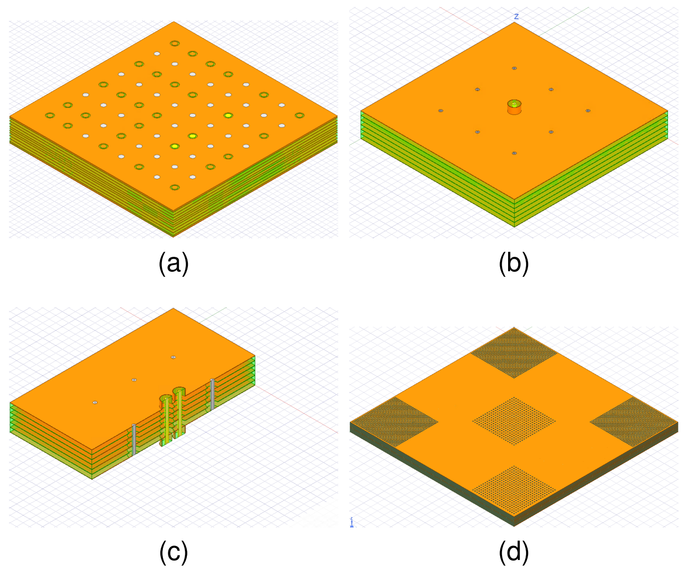

Fig. 1. Automatically generated models of PCB setups that have the benefit of enabling systematic variation and scaling of PCB setups. Signal vias with ports are depicted yellow. Ground vias are depicted grey. (a) shows a FEM model with 64 vias, containing 33 thru signal vias and 3 ports in the third row. (b) and (c) depict a FEM model of 1 and 2 signal vias, respectively, that are enclosed by a ground via fence of 8 ground vias. (d) indicates the power of automatic generation by showing a extremely large FEM model with 38 layers and 3679 blind vias all connected on different layers.

II. Data Generation and Validation Framework

For the choice of simulation method two opposite requirements need to be considered. First, every ML method can only provide accurate predictions of a physical system, if the data it is trained with, resembles the physical system accurately. On the other hand, large datasets are required for the training and therefore require fast simulation of results.

For this purpose a hybrid simulation scheme is proposed that utilizes two different simulation approaches. State of the art full-wave (FW) solvers yield most accurate results. They are best suited as a secondary simulation method, that can be used to provide reference data for validation. In this specific case a commercial FEM solver has been used [5].

As primary simulation method a fast yet accurate method is necessary to generate the main volume of data. In [6] a physics-based (PB) method was proposed and extended in [7].

Herein analytical models of vias and modal decomposition are used to speed up simulation time by at least two orders of magnitude. The applicability to a range of problems was shown with comparisons to both FEM, FIT and measurement data, but a comprehensive analysis of the limitations is missing. Since PB models produce results with a high velocity, they represent a good candidate as primary data source for large scale data generation in the SI and PI domains and are therefore chosen to be used.

Nevertheless, every model has its area of validity as well as limitations and PB models are no exception. A detailed understanding of those limitations is necessary to increase trust in the generated datasets. Up to now, the design space has been explored in specific contained areas. The validation was carried out by manually recreating FW models for representative cases and comparing the results manually. This requires human intervention and hence is costly, time consuming, and prone to errors. To mitigate those problems, an automation of the process is proposed. The automation was carried out using a general purpose programming language that includes interfaces to the commercial solver used [8].

Within the implemented framework a high level description of multilayer PCBs is used. Automatic iterations over every parameter is possible and the generation of simulation sets spanning an arbitrary design space can be achieved. Methods were implemented to create complete simulation setups for both simulation tools, that consistently resemble a representation of the same structure [9].

An overview of the complete framework and the intended usage is illustrated in Fig. 2 and its benefits are threefold. First, the creation is repeatable and eliminates a multitude of errors, which a creation by hand is prone to. Second, the process can be automated without needing human interaction for either the creation or validation. Third, it significantly speeds up the process of creating an equivalent simulation, especially in comparison to manual creation. The translation time from PB setup to FEM model for the setup depicted in Fig. 1b is 26 s, while the more complex model containing 64 vias in Fig. 1a takes 4 min. The possibility to seamlessly create a comparable FW model for every data point facilitates design space exploration and is the foundation for an SI/PI database. The exceedingly large setup depicted in Fig. 1d containing 38 layers and 3679 vias has blind vias connected individually to different layers and displays the adaptability and scalability of the automation process. This way the framework paves the way for large scale data generation for an SI/PI database.

III. Exemplary Design Validation

As a first example, the via array depicted in Fig. 1a was investigated. The setup contains 11 layers with heights between $h = 3.7$ and $9.8\,\text{mil}$, relative permittivity of $\varepsilon_r = 3.7$, loss tangent of $\tan\delta = 0.03$, via radius $r_v = 5\,\text{mil}$, antipad radius of $r_a = 15\,\text{mil}$, pitch of $a = 80\,\text{mil}$ and perfectly matched layer as boundary condition. Three vias in the third row are used as ports, and all others are left open. This setup serves as evidence that the automation in fact is capable of creating

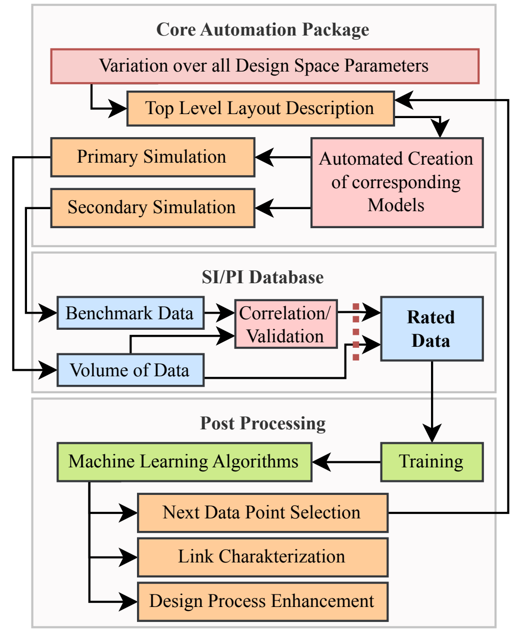

Fig. 2. Scheme of the data generation and validation framework. A top level description of the PCB layout in a general purpose programming language is used. Every design parameter can be varied and an automated process creates simulation models for primary and secondary simulation methods, respectively. Part of the fast generated data is validated against more accurate results. In this way data added to the database can be trusted. Database can be used to train machine learning models in future applications.

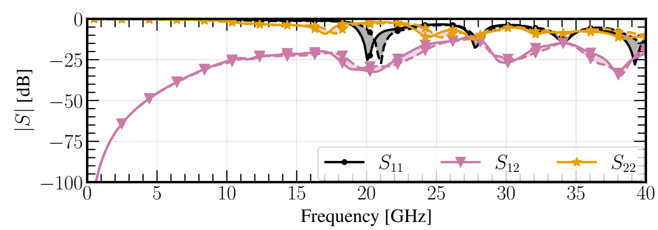

Fig. 3. Reflection and near end crosstalk for the structure of Fig. 1a showing agreement between the two simulation methods. Continuous lines represent PB and dashed lines FW results, respectively.

equivalent simulations with both simulation tools. As can be seen in Fig. 3 the curves of S-parameters lie on top of each other with the exception of a small shift in resonance for the reflection. For quantification of agreement root mean squared difference (RMSD) defined as

$$\text{RMSD} = \frac{\sum_i \sqrt{(|S_i^p| - |S_i^s|)^2}}{N} \tag{1}$$

was chosen. $|S_i^p|$ and $|S_i^s|$ represent the magnitude of S-parameters for primary and secondary simulation methods, respectively and N the number of calculated frequencies. Best agreement can be found for crosstalk with RMSD less than $0.01 \cdot 10^{-3}$. Due to the offset of the resonances, the reflection exhibits a higher RMSD of $0.45 \cdot 10^{-3}$.

Secondly, the automation is being tested by investigating the effect of the distance from a signal via to a ground fence as depicted in Fig. 1b. The setup consists of 4 ground and 3 signal

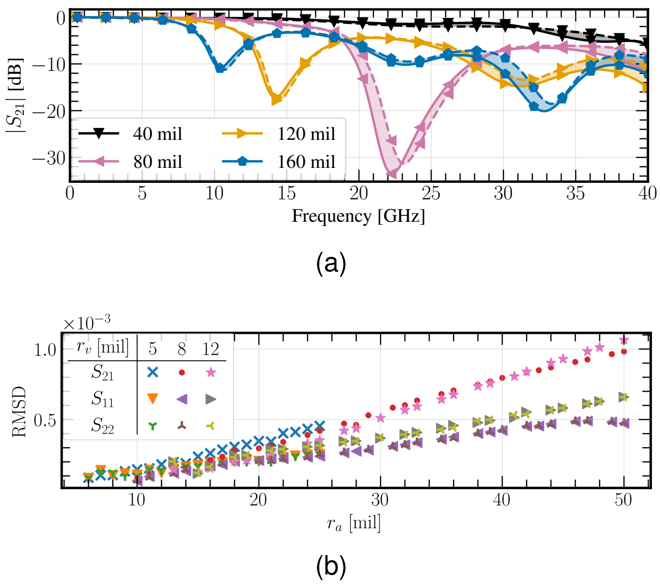

Fig. 4. Correlation results for the setup shown in Fig. 1b. (a) shows S-parameters for different distances to the ground fence. Continuous lines represent PB and dashed lines FW results, respectively. (b) shows a steady increase of RMSD for different antipad radii.

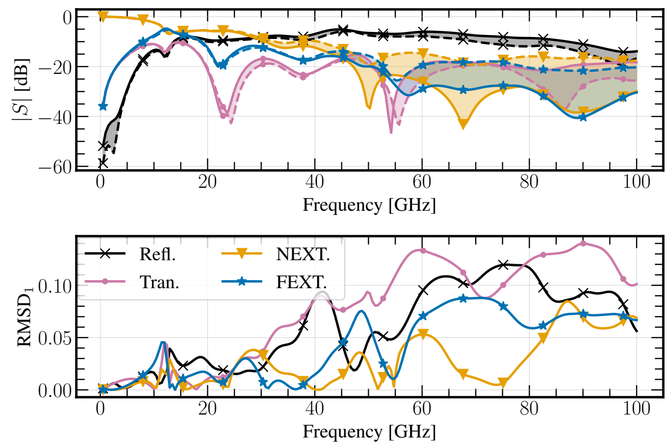

Fig. 5. Transmission, reflection, near and far end crosstalk are plotted over frequency. Continuous lines represent PB and dashed lines FW results, respectively. The RMSD is calculated for each frequency ($N = 1$) and plotted in the figure below. The legend is valid for both plots. An increase in RMSD between PB and FW results with higher frequency becomes apparent.

layers, each with a height of $12, \mathrm{mil}$, a permittivity of $\varepsilon_r = 4.3$, and a loss tangent of $\tan\delta = 0.033$. Other parameters are the same as for the previous setup. It is used as a first design space exploration example for specific parameters. In Fig. 4a, the transmission for different via to ground fence distances can be seen. This implicates that proximity to ground vias is a good way to improve the frequency range of a signal via. Results of both simulation methods are in good agreement, showing a maximum RMSD of $0.28 \cdot 10^{-3}$.

For a fixed distance to the ground fence of $160\,\mathrm{mil}$ the via and antipad radius are varied. Fig. 4b displays RMSD values for different setups indicating that increasing the antipad radius decreases accuracy of simulation data.

Last, a second signal via is added to the setup as can be seen in Fig. 1c, with a distance of $40\,\mathrm{mil}$ between signal vias. Transmission, reflection, and crosstalk of all vias is investigated and plotted in Fig. 5 for frequencies up to $100\,\mathrm{GHz}$. It can be seen that the RMSD for each frequency point rises at $40\,\mathrm{GHz}$ and the S-parameters deviate for higher frequencies, implying that PB models exhibit limitations in that frequency range. The worst RMSD over all frequencies can be found for transmission and results in $0.45 \cdot 10^{-3}$, which is the same value as for reflection in the first example in Fig. 3.

IV. Conclusion and Outlook

The SI/PI design space has many dimensions and finding areas of validity or limitations is a none trivial task. Automated processes aid multi dimensional systematic investigations and are necessary for the creation of a ML ready database. The presented automation interface facilitates comprehensive validity checking of PB models to an extent not conducted previously. In this way trusted data is provided for the SI/PI database, and builds a fundament for the application of ML methods. The RMSD is a reasonable but not optimal metric to describe agreement. For future work alternative metrics are under investigation. The goal is to define clear validity thresholds. For specific PCB setups, where limitations of the PB model are apparent, either the model has to be extended or the fast simulation results need to be complemented with slower FW data at critical design parameter or frequency ranges.

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