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Using Decision Trees for Fast Error Identification in Physics-Based Modeling of PCB Structures

Motivation

- Physics-based (PB) via modeling allows generation of large printed circuit board (PCB) datasets [1].
- However, its accuracy is highly dependent on the PCB design parameters [2].

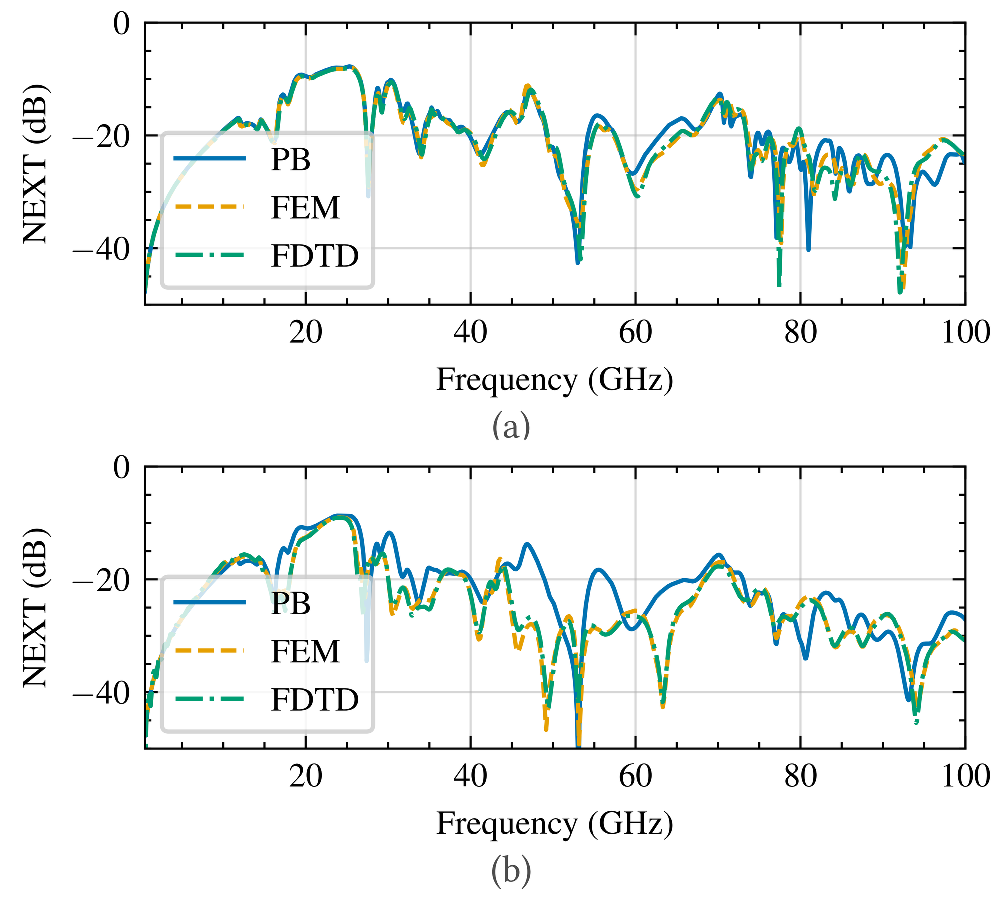

Fig. 1. Near-end crosstalk for a via pair on a PCB with an antipad radius of (a) 8 mil and (b) 15 mil

SI/PI-Database

- Every machine learning (ML) study in signal integrity (SI) and power integrity (PI) requires data.
- Generating data through electromagnetic (EM) simulation is time consuming.
- Therefore, the SI/PI-Database stores PCB simulations in a centralized and searchable database [3] [4].

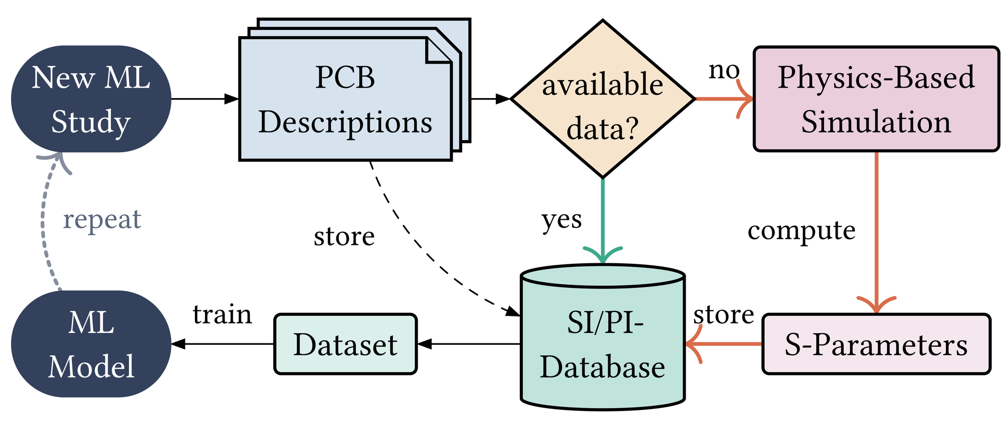

Fig. 2. The ML workflow with the SI/PI-Database

The SI/PI-Database is publicly available online!

Dataset Generation

- 1000 PCB variations are simulated as a test and training dataset.

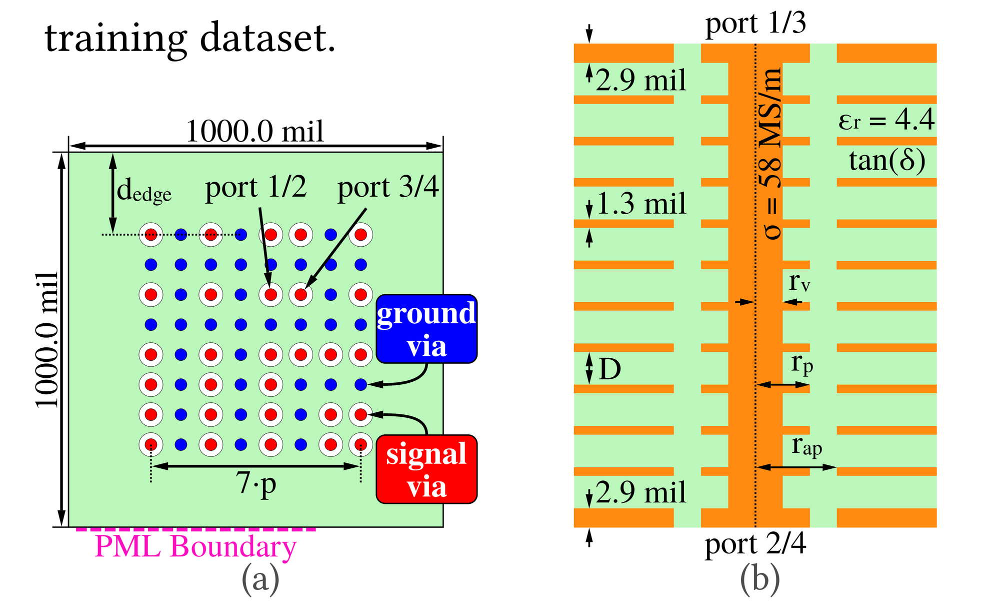

Fig. 3. (a) Board and (b) stackup of the test PCB. Adapted from [5] © 2026 IEEE.

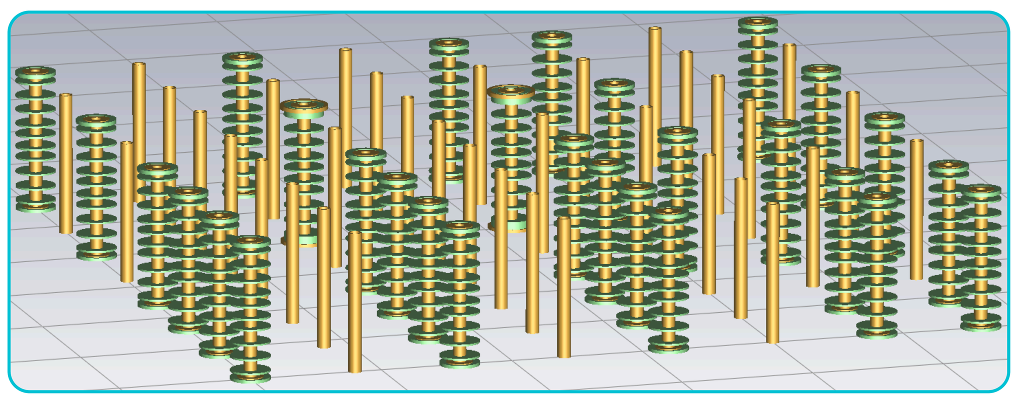

Fig. 4. Auto-generated 3D full-wave (FW) via array model

Decision Tree Error Identification

- Decision trees (DTs) classify designs into *high-/low-error* from PCB design parameters [5].
- The mean relative error (MRE) between PB and FW S-parameters is compared against a threshold θ:

$$y = \begin{cases} \textit{high-error} & \text{if MRE} > \theta \\ \textit{low-error} & \text{otherwise.} \end{cases}$$

- Balanced accuracy reaches up to 85% and is largely independent of frequency and the error threshold.
- Predictions over larger bandwidths are more robust.

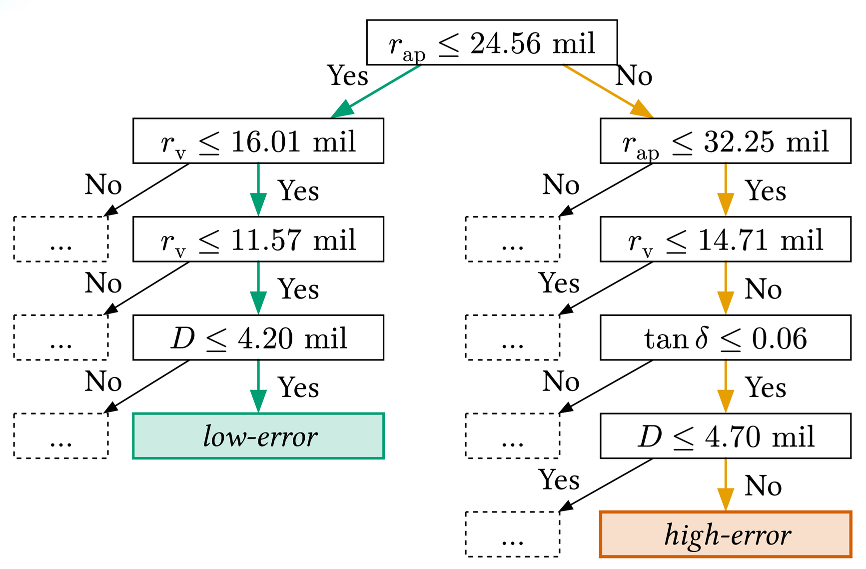

Fig. 5. A partial DT for error classification. Adapted from [5] © 2026 IEEE.

	S_{11}	S_{12}	S_{13}	S_{14}
S_{11}	1.00	0.81	0.95	0.91
S_{12}	0.81	1.00	0.84	0.84
S_{13}	0.95	0.84	1.00	0.95
S_{14}	0.91	0.84	0.95	1.00

Fig. 6. Accuracy correlation between the DTs for different S-Parameters

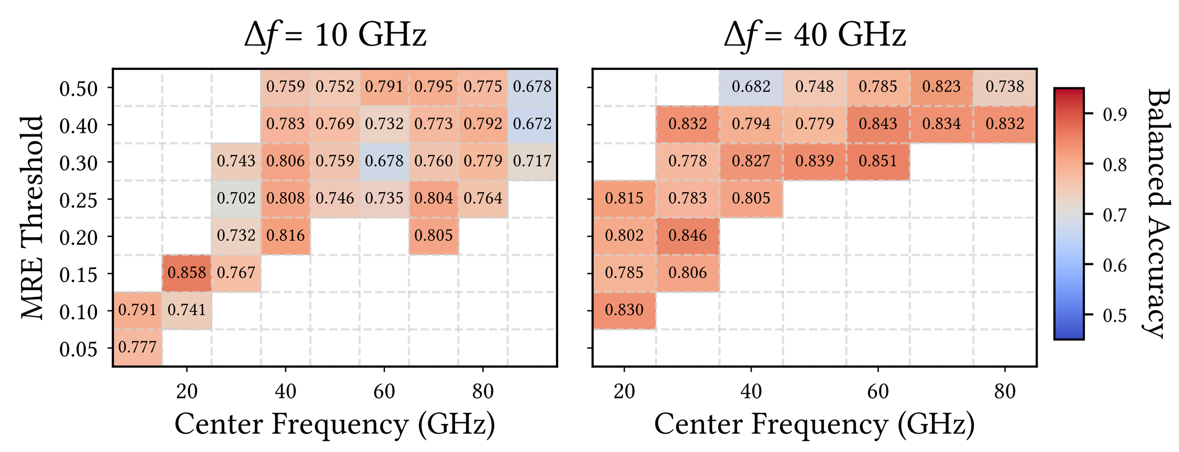

Fig. 7. Classification accuracy with respect to error threshold and frequency for far-end crosstalk accuracy prediction

Generalization to Unseen Data

- The models are tested on unseen data from the SI/PI-Database, first presented in [6].
- Key dataset differences:
  - Variable array
  - Variable stackup
  - More geometric variations
  - More material variations

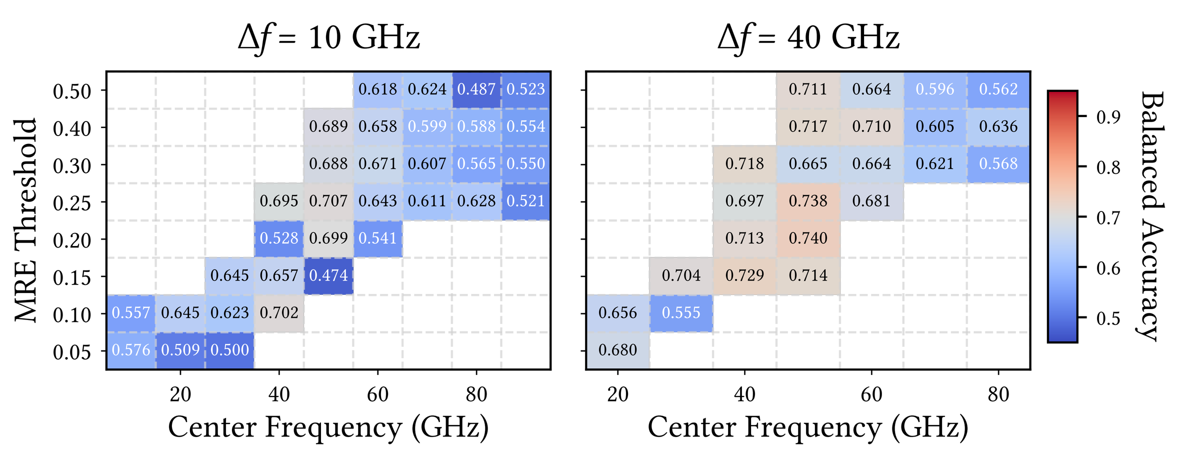

Fig. 8. Classification accuracy on the unseen data for the same models from Fig. 7

Feature Relevance

- Relevance measures how often each design parameter is chosen to split the trees.
- The ranking mirrors the physics: the parameters that most strongly contribute to higher-order modes around the via dominate.

TABLE I

RELEVANCE (%) BY TREE DEPTH

Feature	1	2	3	4	Total
r_v	95.7	25.9	37.9	15.1	26.6
p	0.0	45.9	23.7	15.8	22.4
D	4.3	20.0	17.0	27.1	17.9
$\tan(\delta)$	0.0	2.2	9.4	20.5	13.4
r_{ap}	0.0	3.7	7.6	13.7	11.7
d_{edge}	0.0	1.5	3.1	4.5	4.5
r_p	0.0	0.7	1.3	3.4	3.5

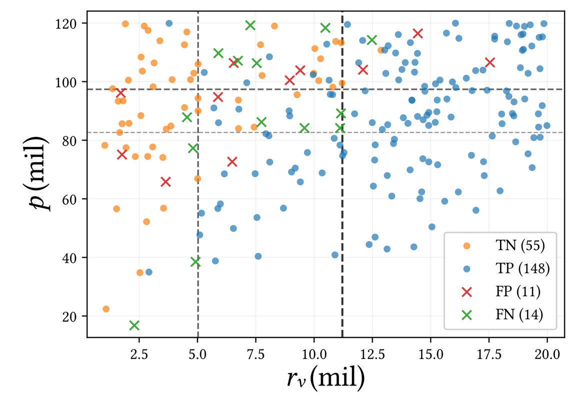

Fig. 9. Predictions on the test dataset over via radius and pitch

Conclusion

- Large databases of PB simulations can be validated quickly, flagging unreliable designs before costly FW simulation.
- Broader generalization may require additional design parameters, more refined error metrics, or more expressive models.
- Feature relevance, read in combination with the underlying physics, guides where to improve PB models in a targeted manner.

Sources

[1] R. Rimolo-Donadio *et al.*, "Physics-based via and trace models for efficient link simulation on multilayer structures up to 40 GHz," *IEEE Transactions on Microwave Theory and Techniques*, vol. 57, no. 8, pp. 2072–2083, 2009, doi: 10.1109/TMTT.2009.2025470.

[2] S. Müller *et al.*, "Accuracy of physics-based via models for simulation of dense via arrays," *IEEE Transactions on Electromagnetic Compatibility*, vol. 54, no. 5, pp. 1125–1136, 2012, doi: 10.1109/TEMC.2012.2192123.

[3] M. Schierholz *et al.*, "SI/PI-database of PCB-based interconnects for machine learning applications," *IEEE Access*, vol. 9, pp. 34423–34432, 2021, doi: 10.1109/ACCESS.2021.3061788.

[4] T. Hillebrecht, T. Weber, J. Alfert, and C. Schuster, "Relational SI/PI-database for a data-driven approach to PCB design automation and performance prediction," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 15, no. 9, pp. 1847–1856, 2025, doi: 10.1109/TCPMT.2025.3597840.

[5] T. Weber, T. Hillebrecht, and C. Schuster, "Using decision trees for fast error identification in physics-based modeling of PCB structures," in *IEEE 30th Workshop on Signal and Power Integrity (SPI)*, 2026.

[6] T. Hillebrecht, M. Schierholz, Y. Hassab, J. Alfert, and C. Schuster, "Generation and application of a very large dataset for signal integrity via array and link analysis," *IEEE Transactions on Electromagnetic Compatibility*, pp. 1–10, 2024, doi: 10.1109/TEMC.2024.3450307.

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www.tet.tuhh.de/si-pi-database-de/

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