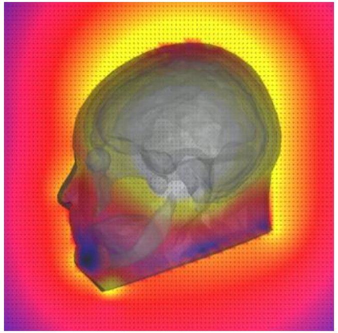
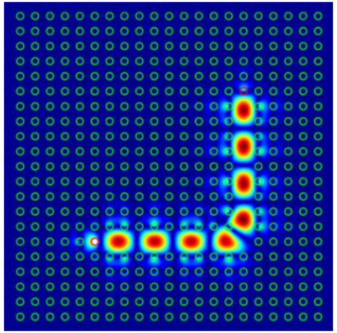
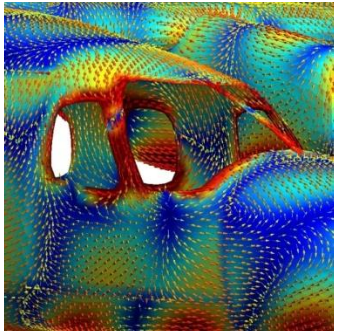
The SI/PI-Database at TUHH: S-Parameters for ML/AI Applications

INSTITUT FÜR
THEORETISCHE
ELEKTROTECHNIK

TUHH
Hamburg
University of
Technology







Prof. Christian Schuster

EMC Forum at SDU Sønderborg, DK
June 29-30, 2026

EMC
Forum

Abstract

The “SI/PI-Database” at Hamburg University of Technology (TUHH) has been providing S-parameters of physics-based printed circuit board (PCB) simulations since 2021. The database started out as a collection of data sets that were originally generated for the design and optimization of signal interconnects and power delivery networks. Meanwhile the database has grown to approx. 90’000 variations of PCB simulations and has been used by both industry and academia to generate applications using methods of machine learning (ML) or more broadly speaking artificial intelligence (AI). To our knowledge, there is no comparable open data source available in the SI/PI domain.

In this presentation we will explain the usage of the database and its latest developments. We will also discuss how we plan to adapt the concept for the European project PATTERN – Enabling AI for EMC.

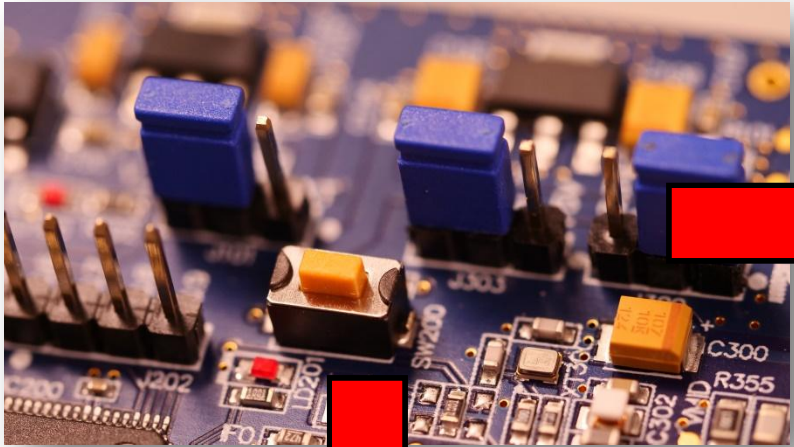
Outline

1. AI, ML and MM in EMC and SI/PI
2. The SI/PI-Database at TUHH
3. Related Projects / PATTERN
4. Wrap-Up

1. AI, ML and MM in EMC and SI/PI

(**AI** = Artificial Intelligence, **ML** = Machine Learning, **MM** = Macromodeling)

AI, ML and MM in EMC, SI and PI?

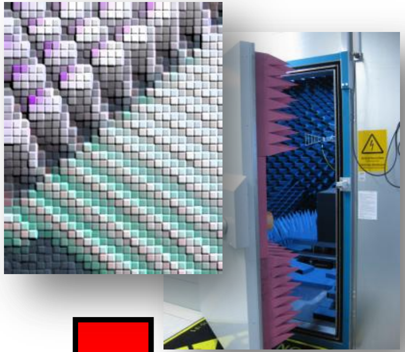


EMC:
Electromagnetic
Compatibility

SI/PI: Signal and Power Integrity

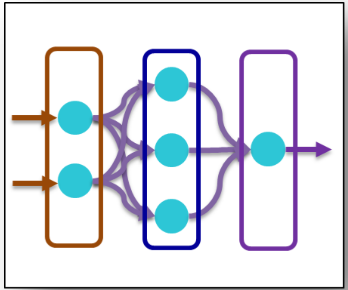
Physics-Based versus Data-Based

Physics-Based Modeling, Design or Measurement



Data / Results

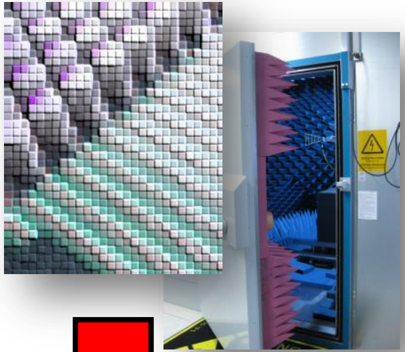
Data / Results



Data-Based Model

Physics-Based and Data-Based

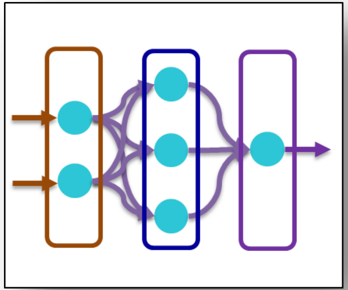
Physics-Based Modeling, Design or Measurement



Data / Results

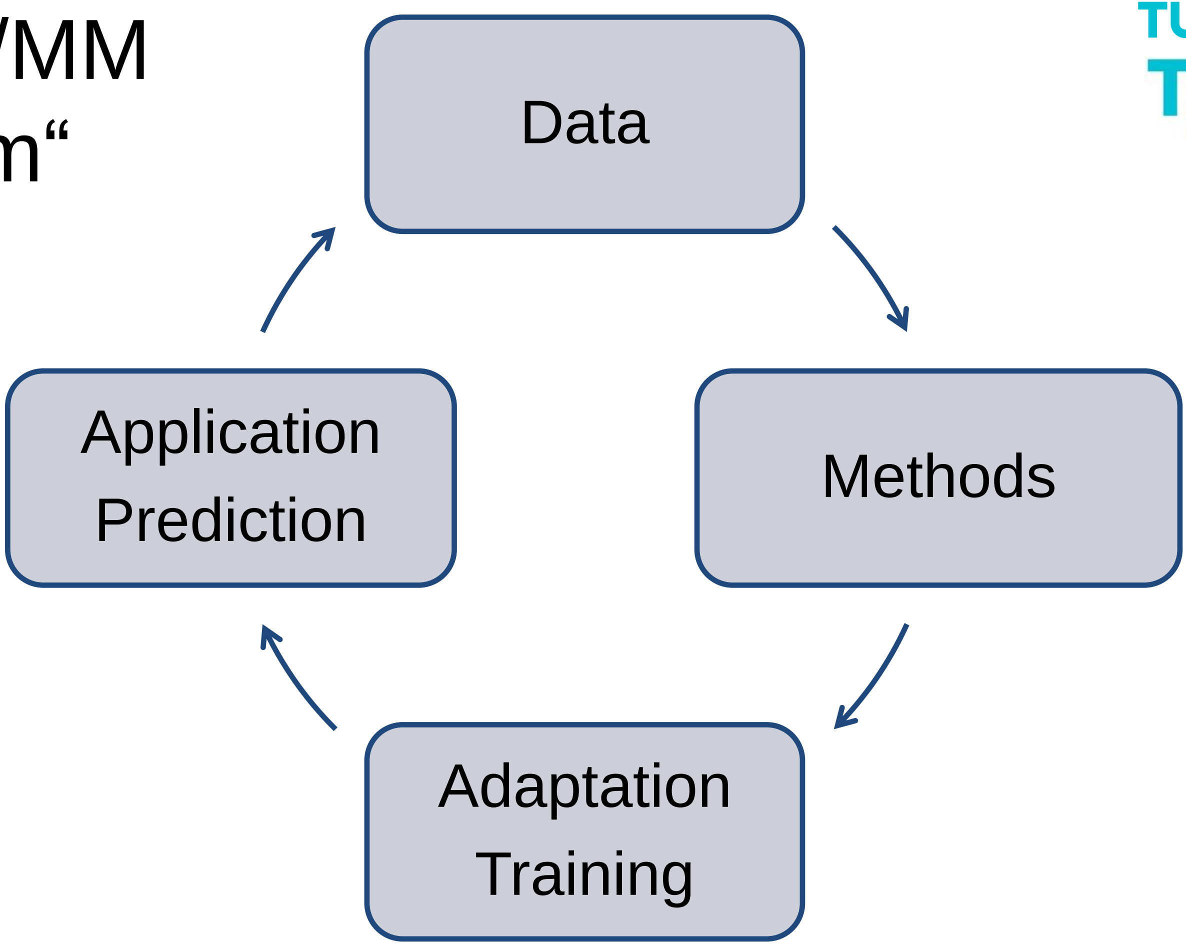
How ?

Data / Results

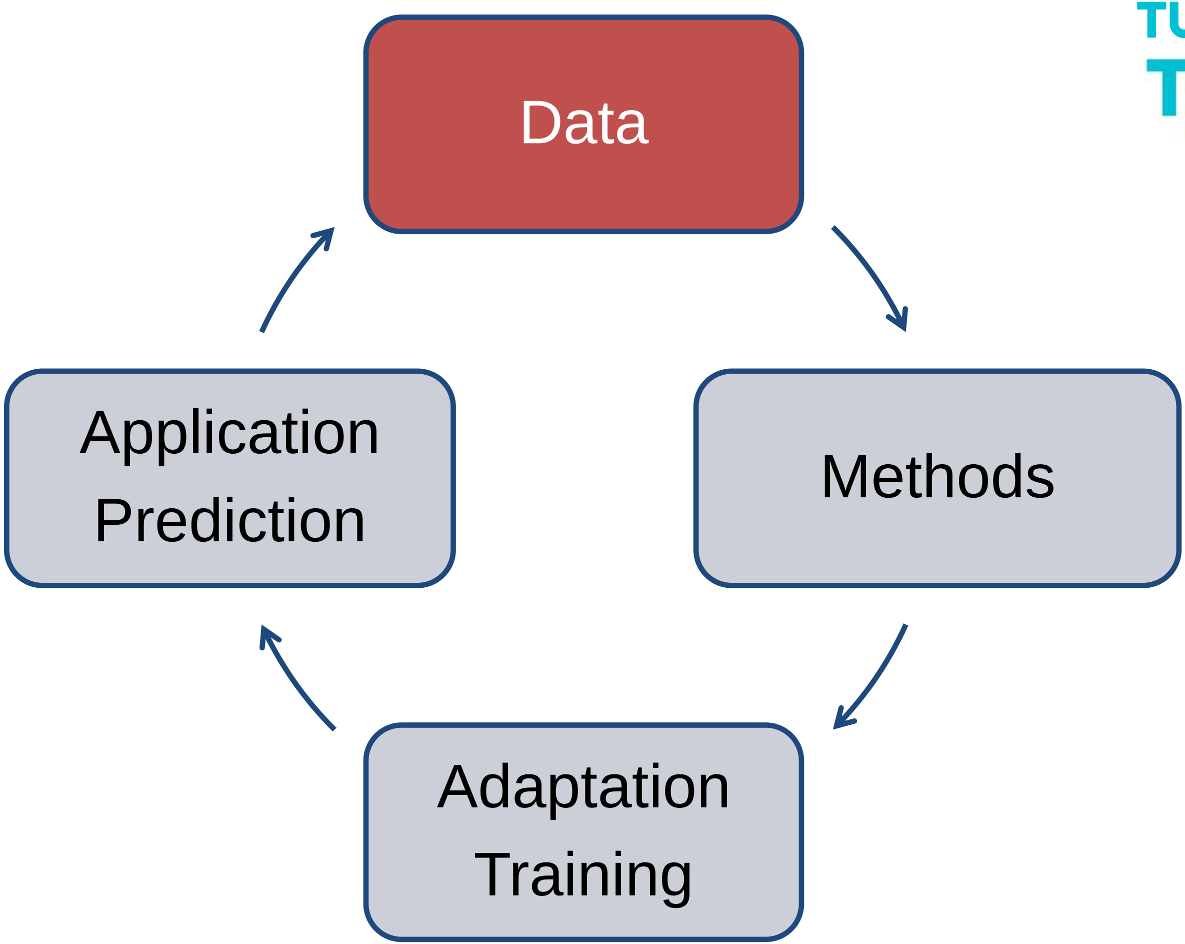


Data-Based Model

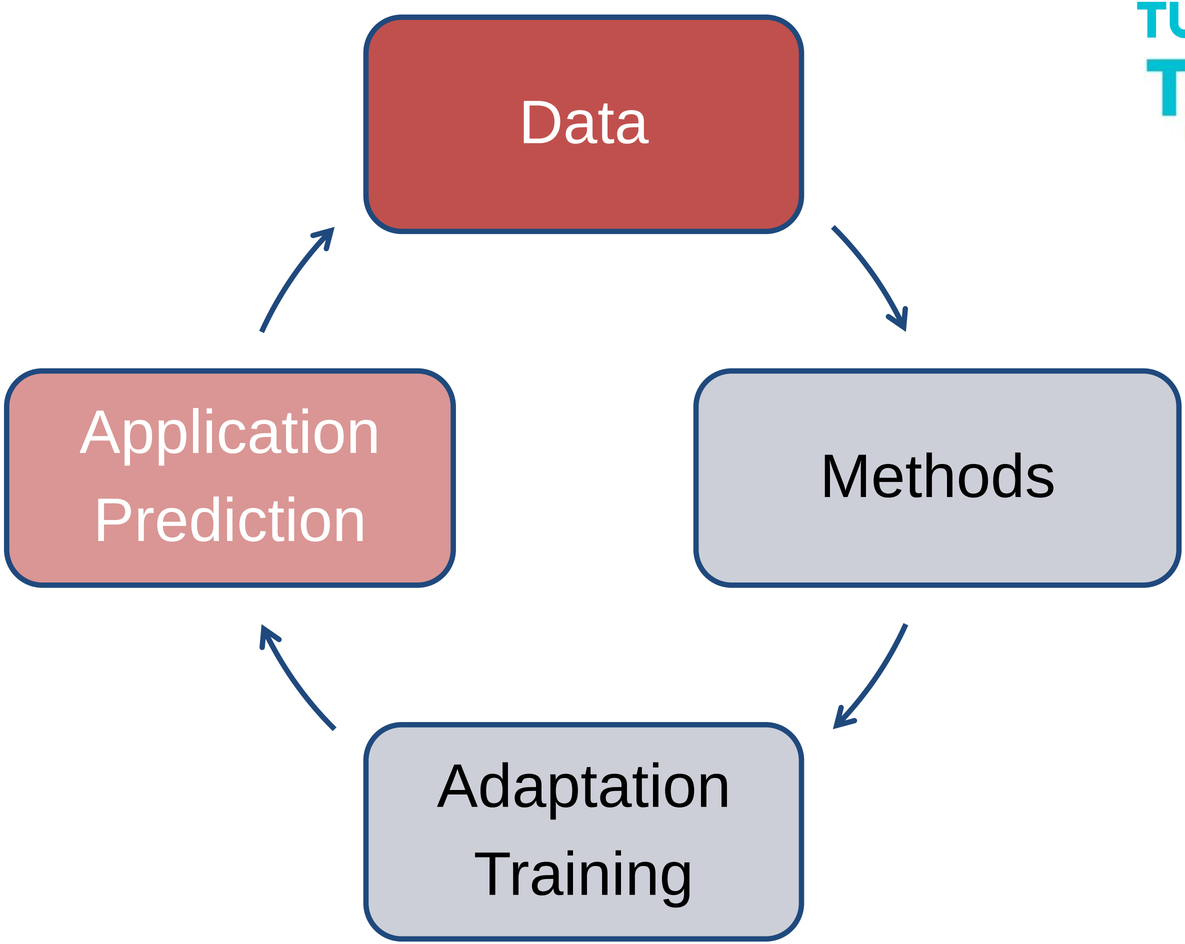
The AI/ML/MM “Ecosystem“



Our Focus


Data
Methods
Adaptation
Training
Application
Prediction

Our Focus


Data
Methods
Adaptation
Training
Application
Prediction

Our Focus

Data

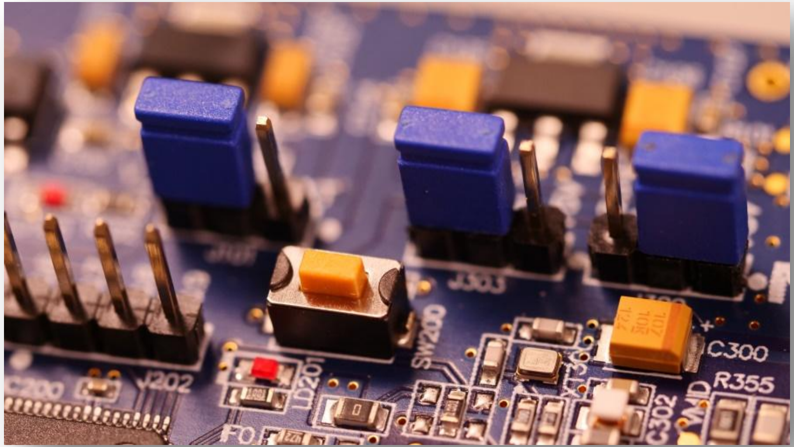
Methods

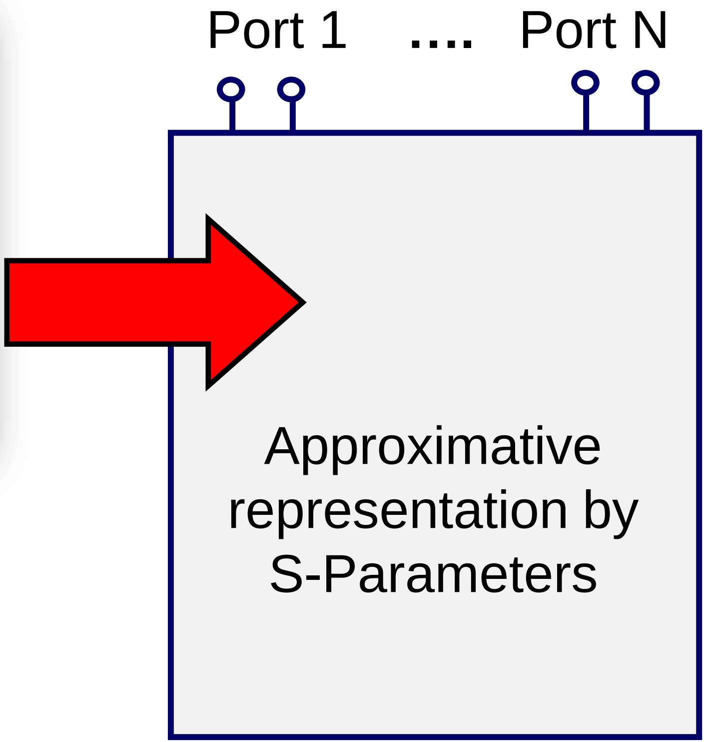
Adaptation
Training

Application
Prediction

2. The SI/PI-Database at TUHH

Physics-Based Modeling of PCBs



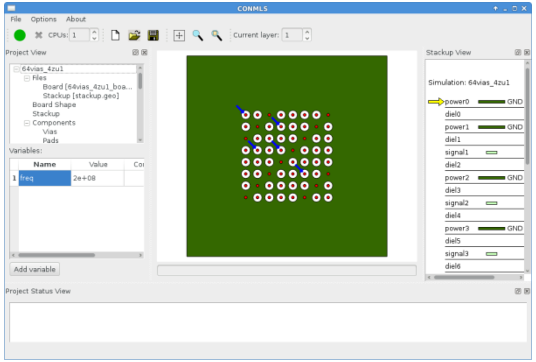


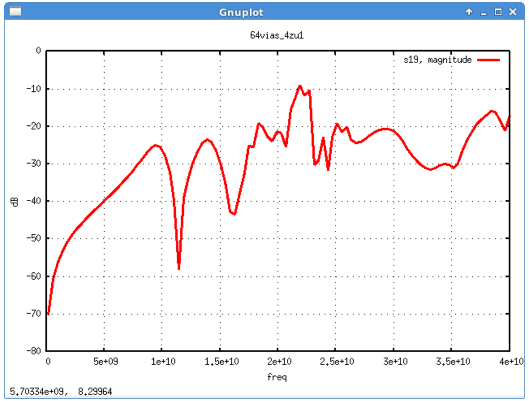
Multilayer PCB = passive, linear system with ports at via antipads on top and bottom layer

Physics-Based Tool

TUHH has developed a tool (CONMLS) that computes network parameters for multilayer boards with an arbitrary number of planes, traces, vias, and terminations in frequency domain and thus provides the fundamental parameters needed for signal and power integrity analysis of PCBs.

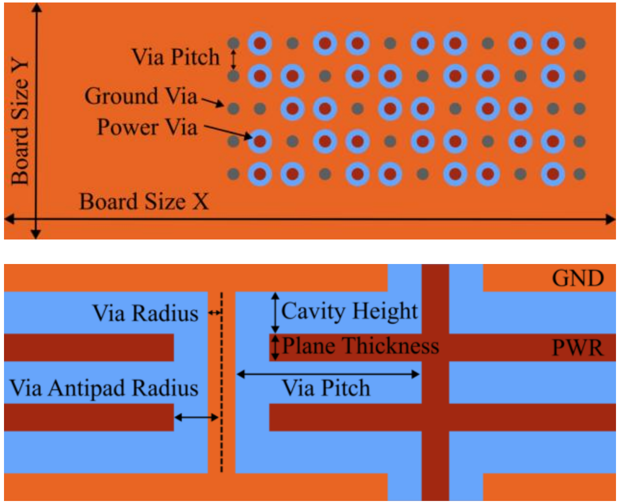
The tool is based on fast, mostly analytical models and 10-100 x faster than typical full-wave simulations.

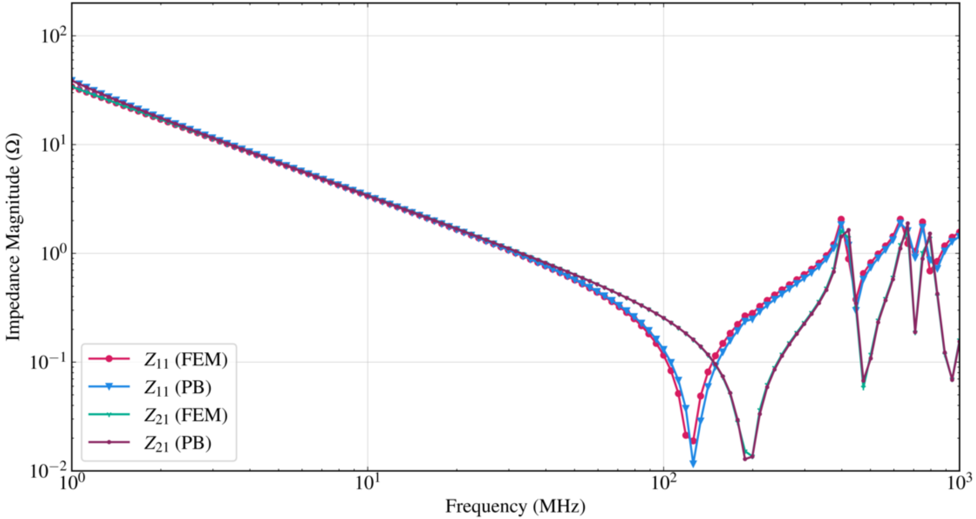




PDN Impedances of 4-Layer PCB (PI)

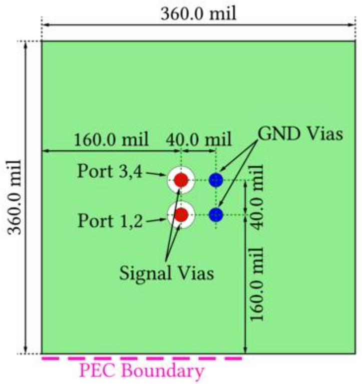
Correlation to full-wave simulation:

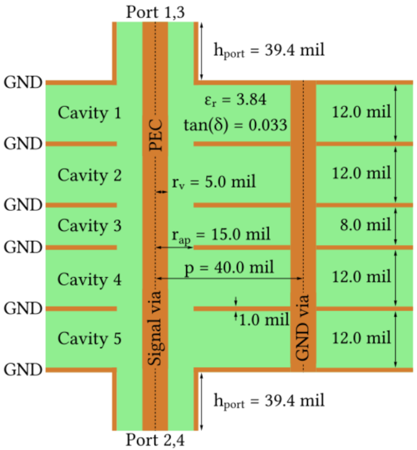


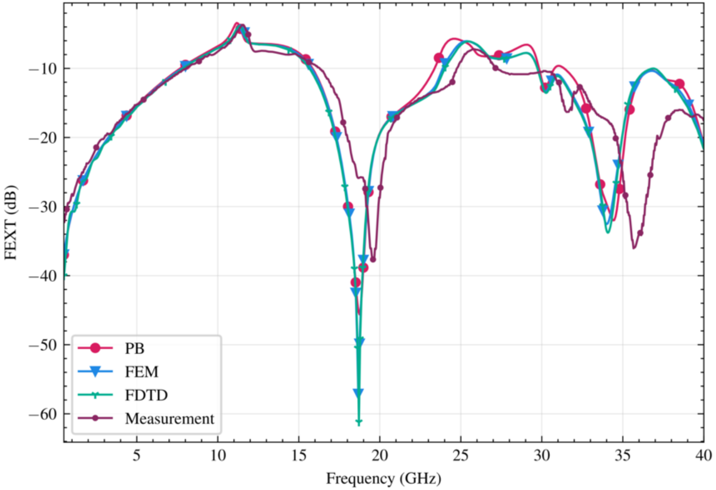


FEXT on 6-Layer PCB (SI)

Correlation to full-wave simulation:



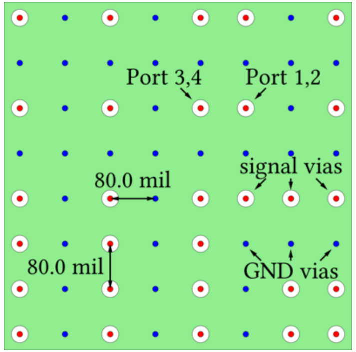


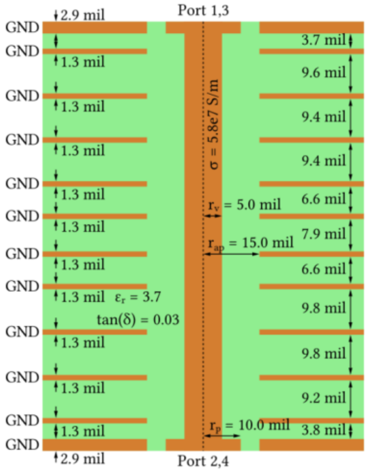


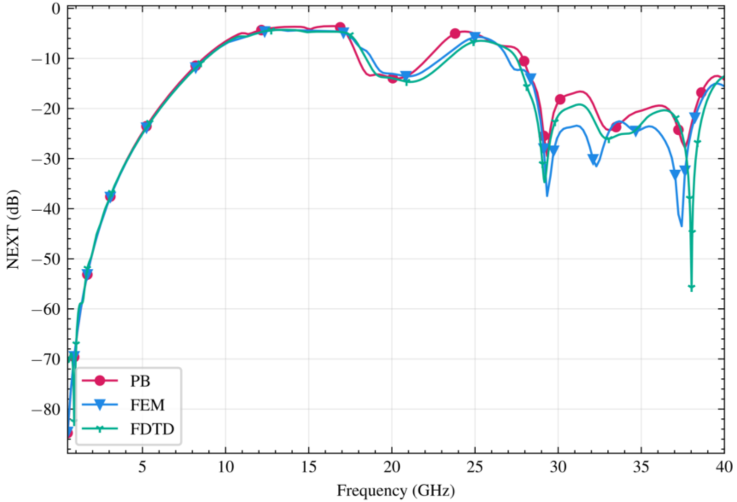
Adapted from: R. Rimolo-Donadio, "Development, Validation, and Application of Semi-Analytical Interconnect Models for Efficient Simulation of Multilayer Substrates," Ph.D. Thesis, TUHH, 2010.

NEXT on 12-Layer PCB (SI)

Correlation to full-wave simulation:



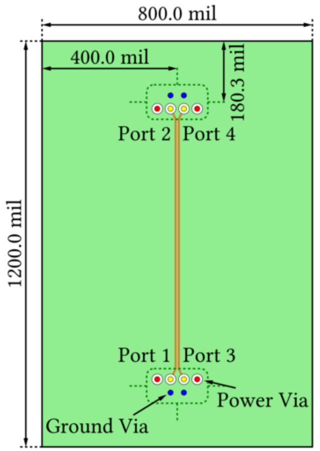


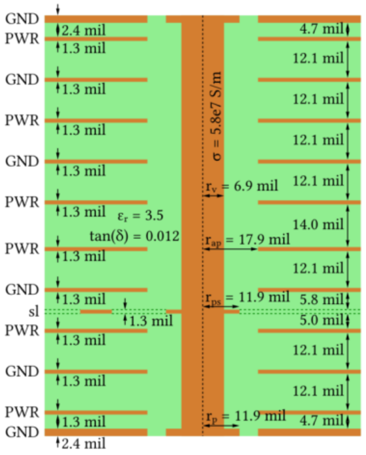


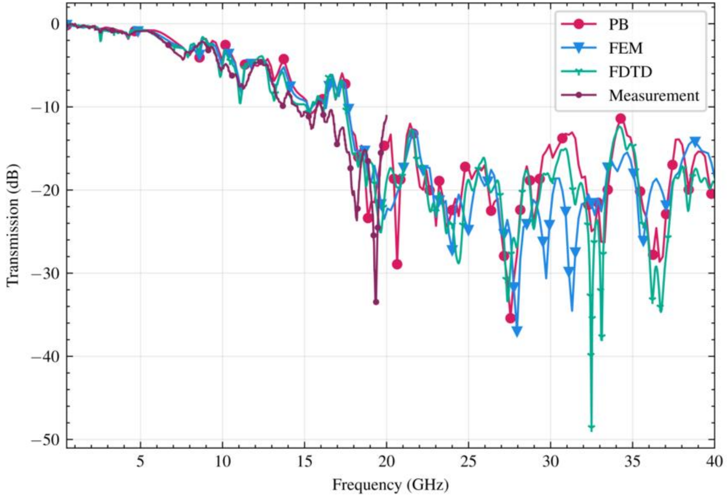
Adapted from: R. Rimolo-Donadio, "Development, Validation, and Application of Semi-Analytical Interconnect Models for Efficient Simulation of Multilayer Substrates," Ph.D. Thesis, TUHH, 2010.

Transmission over 12-Layer PCB (SI)

Correlation to full-wave simulation:





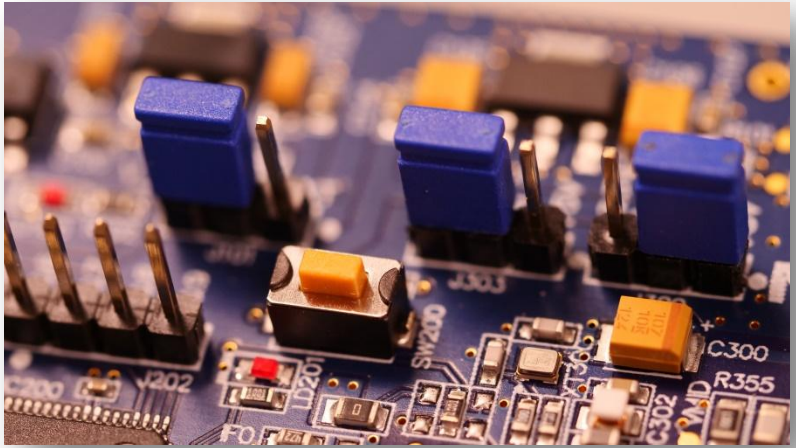


Adapted from: R. Rimolo-Donadio, "Development, Validation, and Application of Semi-Analytical Interconnect Models for Efficient Simulation of Multilayer Substrates," Ph.D. Thesis, TUHH, 2010.

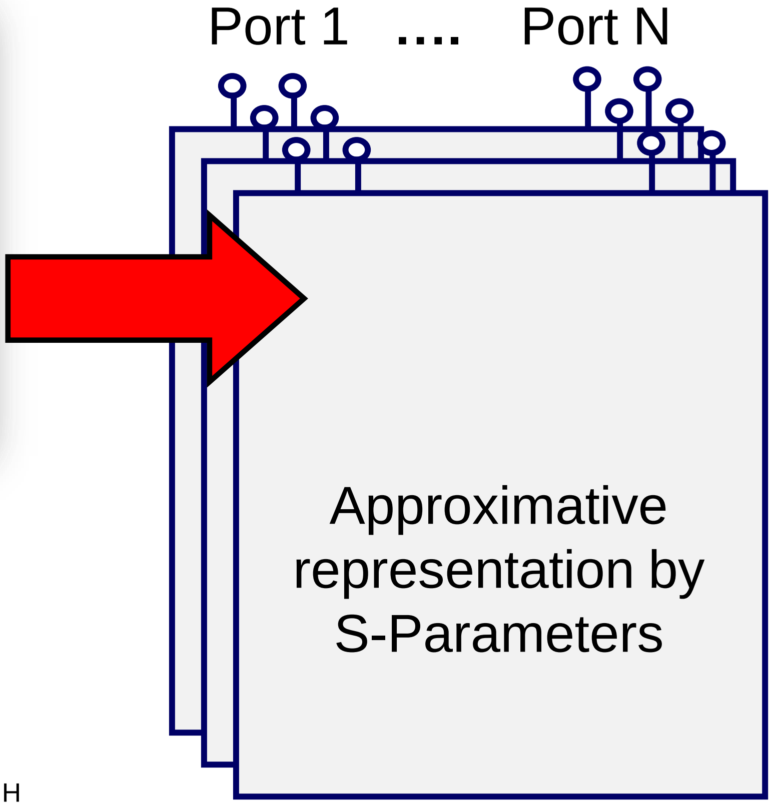
Publications I

- R. Rimolo-Donadio, X. Gu, Y. Kwark, M. Ritter, B. Archambeault, F. de Paulis,Y. Zhang, J. Fan, H.-D. Brüns, C. Schuster, ”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, Aug. 2009.
- X. Duan, R. Rimolo-Donadio, H.-D. Brüns, C. Schuster, “A Combined Method for Fast Analysis of Signal Propagation, Ground Noise, and Radiated Emission of Multilayer Printed Circuit Boards”, IEEE Transactions on Electromagnetic Compatibility, vol. 52, no. 2, pp. 487-495, May 2010.
- X. Duan, R. Rimolo-Donadio, H.-D. Brüns, C. Schuster, “Circular Ports in Parallel-Plate Waveguide Analysis With Isotropic Excitations”, IEEE Transactions on Electromagnetic Compatibility, vol. 54, no. 3, pp. 603-612, Jun. 2012.
- S. Müller, X. Duan, M. Kotzev, Y.-J. Zhang, J. Fan, X. Gu, Y. H. Kwark, R. Rimolo-Donadio, H.-D. Brüns, C. Schuster, “Accuracy of Physics-Based Via Models for Simulation of Dense Via Arrays”, IEEE Transactions on Electromagnetic Compatibility, vol. 54, no. 5, pp. 1125-1136, Oct. 2012.
- S. Müller, F. Happ, X. Duan, R. Rimolo-Donadio, H.-D. Brüns, C. Schuster, “Complete Modeling of Large Via Constellations in Multilayer Printed Circuit Boards”, IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 3, no. 3, pp. 489-499, Mar. 2013.
- S. Müller, A. Hardock, R. Rimolo-Donadio, H.-D. Brüns, C. Schuster, “Analytical Extraction of Via Near-Field Coupling Using a Multiple Scattering Approach” IEEE Workshop on Signal and Power Integrity (SPI), Paris, France, 2013.
- T. Reuschel, S. Müller and C. Schuster, "Segmented Physics-Based Modeling of Multilayer Printed Circuit Boards Using Stripline Ports," IEEE Transactions on Electromagnetic Compatibility, vol. 58, no. 1, pp. 197-206, Feb. 2016.
- T. Hillebrecht, J. Alfert, T. Reuschel and C. Schuster, "Automated Generation and Correlation of Physics-Based Via Models with Full-Wave Simulation for an SI/PI Database," IEEE Conference on Electrical Performance of Electronic Packaging and Systems (EPEPS), Milpitas, CA, USA, 2023.

The Idea



Store S-parameters of PCB simulations in a ″database″!



Publication & Documentation

SI/PI-Database of PCB-Based Interconnects for Machine Learning Applications

M. Schierholz, A. Sanchez-Mais,
A. Carmona-Cruz, X. Duan, K. Roy,
R. Rimolo-Donadio, C. Schuster

IEEE ACCESS, 2021

ieeexplore.ieee.org/document/9361755

Original Simulation Data (2021)

Name	No. of Cavities	No. of Ports	Frequency Range	Max. el. Length	No. of Simulations	Size of Data Set
PWR/GND Plane PCB with 11x11 Via-Array	1	2	Min: 1 MHz Max: 1 GHz Step: 3.33 MHz	2 λ	58 399	1.44 GB
Link on 11 Cavity PCB with two 10x10 Via-Arrays	11	12	Min: 0.5 GHz Max: 100 GHz Step: 0.5 GHz	79 λ	7 031	2.56 GB
Link on 8 Cavity PCB with two 10x10 Via-Arrays	8	12	Min: 0.5 MHz Max: 100 GHz Step: 0.5 GHz	79 λ	7 031	2.65 GB
5x5 Via-Array on 10 Cavity PCB	10	34	Min: 1 GHz Max: 40 GHz Step: 0.196 GHz	2.6 λ	5 000	50.4 GB
Link on 10 Cavity PCB with two 5x5 Via-Arrays	10	68	Min: 1 GHz Max: 40 GHz Step: 0.196 GHz	59 λ	1 500	57.2 GB

> 110 GB

New PI Simulation Data (2026)

Name	No. of Cavities	No. of Ports	Frequency Range	Max. el. Length	No. of Simulations	Size of Dataset
4-Layer Polygonal PCB based PDN	3	2	Min: 1 MHz Max: 1 GHz Step: 3.33 MHz	5 λ	500	12 MB
8-Layer PCB based PDN with two Via Arrays Latin Hypercube Sampling	7	28	Min: 1 MHz Max: 1 GHz Step: 3.33 MHz	4.5 λ	10 000	42 GB
6-Layer PCB based PDN with two Via Arrays Latin Hypercube Sampling	5	36	Min: 1 MHz Max: 1 GHz Step: 3.33 MHz	4.5 λ	985	7.2 GB
4-Layer PCB based PDN with two Via Arrays Random Sampling	3	28	Min: 1 MHz Max: 1 GHz Step: 3.33 MHz	4.5 λ	10 000	44 GB

New PI Simulation Data (2026)

Name	No. of Cavities	No. of Ports	Frequency Range	Max. el. Length	No. of Simulations	Size of Dataset
2-Layer PCB based PDN with Large Via Array	1	2	Min: 1 MHz Max: 1 GHz Step: 3.33 MHz	5 λ	10 000	280 MB
4-Layer PCB based PDN with Two Via Arrays – Central Power Rail	3	4	Min: 1 MHz Max: 1 GHz Step: 3.33 MHz	5 λ	20 000	1.7 GB
4-Layer PCB based PDN with Three Via Arrays – Central Power Rail	3	6	Min: 1 MHz Max: 1 GHz Step: 3.33 MHz	5 λ	20 000	3.8 GB
14-Layer PCB based PDN with Two Via Arrays – Central Power Rail	13	4	Min: 1 MHz Max: 1 GHz Step: 3.33 MHz	5 λ	20 000	1.7 GB

New SI Simulation Data (2026)

Name	No. of Cavities	No. of Ports	Frequency Range	Max. el. Length	No. of Simulations	Size of Dataset
Universal Single Ended SI Via Array with Latin Hypercube Sampling	3 – 47	6 – 58	Min: 250 MHz Max: 100 GHz Step: 250 MHz	42 λ	1 932	7.5 GB
Universal Differential SI Via Array with Latin Hypercube Sampling	3 – 47	4 – 56	Min: 250 MHz Max: 100 GHz Step: 250 MHz	42 λ	1 916	6.7 GB
Universal Differential SI Via Array Link with Latin Hypercube Sampling	11 – 47	8 – 112	Min: 250 MHz Max: 100 GHz Step: 250 MHz	382 λ	1 073	6.8 GB

New Simulation Data – Overview

TUHH

Group	No. of Cavities	No. of Ports	Frequency Range	Max. el. Length	No. of Simulations	Size of Dataset
New PI Simulations	1 – 13	6 – 58	Min: 1 MHz Max: 1 GHz Step: 3.33 MHz	5 λ	91 485	100.7 GB
New SI Simulations	3 – 47	4 – 112	Min: 250 MHz Max: 100 GHz Step: 250 MHz	382 λ	4 921	21 GB
Total New	3 – 47	8 – 112	Min: 250 MHz Max: 100 GHz Step: 250 MHz	382 λ	96 406	121.7 GB

> 120 GB

Usage: Step By Step

1. Download via link from TUHH

2. Review the contents

   Description of dataset

   Table of varied parameters

   Folder containing S-parameters

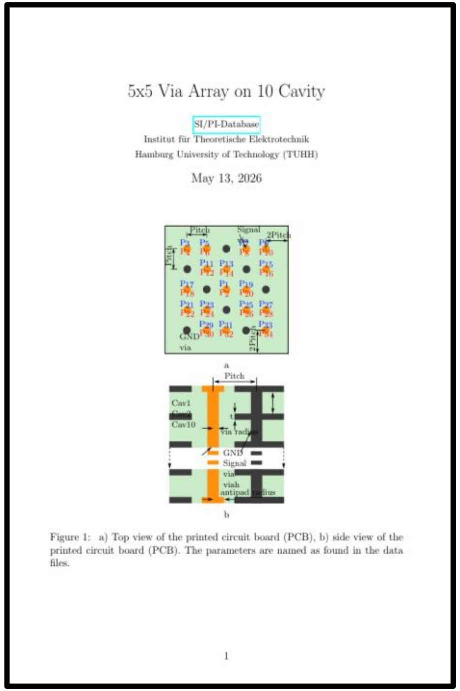
3. Use S-parameters for your investigations!

```
.
├── description.pdf
├── parameter.csv
└── variation
    ├── simu_0000.s34p
    ├── simu_0001.s34p
    ├── simu_0002.s34p
    ├...
    ├── simu_4997.s34p
    ├── simu_4998.s34p
    ├── simu_4999.s34p
    └── simu_4999.s34p

2 directories, 5005 files
```

Description of Dataset

PDF description containing the following:

- Introduction
- PCB Structure
- Parameter Variation
- EM-Simulation
- License agreement
- Contact


5x5 Via Array on 10 Cavity

SI/PI-Database
Institut für Theoretische Elektrotechnik
Hamburg University of Technology (TUHH)

May 13, 2026

Figure 1: a) Top view of the printed circuit board (PCB), b) side view of the printed circuit board (PCB). The parameters are named as found in the data files.

1

```
.
├── description.pdf
├── parameter.csv
└── variation
    ├── simu_0000.s34p
    ├── simu_0001.s34p
    ├── simu_0002.s34p
    ├...
    ├── simu_4997.s34p
    ├── simu_4998.s34p
    ├── simu_4999.s34p
    └── simu_4999.s34p

2 directories, 5005 files
```

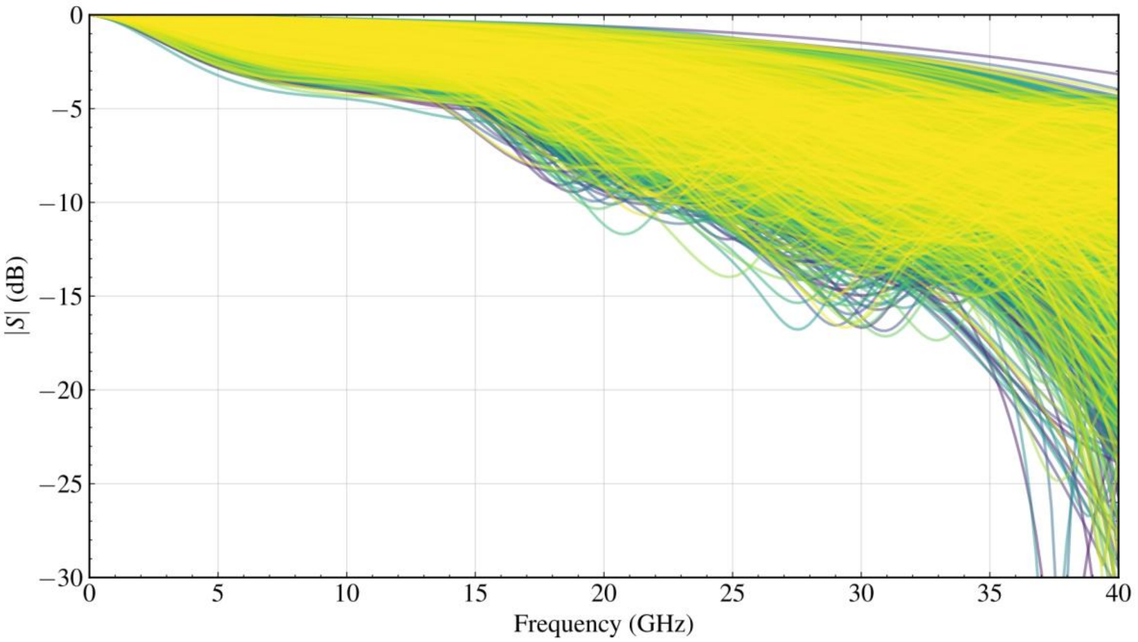
Table of Varied Parameters

The parameter CSV file contains information about all parameters that were varied for the requested dataset.

index	plane_thickness	loss_tangent	epsilon_r	…	cavity_height	pad_radius	via_pitch	simuIndex
i64	f64	f64	f64		f64	f64	f64	f64
0	1.0	0.002	4.36	…	7.53	11.63	32.0	0.0
1	1.0	0.02	4.4	…	7.08	9.87	29.0	1.0
2	1.0	0.2	3.93	…	8.83	7.25	32.0	2.0
3	2.0	0.02	3.88	…	6.08	8.43	54.0	3.0
4	1.0	0.2	3.89	…	8.53	10.19	48.0	4.0
…	…	…	…	…	…	…	…	…
4995	2.0	0.02	4.39	…	6.04	7.58	43.0	4995.0
4996	1.0	0.2	3.98	…	9.33	14.1	46.0	4996.0
4997	2.0	0.02	4.14	…	6.18	7.0	20.0	4997.0
4998	1.0	0.002	3.99	…	9.39	7.0	20.0	4998.0
4999	2.0	0.2	3.99	…	7.0	12.62	55.0	4999.0

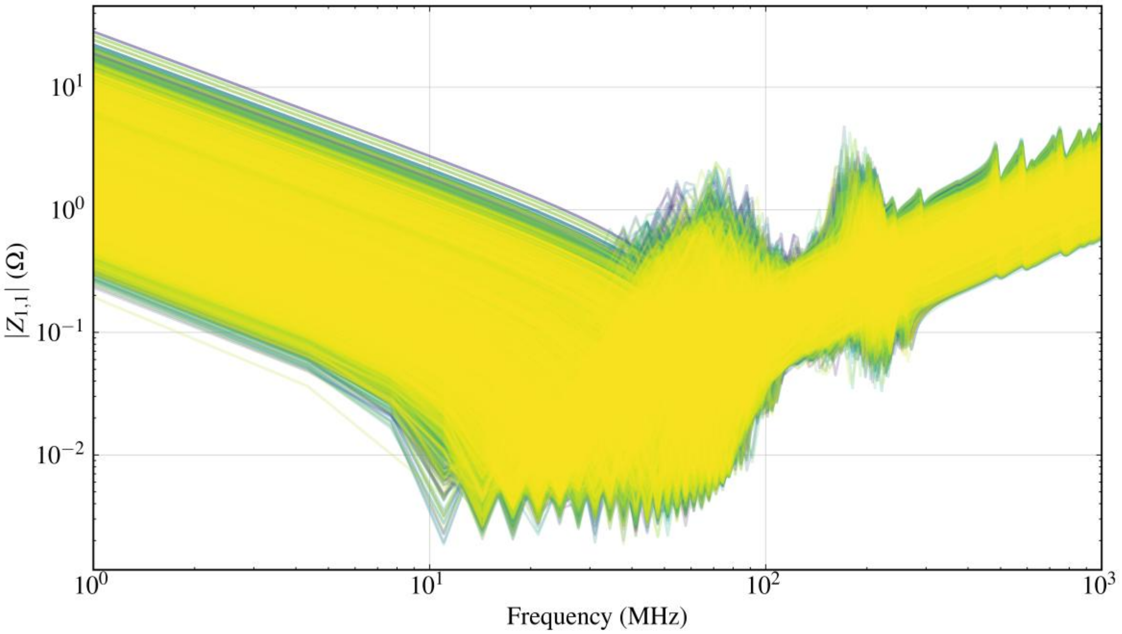
```
.
├── description.pdf
├── parameter.csv
└── variation
    ├── simu_0000.s34p
    ├── simu_0001.s34p
    ├── simu_0002.s34p
    ├...
    ├── simu_4997.s34p
    ├── simu_4998.s34p
    ├── simu_4999.s34p
    └── simu_4999.s34p

2 directories, 5005 files
```

Example: S-Parameters (SI)



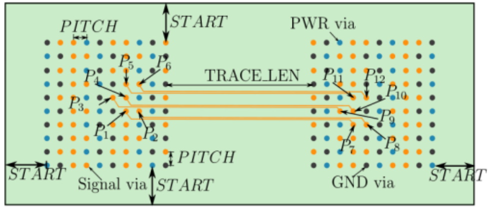

```
.
├── description.pdf
├── parameter.csv
└── variation
    ├── simu_0000.s34p
    ├── simu_0001.s34p
    ├── simu_0002.s34p
    ├...
    ├── simu_4997.s34p
    ├── simu_4998.s34p
    ├── simu_4999.s34p
    └── simu_4999.s34p

2 directories, 5005 files
```

Example: Z-Parameters (PI)



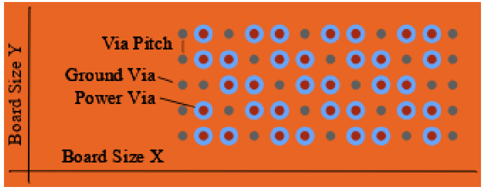

```
.
├── description.pdf
├── parameter.csv
└── variation
    ├── simu_0000.s34p
    ├── simu_0001.s34p
    ├── simu_0002.s34p
    ├...
    ├── simu_4997.s34p
    ├── simu_4998.s34p
    ├── simu_4999.s34p
    └── simu_4999.s34p

2 directories, 5005 files
```

Applications



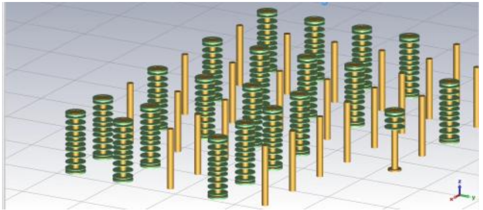
Data-Based SI

M. Sc.
Till
Hillebrecht



Data-Based PI

M. Sc.
Jan
Heßling



Data-Based Validation

M. Sc.
Tommy
Weber

Access

- ➔ Visit www.tet.tuhh.de/en/si-pi-database
- ➔ Choose structure
- ➔ Read and agree to license conditions
- ➔ Send request using online form
- ➔ Wait for download link from TUHH
- ➔ Follow instructions published in IEEE Access

Publications II

- K. Scharff, C. M. Schierholz, C. Yang, C. Schuster, “ANN Performance for the Prediction of High-Speed Digital Interconnects and Multiple PCBs,” IEEE Conference on Electrical Performance of Electronic Packaging and Systems (EPEPS), San Jose, CA, USA, Oct. 2020.
- M. Schierholz, K. Scharff, C. Schuster, “Evaluation of Neural Networks to Predict Target Impedance Violations of Power Delivery Networks,” IEEE Conf. Electrical Performance Electronic Packaging and Systems (EPEPS), Montreal, CA, Oct. 2019.
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DesignCon 2023 Early-Career Best Paper Award

- M. Schierholz, Y. Hassab, C. Schuster, “Engineering-informed design space reduction for PCB based power delivery networks,” IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 13, no. 10, pp. 1613-1623, Oct. 2023.
- M. Schierholz, I. Erdin, J. Balachandran, C. Schuster, “Applying Techniques of Transfer and Active Learning to Practical PCB Noise Decoupling”, DesignCon Conference, Santa Clara, CA, USA, Jan./Feb. 2024.

DesignCon 2024 Early-Career Best Paper Award

Publications III

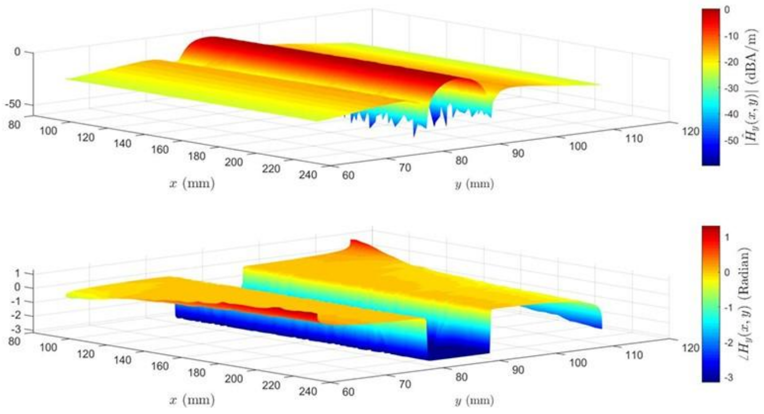
- Y. Hassab, T. Hillebrecht, F. Lurz and C. Schuster, "Machine Learning Based Data Validation for Signal Integrity and Power Integrity Using Supervised Time Series Classification," IEEE Transactions on Electromagnetic Compatibility, vol. 66, no. 6, pp. 2150-2158, Dec. 2024.
- T. Hillebrecht, T. Weber, J. Alfert, and C. Schuster, “Relational SI/PI- database for a data-driven approach to PCB design automation and performance prediction,” IEEE Trans. on Components, Packaging and Manufacturing Technology, vol. 15, no. 9, pp. 1847–1856, Sep. 2025.
- Y. Hassab, J. Hessling, M. Schierholz, I. Erdin, J. Balachandran, and C. Schuster, “Impedance profile prediction and classification for PCB based PDN decoupling using autoencoders,” in DesignCon 2025, Santa Clara, CA, USA, 2025.
- 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," in IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 15, no. 9, pp. 1847-1856, Sept. 2025
- 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, vol. 66, no. 6, pp. 1967-1976, Dec. 2024
- M. Schierholz, C. Schuster, Z. Nezhi and M. Stiemer, "PCB Based Power Delivery Network Analysis Using Transfer Learning and Artificial Neural Networks," IEEE Workshop on Signal and Power Integrity (SPI), Lisbon, Portugal, 2024.
- J. Hessling, Y. Hassab, J. Balachandran, I. Erdin, and C. Schuster, “Fast PDN Impedance Matrix Prediction for PCB Design Utilizing Latent Space Embedding,” DesignCon 2026, Santa Clara, CA, USA, 2026.

3. Related Projects / PATTERN

Measurement: Fast Near-Field Scans

Cheng Yang, Ph. D.

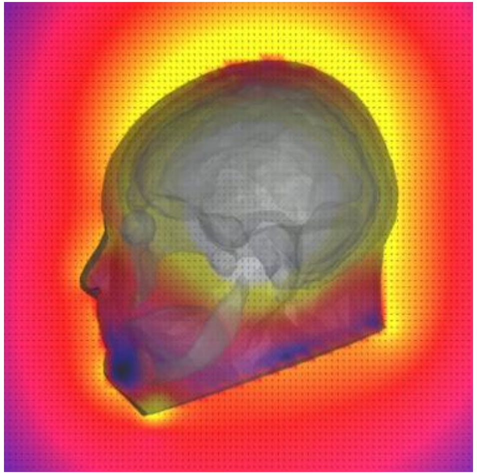
- Started in 2019 (permanent position)
- Ober-Ingenieur
- Funded by TUHH
- Adaptive On-the-Fly Near-Field Scanning via Gaussian Process Regression and Bayesian Optimization



Bio-EMC: SAR-Prediction

<u>Malte Thode, M.Sc.</u>

- 4 year project, started in 4.2026
- Internal Ph.D. position
- Funded by TUHH
- Generation of SAR values using machine learning models based on simulation data



Marie Sklodowska Curie - No 101169295

PATTERN

European Doctoral Network Enabling AI for Electromagnetic Compatibility

(2025 – 2028)

This project has received funding from the European Union's EU Framework Programme for Research and Innovation Europe Horizon (Grant Agreement No 101169295, for Doctoral Candidates 1-15) and DMU (De Montfort University, for Doctoral Candidate 16).

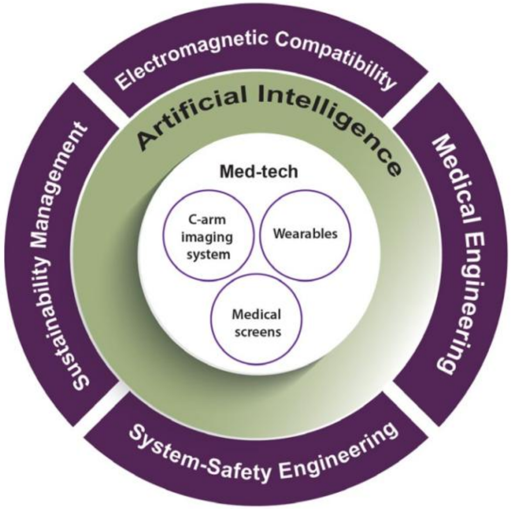
Funded by the European Union

PATTERN

Project Motivation and Objectives

Enabling Artificial Intelligence for Electromagnetic Compatibility

- Create a multidisciplinary, academic-industrial **network for doctoral training** with leading European industry and academia
- Design **innovative EMI solutions** for Med-tech throughout their lifecycle
- Enable **Artificial intelligence (AI)** as the key enabler of a new design philosophy
- Implement **SSbD = Safe and Sustainable by Design** of medical equipment



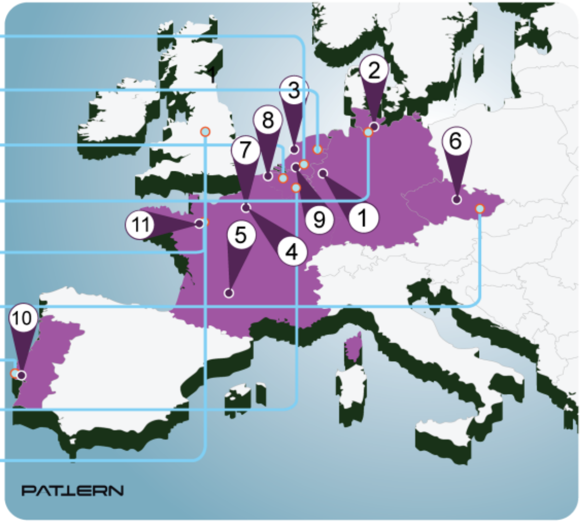
Project Consortium

Enabling Artificial Intelligence for Electromagnetic Compatibility

Beneficiaries

1. The Eindhoven University of Technology
2. University of Twente
3. Gent University
4. TUHH
5. IETR (CNRS)
6. Univerzita Tomáše Bati ve Zlíně
7. NOVA
8. KU Leuven
9. De Montfort University

Beneficiaries 1–9



Associated Partners

1. Rosenberger
2. Nexperia
3. Schneider
4. SAFRAN
5. Prana
6. Idiada
7. Thales
8. Barco
9. Philips
10. PLUX
11. INSA Rennes

Associated Partners 1–11

Project lead is TU/e with Prof. Anne Roc'h.

PATTERN – Project #6 (Nexperia)

<u>Nazim Talibzade, M.Sc.</u>

- 3 year project, started in 11.2025
- Internal Ph.D. position
- Funded by EU
- Generation of an Adaptive Database for SI and EMI Prediction and Optimization of High-Speed Packages

This project has received funding from the European Union's EU Framework Programme for Research and Innovation Europe Horizon (Grant Agreement No 101169295, for Doctoral Candidates 1-15) and DMU (De Montfort University, for Doctoral Candidate 16).

PATTERN – Project #9 (Rosenberger)

<u>Mikhail Kvizhinadze, M.Sc.</u>

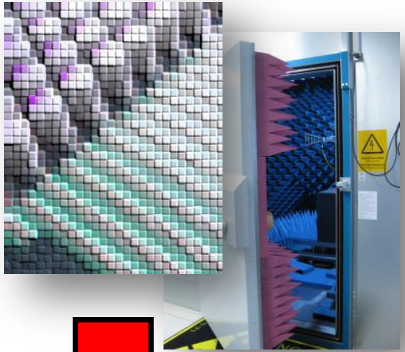
- 3 year project, started in 11.2025
- Internal Ph.D. position
- Funded by EU
- Automated Evaluation of Physics- and Data-Based Approaches for SI and EMI Optimization of Cable and Connector Assemblies

This project has received funding from the European Union's EU Framework Programme for Research and Innovation Europe Horizon (Grant Agreement No 101169295, for Doctoral Candidates 1-15) and DMU (De Montfort University, for Doctoral Candidate 16).

4. Wrap-Up

Physics-Based with Data-Based

Physics-Based
Modeling,
Design or
Measurement

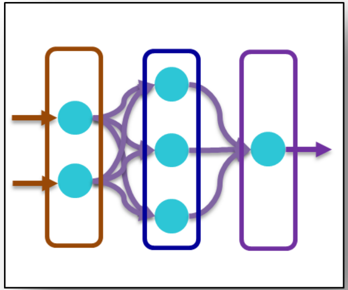


Data / Results

How ?

Data / Results

Data-Based
Model



INSTITUT FÜR THEORETISCHE ELEKTROTECHNIK

Prof. Christian Schuster

Institut für Theoretische Elektrotechnik
Hamburg University of Technology
Blohmstr. 15, 21079 Hamburg

schuster@tuhh.de

www.tet.tuhh.de

TUHH
Hamburg University of Technology