

Design-ready forward and inverse surrogate modeling of high-frequency structures using deep learning and dimensionality reduction

Development of contemporary high-frequency systems, including individual components is a daunting task. Emerging applications (5G, IoT, RFID), impose stringent requirements on performance, functionality (tunability, multi-band operation, etc.), and compact size. To meet these demands, high-frequency structures have become increasingly sophisticated. A consequence is the increasing number of design variables and the need for full-wave electromagnetic (EM) analysis to ensure a reliable evaluation of the system outputs. These factors make the design process challenging and heavily reliant on EM tools and rigorous optimization algorithms. The main bottleneck of EM-driven design is its excessive computational cost. Addressing this issue has led to the development of accelerated techniques. Many of these methods employ surrogate modeling approaches. Unfortunately, factors such as the curse of dimensionality and nonlinearity of system outputs impede the construction of reliable surrogates for most practical situations. A workaround is machine learning (ML) frameworks, which achieve efficiency at the expense of degraded exploration capability: the search quickly focuses on the promising region, leaving most of the space unexplored. The available surrogate-assisted methods employ conventional techniques (kernel-based methods, feedforward neural networks), combine well-known techniques, or use undemanding test cases.

This project aims to develop efficient and reliable design-ready surrogate modeling methods involving deep learning, dimensionality reduction, domain confinement, and response features. The primary approach will be the utilization of recurrent neural networks (RNNs) with long short-term memory (LSTM) and gated recurrent units (GRUs) to accurately represent frequency characteristics of the device of interest by treating frequency as a sequential parameter. Domain confinement, realized through dimensionality reduction, will focus the modeling process on the most relevant parameter space regions, significantly enhancing cost efficiency without compromising design utility. Other goals include the development of design-ready inverse models for rapid global, multi-objective, and tolerance-aware design. The procedures will be demonstrated using real-world design case studies. These methods will push forward the state of the art in high-frequency CAD and design automation, and mitigate the difficulties of the existing techniques regarding rendition of accurate surrogates, coverage of large parameter spaces, and making search procedures computationally feasible.

The project contains several highly innovative components, which can be identified as follows:

- Development of deep-learning methods for surrogate modeling of antenna and microwave components with sequential processing of frequency characteristics using LSTM and GRU.
- Using the attention mechanism for improved representation of the most relevant frequency spectrum parts.
- Development of dimensionality reduction techniques using pre-screening and rapid global sensitivity analysis that improve the modeling process's efficiency without compromising the models' design utility.
- Development of methods for inverse modeling of high-frequency components, incorporating response features and automated determination of the model domain regarding the system's operating parameters.
- Development of surrogate-assisted and machine-learning-based design optimization frameworks employing reliable and low-cost deep learning modeling methods, along with customized CAD software.

The project is anticipated to significantly advance both the state of the art and practical engineering in high-frequency computer-aided design, design automation, surrogate modeling, and optimization. It introduces several conceptually novel approaches, including the use of recurrent neural networks with LSTM, GRU, and attention mechanisms for sequential processing of system responses; dimensional and spatial model domain reduction focused on maintaining design applicability; inverse modeling; and representing systems in terms of operating parameters rather than design variables—all aimed at overcoming current limitations and enhancing design efficiency. The outstanding performance of the developed modeling procedures and design automation frameworks—especially in efficiently addressing complex real-world design problems—is expected to promote their broad adoption within the research community, thereby impacting the state of the art in the field. The modeling and design optimization frameworks—along with their software implementations—developed for tasks such as local and global parameter tuning, multi-objective design, and uncertainty quantification will offer practical, design-ready tools for researchers and industry professionals. Their integration with leading commercial CAD tools (e.g., CST Microwave Studio, Ansys HFSS, Keysight ADS/Momentum) further enhances their accessibility and utility in real-world applications. High-performance modeling and design procedures are expected to attract interest from academic researchers and practitioners, especially in environments where developing advanced components and devices must be achieved under tight time and computational constraints.

Project outcomes will be disseminated through publications in top-tier technical journals in RF electronics and through contributions to international conference proceedings. The proposed techniques will be shared with major EM simulation software developers (Dassault Systemes, Sonnet *em*) to foster potential future collaboration.