Design automation and simulation-driven optimization of high-frequency systems using machine learning

Modern high-frequency systems exhibit increasing technological sophistication, which is a consequence of performance demands dictated by the needs of emerging application areas (mobile communications, IoT, microwave imaging, RFID). The characteristics of interest and the required functionalities include reconfigurability, broad bandwidth, circular polarization, multi-band operation, or miniaturization. Fulfilling these needs leads to geometrically complex structures that involve a variety of auxiliary components such as defected ground structures or metamaterials. These increase the number of parameters to be tuned, whereas accurate system evaluation necessitates full-wave electromagnetic (EM) analysis. This makes high-frequency design a challenging task. Yet, EM simulation is a major design tool, essential at all development stages (topology evolution, parametric studies, final tuning). An increasing role has been played by optimization methods, needed for local tuning but also global and multi-criterial design, as well as uncertainty quantification. High cost of repetitive EM simulations incurred by these procedures fostered development of accelerated methods. Available approaches rely on surrogate modelling techniques, and often take the form of machine learning (ML) frameworks, where the surrogate is employed as a fast predictor, which is iteratively refined using the accumulated EM simulation data. The fundamental bottleneck is surrogate model construction, impeded by the curse of dimensionality, nonlinearity of system outputs, and the sheer size of parameter spaces. Hence, the existing surrogate-based optimization (SBO) and ML frameworks are demonstrated using simple test cases and exhibit poor scalability with respect to the search space size.

The purpose of this project is the development of efficient and dependable procedures for SBO- and ML-based design of high-frequency systems. We plan to develop tools that extend the applicability range of SBO/ML for complex tasks (higher dimensionality, wider parameter ranges), and improve the efficacy of design processes. Another goal is development of frameworks for global and multi-objective optimization, and tolerance-aware design. The procedures will be demonstrated using real-world case studies. The devised methodologies will expand the capabilities of the state-of-the-art techniques, and alleviate the difficulties pertinent to the existing approaches, especially in terms of problems associated with rendition of accurate surrogates, coverage of large portions of the parameter spaces, and making costs of search procedures acceptable. The accomplishment of the objectives will push forward the state of the art in EM-based design and CAD of high-frequency systems.

The project contains a number of highly innovative components, which can be identified as follows:

- Development of reduced-cost pre-screening algorithms to facilitate global exploration of large parameter spaces. Their efficiency will be ensured by using multi-fidelity EM simulations, and problem re-formulation in terms of operating (rather than geometry) parameters of the components under design.
- Development of ML-based procedures for cost-efficient global optimization of high-frequency components, involving regularization mechanisms, pre-screening, and dimensionality reduction.
- Improving the efficacy of ML-based algorithms by incorporating inverse modeling methods so that the search process is delegated to low-dimensional objective space, thereby reducing the CPU expenses.
- Development of ML-enabled methods for improving EM-driven local parameter tuning methods. The goal is to mitigate the issues related to expensive/inaccurate sensitivity estimation in gradient-based procedures.
- Development of customized CAD software, which integrates surrogate modeling techniques and optimization algorithms into automated design frameworks capable of solving real-world design tasks.
- Demonstrating design utility of the developed frameworks for selected applications.

The modeling and design optimization methodologies being the project outcome will contain a number of conceptually novel approaches that go beyond current paradigms. On the other hand, demonstrated competitive performance of the developed design procedures, especially in terms of handling highly-dimensional parameters spaces, will foster utilization of the aforementioned mechanisms and their widespread use by other researchers, thereby affecting the state of the art in the field. At the same time, specific design frameworks and their software implementations, developed for solving tasks such as local/global parameter tuning, multi-criterial design, or uncertainty quantification, will provide design-ready tools for both researchers and industrial engineers, particularly due to being integrated with commercial CAD software. Improved-efficacy design procedures will be of interest to engineers from academic institutions, as well as industrial enterprises, where design of high-performance components and devices has to be carried out using limited time and computational resources.

The results of the project will be published in the leading technical journals in the field of RF electronics and disseminated in the form of international conference papers. The developed techniques will be also presented to the leading EM simulation software manufacturers (Dassault Systemes, Sonnet ***em***) to stimulate future collaboration.