Electromagnetic Simulation with 3D FEM for Design Automation in 5G Era

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Abstract: Electromagnetic simulation and electronic design automation (EDA) play an important role in the design of 5G antennas and radio chips. The simulation challenges include electromagnetic effects and long simulation time and this paper focuses on simulation software based on finite-element method (FEM). The state-of-the-art EDA software using novel computational techniques based on FEM can not only accelerate numerical analysis, but also enable optimization, sensitivity analysis and interactive design tuning based on rigorous electromagnetic model of a device. Several new techniques that help to mitigate the most challenging issues related to FEM based simulation are highlighted. In particular, methods for fast frequency sweep, mesh morphing and surrogate models for efficient optimization and manual design tuning are briefly described, and their efficiency is illustrated on examples involving a 5G multiple-input multiple-output (MIMO) antenna and filter. It is demonstrated that these new computational techniques enable significant reduction of time needed for design closure with the acceleration rates as large as tens or even over one hundred.

Keywords: design by optimization; electronic design automation; fast frequency sweep; interactive design tuning; mesh morphing

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1 Introduction

5G technology is going to revolutionize the next decade, allowing wireless connectivity to penetrate the industrial world and society. Huge new markets will open for business, which are expected to play an important role in economy recovery and growth, offering new business opportunities and changing our lives. Smart cities, factories, autonomous vehicles, intelligent infrastructure, electric grids, massive machine-to-machine communications are just a few examples of the 5G application scenarios where billions of devices will be connected in radio networks. With 5G infrastructure and technology, companies will provide new mobile services and offer new wireless products with unprecedented capabilities. To meet the demands for high data throughput, low latency, low power consumption, quality of service and safety simultaneously, wireless devices will have to fulfill stringent system and regulatory requirements that can only be satisfied by carefully engineered hardware. Engineers will have to overcome enormous technical challenges and this will not be possible without new generation of electronic design automation (EDA) software that is capable of addressing these challenges with accuracy and speed not seen before. The core of 5G is wireless

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connectivity, so EDA software for fast electromagnetic analysis, which is necessary for accurately simulating 5G antennas and radio chips, will be essential for timely delivery of 5G innovations to market.

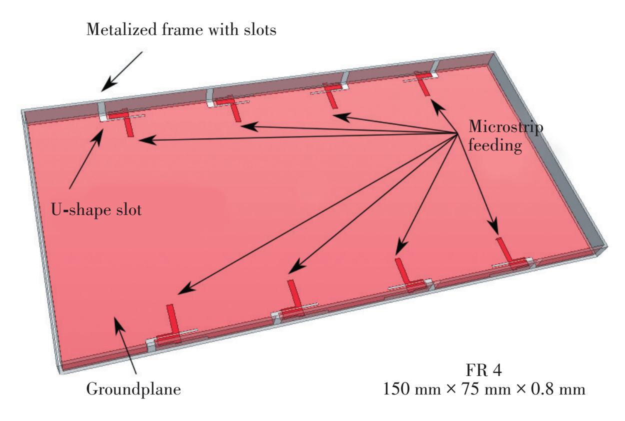
2 Simulation Challenges and Solutions

RF circuits cannot be designed easily by using lumped element models. The size of each element and wavelength and electromagnetic effects, such as dispersion, radiation, conductor and dielectric loss, and parasitic coupling have to be considered. EDA simulates the behavior of a circuit by numerically solving Maxwell's equations and facilitate accurate results with these effects are taken into account. This is not a trivial task and often requires substantial computer resources. To address the challenges related to electromagnetic design, software tools have to use state-of-the-art numerical algorithms[1–7] that speed up simulations and allow designers to find the solution that meet stringent specifications.

2.1 Frequency Sweeps

To get an idea of challenges associated with computer aided design of RF circuits for the fifth generation (5G) mobile communications, let us consider an antenna, which is a basic element of any handheld wireless device. To meet the requirements for higher data transfer rate, 5G communications systems have to use multiple-input multiple-output (MIMO) technology. Because a high throughput is essential in 5G, massive MIMO antenna systems are necessary and designed for any handheld devices. On the other hand, different countries have allocated different parts of the spectrum for 5G service. As a result, MIMO antennas for consumer applications have to cover more than one band. Therefore, numerical simulation of a broadband or multi-band MIMO antenna can be very lengthy. To illustrate this, let us consider modelling of a 4 × 2 broadband antenna for a smartphone proposed in Ref. [8]. As shown in **Fig. 1**, the antenna array consists of eight radiating elements, each fed by a microstrip line with a tuning stub. The antenna array operates in 3.3 GHz to 6 GHz and provides high isolation between elements.

To analyze the antenna, we will use the finite-element method (FEM), which is amongst the most powerful numerical modelling techniques, for solving partial differential equations often used in computational electromagnetics software for high-frequency electromagnetic field simulations (**Table 1**).



▲ **Figure 1. Simulation of an 8-element multiple-input multiple-output (MIMO) antenna for a 5G terminal[8].**

▼**Table 1. Examples of commercial software or modules in software packages for electromagnetic EDA with a computational kernel based on FEM**

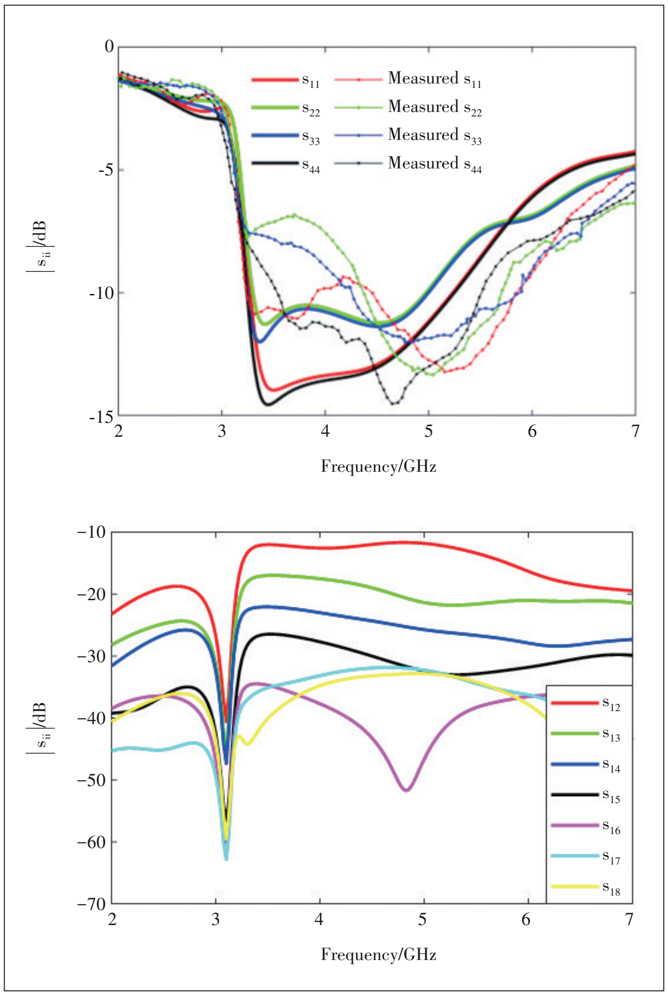
Software/FEM Module (Company)	Features
Feko (Altair HyperWorks)	· Several solvers (including FEM) integrated in one software package · Fast frequency sweep (interpolating) · Scripting · Several optimization procedures
HFSS (Ansys)	· Optimization (separate module) · Fast frequency sweep (interpolating or model order reduction) · Interactive design tuning (separate module)
COMSOL Multiphysics/RF Module (COMSOL)	· Several optimization techniques (separate module) · Fast frequency sweep using Padé interpolation (asymptotic wave evaluation method)
SIMULIA/CST Studio Suite/Frequency Domain Solver (Dassault Systèmes)	· Several solvers (including FEM) integrated in one software package · Optimization with movable mesh · Fast frequency sweep (adaptive sampling or model order reduction) · 3D filter CAD (separate module)
InventSim (EM Invent)	· Fast frequency sweep (MOR or interpolating) · Optimization with deformable mesh and MOR · Filter synthesis and 3D shape optimization – integrated · Mixed precision solver · Interactive design tuning (integrated)
PathWave EM Design (EMPro) (Keysight Technologies)	· Adaptive fast frequency sweep (interpolating) · Integration with ADS

ADS: Advanced Design System
CAD: computer aided design
EDA: electronic design automation
FEM: finite-element method
HFSS: High Frequency Structure Simulator
MOR: model order reduction

FEM uses a volumetric mesh where the 3D space is divided into small tetrahedral sub-regions (elements). Field in each tetrahedron is represented by a sum of simple (linear, quadratic or cubic) local functions. Field equations are enforced within each element and across all elements. This results in a large system of linear equations that is then numerically solved at the desired frequency. The number of equations is very large (often in the order of millions) so the solution is time consuming. **Fig. 2** shows the results of the simulation of the antenna using InventSIM EDA software[9] for the frequency band from 2 GHz to 7 GHz. The plot shows selected scattering parameters, computed characteristics and the results of measurements reported in Ref. [8]. It is seen that the agreement is good.

Let us now have a closer look at the simulation runtime. In the basic simulation scenario, called discrete sweep, a certain number of frequency points (N_f), uniformly distributed in the band of interest, are selected, and FEM equations are solved at these points. The runtime needed to complete the simulations depends on the number of frequency points, mesh density and the order of local functions for tetrahedra. In the case of our MIMO antenna, we selected N_f =201 and the second order interpolation within each tetrahedron. The runtime for a coarse mesh (118 thousand tetrahedra) was 20 minutes, while for the mesh approximately 3.3 times finer (390 thousand tetrahedra), it was 3 hours and 25 minutes. The runtimes are given for a server with two Intel Xeon Gold 6136 processors and 576 GB RAM installed. This is certainly not attractive for a designer to wait for almost 3.5 hours to see the results. If the mesh is further refined, by a factor of three, which may sometimes be needed for getting very accurate results, the number of tetrahedra grows to 1.185 million and the runtime for 201 frequency points increases to over 16 hours. Such long computing time would make FEM simulations unattractive. This is why all EDA tools presented in Table 1 offer a feature called a fast frequency sweep, which enables much faster broadband response. With the interpolating sweep, one of the two most common used sweep approaches, the solution is found at a small number of frequency points and the response between these points is interpolated from them. The points for interpolation are selected automatically. One disadvantage of this approach is that while the scattering characteristics can be calculated between the sampling frequencies, the electromagnetic field can be computed only for the nodes. This disadvantage can be avoided in the fast frequency sweeps using model order reduction algorithms[4–5], [7]. In a nutshell, the reduced order model is a mathematical technique that constructs a cheap to evaluate model of a dynamical system by finding a compact set of vectors that allow to represent the electromagnetic field at any frequency within a limited frequency band. This is possible since the electromagnetic field does not change very rapidly from one frequency point to another, so in fact it can be represented as a linear combination of frequency-independent field patterns defined in the entire computational space, called basis vectors. What change with frequency are the amplitudes of basis vectors and these amplitudes can be computed very fast. The acceleration is impressive; for instance, it took InventSIM 13 minutes to compute the response of the same 4 × 2 MIMO antenna at the 201 frequency points using wideband model order reduction algorithm for the moderately dense mesh consisting of 390 thousand tetrahedra, which is 15 times faster than the original discrete sweep. For the finest mesh of 1.185 million tetrahedra, the speedup is even larger. For this case the computations are completed in 44 minutes rather than 16 hours (21 times faster). **Table 2** provides detailed data for the simulations and the runtimes for the interpolating sweep.

It is evident that a good fast frequency sweep technique in an EDA software is crucial for enabling engineers to design and validate the performance of antennas and RF and microwave components. An optimal design is hard to achieve without fast frequency sweep.



▲**Figure 2. Selected scattering parameters (S_{ij}) of multiple-input multiple-output (MIMO) antenna.**

▼Table 2. Runtime for wideband simulation of a 4×2 MIMO antenna for 5G and three mesh densities

Number of Tetrahedra	Matrix Size	Direct Sweep Time/s (201 freq. points)	Interpolating Sweep Time/s	Fast Frequency Sweep (MOR) Time/s
118 367	727 514	1 095	181	247
390 136	2 444 052	12 296	2 062	822
1 185 523	7 337 304	58 385.4	8 647	2 692

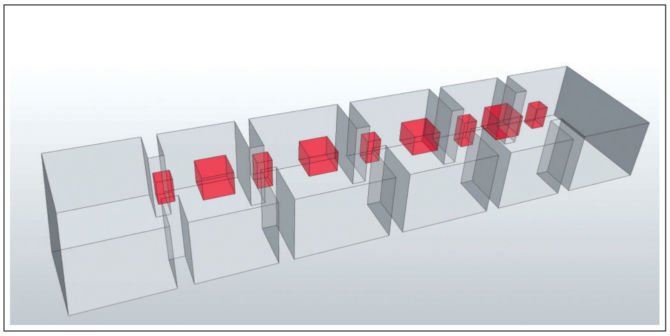
MIMO: multiple-input multiple-output MOR: model order reduction

2.2 Optimization

Often the simulation shows that the designed structure does not fulfil the desired specification. The way electromagnetic waves interact with objects, which determines the response of the circuits, depends on their shape. To ensure that the specifications are met, the geometry of antennas and microwave components in RF chips has to be altered. To achieve good performance, optimization algorithms will be applied. This requires a number of electromagnetic simulations that are performed in the optimization loop with design parameters as optimization variables. In each iteration the geometry is altered (dimensions change) and numerical analysis is then carried out from scratch. Simulations are repeated many times until the response meets the specifications. The number of iterations depends on the optimization method used and on the quality of the initial design. It is evident that the challenge related to long computing time becomes much more severe when it comes to optimization.

A new generation of FEM EDA tools can address the challenges not only via fast frequency sweeps, but also by treating iterations as a part of the entire design process in which the geometry gradually evolves rather than as a set of independent simulations for different geometries. In this framework, iterations are connected via the mesh and the workflow is arranged so that the same mesh is used throughout optimization rather than being generated anew each time a geometry is modified. To enable this, the coordinates of each mesh node change continuously as the values of the design variables are modified in an optimization process. This technique is known as mesh deformation or mesh morphing[10–12] and has been found to greatly improve the efficiency of optimization[4].

A four-pole microwave filter is optimized to illustrate the implementation of FEM-based optimization and the significance of a fast frequency sweep using reduced order model and mesh morphing. The geometry of the filter is shown in **Fig. 3**. The goal is to achieve an equiripple response in a certain bandwidth, and five geometrical variables could be modified to reach this goal. The design variables are the heights of posts in the coupling windows and the heights of the posts in the resonant cavities. Full details related to the geometry and specifications are provided in Ref. [3], where several gradient-based optimization techniques were discussed using FEM and the runtime for simulations was provided. The approaches considered in Ref. [3] are the direct EM optimization using sequential nonlinear programming (SNLP), which is one of the optimization techniques available in a commercial tool for electromagnetic design High Frequency Structure Simulator (HFSS), direct EM optimization using MATLAB's fminimax procedure with the quasi-Newton method for mesh deformation, and the new formulation of Newton's method with constraints (the Lagrangian method) with mesh deformation developed specifically for EM optimization. The number of iterations and runtime used for these three approaches with two starting points are compared in **Table 3**. Besides, in the last two rows of Table 3, we add the results obtained by InventSIM and its implementation of mesh deformation and fast frequency sweep using reduced order modelling, with MATLAB's



▲Figure 3. Structure of the four-pole waveguide filter[3] with five geometrical variables used for direct EM design optimization.

▼Table 3. Comparison of the number of iterations and runtime of different methods for FEM-based optimization of a four-pole waveguide filter

Method	Good Starting Point		Bad Starting Point	
	No. of Iterations	Total Runtime	No. of Iterations	Total Runtime
HFSS's SNLP without mesh deformation[3]	71	17.8 h	135	33.8 h
Quasi-Newton with mesh deformation[3]	31	8.2 h	65	17.1 h
Quasi-Newton with Lagrangian method and mesh deformation[3]	9	2.7 h	24	7.2 h
Quasi-Newton using InventSim FEM solver and mesh deformation	17	39 min 16 s	30	1.5 h
InventSim generalized Chebyshev filter optimizer with mesh deformation	9	11 min 13 s	14	18 min 43 s

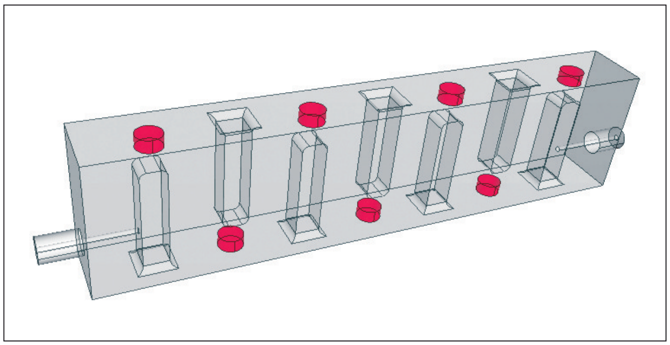
FEM: finite-element method SNLP: sequential nonlinear programming HFSS: High Frequency Structure Simulator fminimax and a built-in optimizer for general Chebyshev filters. An important observation that can be made from the data given in the table is that there can be huge differences both in the convergence rate and the total time taken by optimization. As seen from the results, mesh deformation has a significant impact on the convergence rate. The number of iterations is much higher for the HFSS that does not offer mesh morphing, than for any other case presented in the paper, where mesh morphing is employed. For a bad starting point, one EDA software tool results in the time needed for the design closure 100 times shorter than another EDA tool.

The optimization of the filter in Ref. [3], even though considered as a challenge for direct EM optimization for most EDA tools based on FEM, is still relatively simple in terms of the number of optimizable parameters; the example considered above involved just five design variables. In practice, the number of geometry variables that have to be considered by an engineer is much larger. In the next example, we consider an interdigital combine filter with 18 design variables. The geometry of the filter is shown in **Fig. 4**. The design variables include 7 tuning screws, 8 lengths between posts, input and output height, and the height of resonators (common for all). No symmetry was assumed and optimization was performed in InventSIM with both mesh morphing and fast frequency sweep enabled. For this example, the FEM matrix had 350 thousand rows and columns, and the optimizer needed 18 iterations and less than 56 minutes to converge from the initial design shown by the red curve in **Fig. 5** to the passband response shown by the blue one in the same figure.

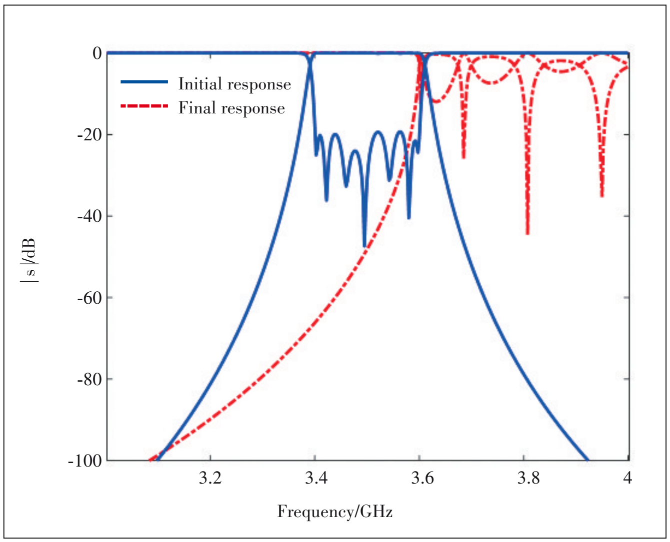
2.3 Interactive Design Tuning

The optimization algorithm is a powerful tool for EDA, but it is time consuming. Moreover, an optimization algorithm itself has no knowledge of the physics governing the operation of a device. It just executes a sequence of steps based on the data provided by a simulator. However, the knowledge-based design is likely to enable an acceptable result much quicker, by which the decisions of what parameters should be adjusted come from the understanding of the operating principle of a circuit or a role of a particular component in shaping the response. A skilled engineer can use his experience to modify certain parameters to improve the performance of the circuit. A very efficient way to do these adjustments is interactive design tuning. The idea is to allow an engineer to continuously change one or more design parameters while monitoring the effect of the changes. In order to realize interactive design tuning, the result of any change should be reflected in the response instantaneously. At first glance it seems impossible for EDA of RF circuits; as we showed in the previous sections, the simulations using full-wave FEM take long time and one has to wait for minutes or even hours before the response can be evaluated and displayed. However, this seemingly impossible real-time interactive tuning can be achieved if a parametric surrogate model is used instead of full-wave simulations to quickly evaluate the response and display the results on the fly each time any design parameter is changed. The surrogate model is constructed from the data computed by the FEM solver at the initial design point. Obviously, the accuracy of the surrogate model is limited and this model is valid only in the neighborhood of the point in the design space where the FEM model was computed. Nevertheless, this accuracy is often sufficient, and what is more, once an engineer is satisfied with the response obtained while manually adjusting the design variables, FEM simulations can be run and the surrogate model updated. As an example, we show the results of interactive tuning of a dielectric resonator filter proposed in Ref. [13] for use in 2 × 2 Doherty power amplifier for a 5G massive MIMO system application. The geometry of the filter is shown in **Fig. 6**.

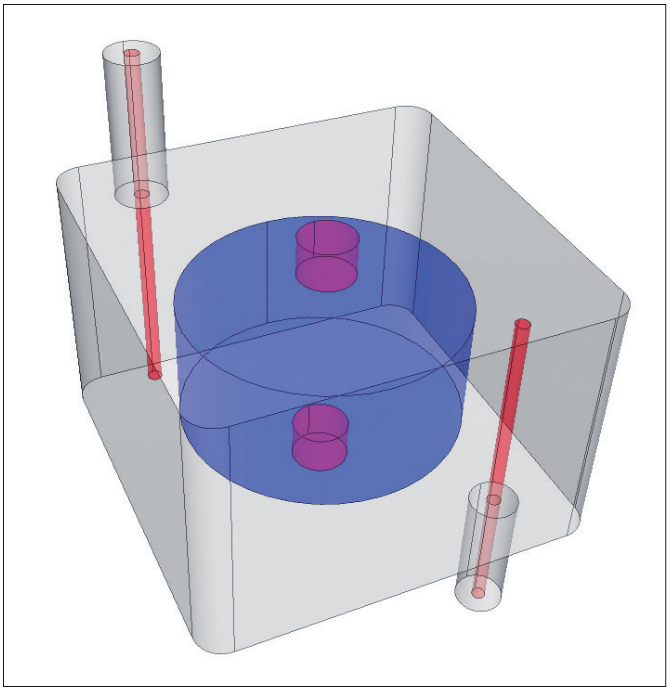
Following classical synthesis, the filter was simulated in InventSIM and then manually tuned by adjusting seven geometry parameters. Regular FEM simulation for this filter using a fast frequency sweep takes about 150 s. If one runs the interactive tuning, the solver needs additional 21 seconds to set up a surrogate model, so manual tuning with on the fly response



▲**Figure 4. Inline 7th order interdigital filter operating in 5G band 3.4 – 3.6 GHz.**



▲**Figure 5. Initial and final response of optimized interdigital filer.**



▲Figure 6. Single-channel of two-pole dielectric resonator (DR) filter for 5G applications[13].

display for this example needs less than three minutes of preprocessing.

Table 4 gives the values of the design variables before and after manual tuning. During the interactive tuning, the variables were modified one by one and the characteristics were updated on the fly using the surrogate model. All design variables were altered, most of which were changed by less than 1% – 2% but some changed quite significantly (e.g. the tuning screw). **Fig. 7** shows the initial response computed with FEM (dashed blue curve) while the solid lines shows filter characteristics for final values of design variables, after interactive tuning. The black curve shows the characteristics predicted by surrogate model prediction while the red curve corresponds to the results recomputed with the full-wave FEM solver. It is evident that there is a very good match.

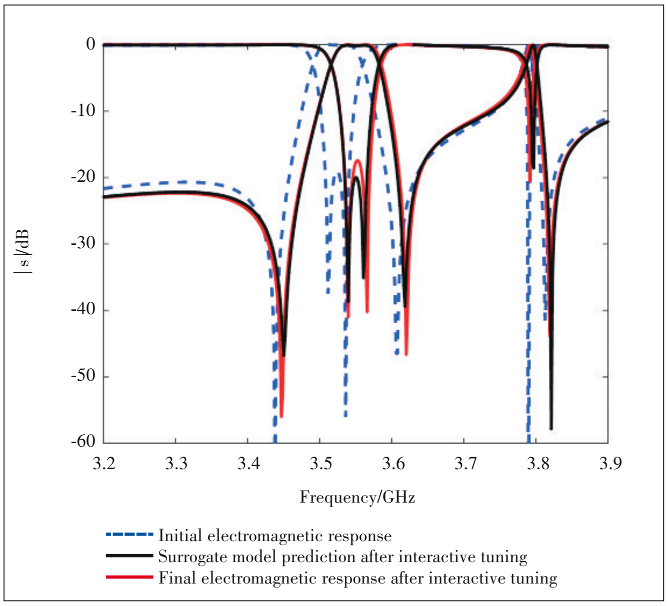
3 Conclusions

Major challenges for electronic design automation tools for 5G solutions have been discussed. Various approaches to address these challenges and speed up the computation time of FEM-based simulation problems have been presented. Fast frequency sweeps, model order reduction, and using mesh morphing in optimization have been shown to give significant reduction of the time needed by EDA software tools to simulate and optimize the performance of antennas and RF passive circuits. The concept of interactive design tuning based on a surrogate model has also been discussed as a good alternative to the optimization process.

▼Table 4. Interactive tuning of dual-channel dielectric resonator filter for use in a Doherty power amplifier for 5G massive MIMO system application

Parameter	Description	Initial Value/ mm	Final Value/ mm
a	Cavity width, length	25.85	25.94
c	Cavity height	18.44	18.0
D	DR diameter	19.32	19.3
H	DR height	9.47	9.38
X	Distance of coax from cavity wall	4.2	4.18
L	Coax probe length	16.0	16.1
Lp	Tuning screw length	0.28	0.88

DR: dielectric resonator MIMO: multiple-input multiple-output



▲Figure 7. Example of interactive tuning technique.

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Biographies

Lukasz BALEWSKI received his M.Sc. and Ph.D. (with honors) degrees in microwave engineering from Gdansk University of Technology (GUT), Poland in 2003 and 2008, respectively. He works with EM Invent, Poland. His research interests include CAD of microwave devices, filter design, and optimization techniques. He is the co-author of several software tools for microwave filter design.

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Adam LAMECKI received the M.Sc., Ph.D. and D.Sc. degrees in electronics and electrical engineering from Gdansk University of Technology (GUT), Poland in 2002, 2007 and 2019, respectively. In 2006 he joined the Department of Microwave and Antenna Engineering, Faculty of Electronics, Telecommunications and Informatics at GUT, where he is an associate professor. His research interests include surrogate models and their application in the CAD of microwave components, computational electromagnetics, mainly focused on the finite element method, filter design and optimization techniques. He was a recipient of the Young Scientist Grant awarded by the Foundation for Polish Science, the Prime Minister of Poland Award for outstanding Ph.D. thesis, and the Scholarship for outstanding young researchers from the Polish Ministry of Science and Higher Education. He has been a principal investigator on several research projects funded by the Polish Ministry of Science and Higher Education, the Polish National Science Centre, and the Polish National Centre for Science and Development. He has co-authored over 35 papers in peer reviewed journals, including IEEE Transactions on Microwave Theory and Techniques, IEEE Microwave and Wireless Components Letters, and IEEE Antennas and Wireless Propagation Letters.

Michal MROZOWSKI received the M.Sc. and Ph.D. degrees, both with honors, from Gdansk University of Technology in 1983 and 1990, respectively. In 1986, he joined the Faculty of Electronics, Gdansk University of Technology, where he is now a full professor and the head of the Department of Microwave and Antenna Engineering. He is a member of Polish Academy of Sciences, Fellow of IEEE and Fellow of Electromagnetics Academy. He currently serves as an associate editor for the *Proceedings of IEEE*. He published more than 150 papers, mostly in IEEE journals. His current research interests include computational electromagnetics, the EDA of microwave devices, filter and sensor design, and optimization techniques.