Improved Design Closure of Compact Microwave Circuits by Means of Performance Requirement Adaptation

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Abstract. Numerical optimization procedures have been widely used in the design of microwave components and systems. Most often, optimization algorithms are applied at the later stages of the design process to tune the geometry and/or material parameter values. To ensure sufficient accuracy, parameter adjustment is realized at the level of full-wave electromagnetic (EM) analysis, which creates perhaps the most important bottleneck due to the entailed computational expenses. The cost issue hinders utilization of global search procedures, whereas local routines often fail when the initial design is of insufficient quality, especially in terms of the relationships between the current and the target operating frequencies. This paper proposes a procedure for automated adaptation of the performance requirements, which aims at improving the reliability of the parameter tuning process in the challenging situations as described above. The procedure temporarily relaxes the requirements to ensure that the existing solution can be improved, and gradually tightens them when close to terminating the optimization process. The amount and the timing of specification adjustment is governed by evaluating the design quality at the current design, and the convergence status of the algorithm. The proposed framework is validated using two examples of microstrip components (a coupler and a power divider), and shown to well handle design scenarios that turn infeasible for conventional approaches, in particular, when decent starting points are unavailable.

Keywords: Microwave design, simulation-based optimization, performance requirements, design specification adaptation.

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1 Introduction

The involvement of numerical optimization techniques has been constantly growing in the area of high-frequency electronics [1], [2]. Parameter tuning through rigorous optimization replaces interactive methods, mostly involving parameter sweeping, due to inadequacy of the latter. Topologically complex designs developed to meet the demands of emerging application areas (wireless sensing [3], Internet of Things (IoT) [4], 5G communications [5], autonomous vehicles [6]) require simultaneous adjustment of multiple variables and handling several performance figures and constraints. For reliability reasons, design closure is normally executed with the aid of full-wave electromagnetic (EM) analysis. EM-driven tuning is especially important for compact devices [7], [8], where common miniaturization means such as replacing conventional transmission lines by compact microstrip resonant cells (CMRCs) [9], [10], or incorporation of defected ground structures [11], lead to cross-coupling effects that cannot be accounted for by equivalent network models.

The major bottleneck of simulation-based microwave optimization is its high computational cost. It can be alleviated using various means such as utilization of adjoint sensitivities [12], sparse sensitivity updates [13], or surrogate-assisted procedures incorporating both data-driven [14], and physics-based replacement models [15]. Approximation models (e.g., kriging [16], support vector regression [17], polynomial chaos expansion [18], neural networks [19]) are fast and widely accessible but they are strongly affected by the curse of dimensionality. The methods of the second group (e.g., space mapping [20], response correction methods [21]) are more immune to dimensionality issues but require an underlying lower-fidelity model, which has to be customized for a given problem and application area. Another option are variable-fidelity methods such as co-kriging [22], or machine learning frameworks [23].

Computational efficiency is one of the essential aspects of the optimization routines. In many cases, the reliability, understood as the capability of the algorithm to deliver a satisfactory solution, is even more important. An example is the lack of good initial designs, which commonly occurs whenever the component at hand is to be re-designed to different operating frequencies. Another example is optimization of CMRC-based devices [9], where identification of a decent starting point may be difficult due to significant topology modifications incurred by the incorporation of the compact cells. Local search routines are prone to a failure under such circumstances, whereas utilization of global optimizers is associated with significant CPU expenses. The techniques outlined before [12]-[23] are mostly focused on achieving the computational speedup. Combining surrogate modelling methods with nature-inspired algorithms (e.g., [24]) may be a step towards reliability improvement, yet applicability of such methods is limited in microwave design due to high level of nonlinearity of the system outputs. As a matter of fact, only low-dimensional cases can be treated this way [25].

This paper proposes an alternative approach to improving the reliability of microwave design closure using local search procedures. The major component of our technique is design specification adaptation, which operates by adjusting the performance specifications on the grounds of the misalignment between the target and the actual operating frequencies and/or bandwidths of the device of interest. At the initial stages of the optimization process, the specifications are relocated to the vicinity of the actual operating frequencies, and gradually tightened to eventually reach their original values

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upon the convergence of the process. The major advantages of the proposed methodology include: (i) reducing the sensitivity of the search process to the starting point quality, (ii) enabling the possibility of system re-design within wide frequency ranges by means of local algorithms, (iii) eliminating the need for global procedures when handling challenging design scenarios. The presented framework is validated using two microstrip circuits, a branch-line coupler and a power divider. Successful optimization is demonstrated using inferior initial designs at which the operating conditions are severely misaligned with respect to the targets.

2 Microwave Design Closure with Adaptive Adjustment of Design Requirements

This section introduces the concept and the implementation of the adaptively adjusted performance requirements. For the sake of illustration, it is incorporated into the trust-region gradient-based algorithms, although the adaptation procedure itself is generic, i.e., can be combined with various iterative search routines.

2.1 Adaptive Adjustment of Performance Requirements. The Concept

The purpose of this work is to improve the reliability of EM-driven design closure of compact microwave circuits with the emphasis on handling poor initial designs. As mentioned before, a representative situation is dimension scaling of a given structure for the operating frequencies that are distant from those at the current design. The task is particularly challenging when the system at hand features narrow-band characteristics, and local optimization routines are prone to a failure. At the same time, globalized procedures (e.g., nature-inspired algorithms [26]) tend to be prohibitively expensive.

We begin by recalling the simulation-based parameter adjustment problem formulation. The assumption is that the intended operating frequencies of the circuit are f_k, k = 1, …, N; here, N stands for the number of the operating bands. These frequencies are assembled into the target vector $\boldsymbol{F} = [f_1 \ldots f_N]^T$. The EM-evaluated system response will be denoted as $\boldsymbol{S}(\boldsymbol{x})$, where $\boldsymbol{x}$ is the vector of independent design variables. The design problem is defined as

$$\boldsymbol{x}^* = \arg\min_{\boldsymbol{x}} U(\boldsymbol{S}(\boldsymbol{x}), \boldsymbol{F}) \tag{1}$$

The function U in (1) is a scalar metric of the design utility. For the sake of clarification, let us consider a coupler circuit, which is to operate at the centre frequency f_0. The characteristics of interest (all complex functions of frequency) are matching S_{11}, transmission S_{21} and S_{31}, and port isolation S_{41}. The coupler is supposed to provide an equal power split, i.e., $|S_{21}| = |S_{31}|$ at f_0 (here, $|.|$ stands for the modulus of the complex number), and minimize both matching and isolation, also at f_0. Having this in mind, the objective function is formulated as follows

$$\begin{gathered} U(\boldsymbol{S}(\boldsymbol{x}), \boldsymbol{F}) = U\left([S_{11}(\boldsymbol{x}, f), S_{21}(\boldsymbol{x}, f), S_{41}(\boldsymbol{x}, f), S_{41}(\boldsymbol{x}, f)], [f_0]\right) = \\ \max\left\{|S_{11}(\boldsymbol{x}, f_0)|, |S_{41}(\boldsymbol{x}, f_0)|\right\} + \beta\left[|S_{21}(\boldsymbol{x}, f_0)| - |S_{31}(\boldsymbol{x}, f_0)|\right]^2 \end{gathered} \tag{2}$$

In (2), minimization of $|S_{11}|$ and $|S_{41}|$ is executed explicitly, whereas the equal power split condition is handled by means of a penalty function.

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The typical challenges pertinent to parameter tuning have been illustrated in Fig. 1. There are two initial designs shown in the picture, one of which (marked black) is of sufficiently good quality to ensure that local optimization is capable of identifying the optimum at the target operating frequency. The second design (marked grey) is severely misaligned frequency-wise with respect to the target, and local search initiated from this point fails.

In this work, we aim at the conceptual development and implementation of the algorithmic framework capable of handling situations such as those illustrated in Fig. 1, while using local algorithms. This is realized by an adaptive adjustment of performance requirements, where the target operating frequencies are relocated having in mind the circuit characteristics at the current design. In particular, we strive to ensure attainability of the re-adjusted specifications at each iteration of the optimization algorithm. Clearly, the design requirements are to reach their original values upon the algorithm convergence.

The concept of design specifications adaptation has been graphically illustrated in Fig. 2. As the operating frequency at the initial design is away from the target, the specifications are relocated to about 1.1 GHz to become attainable by means of local search. The adjustments are subsequently made at each iteration of the process based on the operating frequency of the current design. Examples of intermediate stages are shown in Figs. 2(b) and 2(c). Towards the end of the optimization run, the target is allocated at its original value. It should be noted that performance requirement relocation and design update (e.g., within the iteration of a descent procedure) are interleaved. This allows for accomplishing the entire procedure within a single algorithm run. Section 2.2 will provide a rigorous formulation of the adaptation scheme.

2.2 Adaptive Adjustment of Performance Requirements. The Procedure

The proposed scheme for adaptive adjustment of performance requirements is developed having in mind the following factors:

- The amount of performance requirement adjustment should be computed using the actual operating frequencies of the current design;
- The attainability of the relocated specifications using local search should be ensured at each stage of the process;
- The aforementioned assessments should be accomplished at low computational expense, ideally without involving any additional full-wave EM simulations.

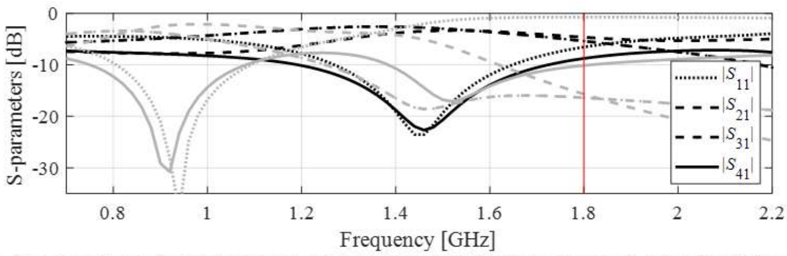

Fig. 1. *S*-parameters of a miniaturized microwave coupler (cf. Section 3.1). The circuit is supposed to operate at 1.8 GHz (marked with a vertical line). The target is attainable through local optimization from the design marked with the black lines. It is not attainable from the other (marked with the grey lines) because of too severe misalignment of the operating bandwidth and the target.

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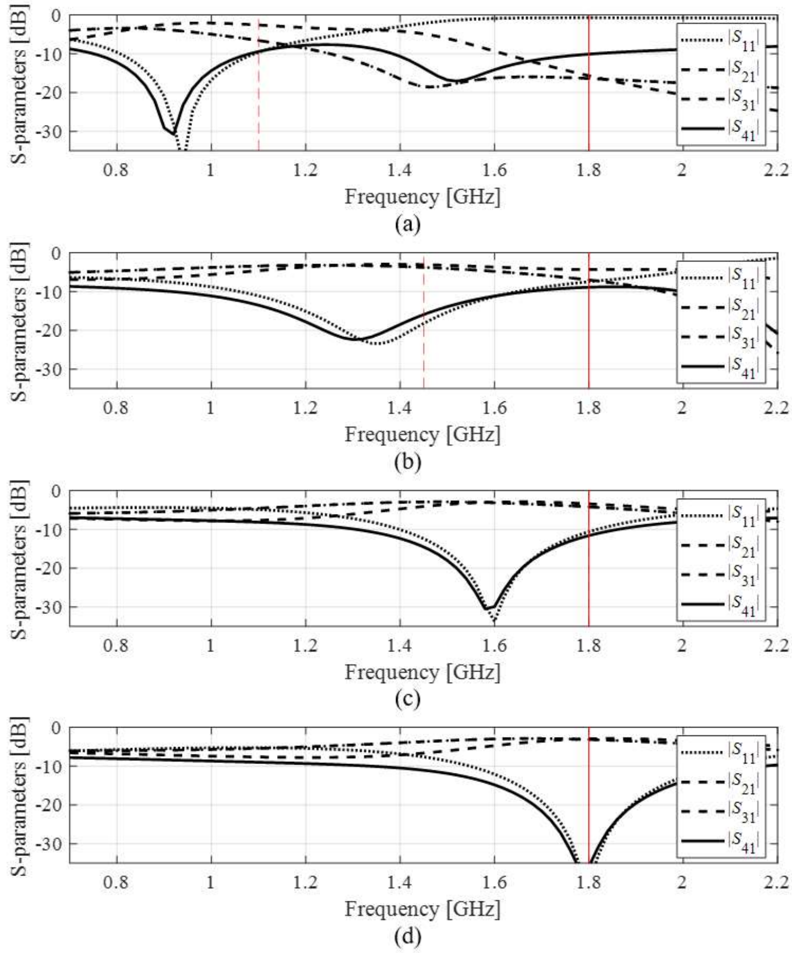

Fig. 2. Performance requirement adjustment concept explained using a microwave coupler (the initial design and the target, are as in Fig. 1): (a) target frequency moved towards the operating frequency at the initial design to ensure attainability of the current specifications (dashed line), (b) current design and specifications in the middle of the optimization run, (c) final stage: the target frequency converged to its original value, (d) final design optimized w.r.t. the original requirements.

The cost issue is particularly important from the perspective of practical utility of the optimization procedure. In this paper, the aim is to incorporate the specification adjustment procedure into gradient-based procedures, specifically, the trust-region framework briefly outlined in Section 2.3. Therein, the primary tool employed to render the candidate designs is the first-order (linear) expansion model of the circuit frequency characteristics. It is constructed using the Jacobian matrix, which needs to be estimated before each iteration of the trust-region algorithm as a part of its operation. Consequently, it is available at no extra cost.

For the purpose of subsequent considerations, we will denote the Jacobian matrix, representing the gradients of all relevant system outputs at the design $\boldsymbol{x}$, as $\boldsymbol{J}(\boldsymbol{x})$. The

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optimization algorithm is assumed to be iterative and to generate a series $\boldsymbol{x}^{(i)}$, $i = 0, 1, \ldots$, which are approximations of the optimum $\boldsymbol{x}^*$ of (1). The design $\boldsymbol{x}^{(0)}$ stands for the starting point. Let

$$L^{(i)}(\boldsymbol{x}) = \boldsymbol{S}(\boldsymbol{x}^{(i)}) + \boldsymbol{J}(\boldsymbol{x}^{(i)}) \cdot (\boldsymbol{x} - \boldsymbol{x}^{(i)}) \tag{3}$$

be the first-order model of $\boldsymbol{S}(\boldsymbol{x})$ at the design $\boldsymbol{x}^{(i)}$. We consider an optimization sub-problem

$$\boldsymbol{x}^{tmp} = \arg \min_{\|\boldsymbol{x}-\boldsymbol{x}^{(i)}\| \leq D} U(L^{(i)}(\boldsymbol{x}), \boldsymbol{F}) \tag{4}$$

where D is a search radius. The value of D is not critical, and will be set to unity in the numerical experiments of Section 3.

We use the following factors to adjust the design specifications in the course of the optimization process:

- The improvement factor F_r defined as

$$F_r = \left| U(L^{(i)}(\boldsymbol{x}^{tmp}), \boldsymbol{F}) - U(L^{(i)}(\boldsymbol{x}^{(i)}), \boldsymbol{F}) \right| \tag{5}$$

- The distance between the actual operating frequencies of the circuit at $\boldsymbol{x}^{(i)}$, denoted as $\boldsymbol{F}_c = [f_{c.1} \ldots f_{c.N}]^T$, and the target frequencies $\boldsymbol{F} = [f_1 \ldots f_N]^T$, defined as

$$D_c = \| \boldsymbol{F}_c - \boldsymbol{F} \| \tag{6}$$

Herewith, F_r is used to evaluate the capability to improve the design when using $\boldsymbol{x}^{(i)}$ as the starting point. D_c is employed to ensure that the current (re-adjusted) performance requirement are sufficiently close to the actual operating frequencies of the circuit, also at $\boldsymbol{x}^{(i)}$. Furthermore, the two acceptance thresholds are defined, $F_{r.\min}$ and $D_{c.\max}$, and used to establish the conditions for performance requirement relocation. These are:

- $F_r < F_{r.\min}$, which indicates that the current design is unlikely to be improved when starting from $\boldsymbol{x}^{(i)}$, or
- $D_c > D_{c.\max}$, which indicates that the operating frequencies at $\boldsymbol{x}^{(i)}$ are too far away from the current targets.

Satisfaction of either of these conditions means that the current requirements may be too stringent, i.e., unlikely to be met through local search from $\boldsymbol{x}^{(i)}$. Consequently, a relocation is necessary. The specific value of the aforementioned thresholds should take into account the shape of the system characteristics. A simple procedure for establishing both $F_{r.\min}$ and $D_{c.\max}$ is as follows:

1. Adjust $D_{c.\max}$ to approximately half of the system bandwidth(s) (frequency-wise) at the starting point $\boldsymbol{x}^{(0)}$. With this value, satisfaction of the condition $D_c < D_{c.\max}$ corresponds to the target frequency (or frequencies) being allocated on the slopes of the frequency characteristics near the respective operating bandwidths;
2. Adjust the target operating frequencies to ensure $D_c = D_{c.\max}$;
3. Find $\boldsymbol{x}^{tmp}$ as in (4) using $D = 1$;
4. Set $F_{r.\min} = F_r$ with F_r computed using $\boldsymbol{x}^{tmp}$ obtained in Step 3.

The above procedure allows for setting up $F_{r.\min}$ so that it accounts for a typical objective function improvement under the assumption that the performance requirements have been altered to ensure $D_c < D_{c.\max}$. With this setup, the relocated specifications are attainable from the current design using local search.

For the purpose of subsequent considerations, the relocated target frequencies will be denoted as $\boldsymbol{F}_{current}(a) = [f_{current.1}(a) \ldots f_{current.N}(a)]^T$. Here, a is a scalar (scaling) parameter, $0 \leq a \leq 1$. The entries of the vector $\boldsymbol{F}_{current}$ are computed as

$$f_{current.k}(a) = (1-a)f_{c.k} + af_k \quad \text{for} \quad k = 1, \ldots, N \tag{7}$$

where $f_{c.k}$ are the components of $\boldsymbol{F}_c = [f_{c.1} \ldots f_{c.N}]^T$ (the vector of the operating frequencies at $\boldsymbol{x}^{(i)}$). The key factor is an appropriate determination of a. It is set to be the maximum number within the interval [0, 1], such that both $F_r \geq F_{r.\min}$ and $D_c \leq D_{c.\max}$ at $\boldsymbol{x}^{tmp}$ obtained as

$$\boldsymbol{x}^{tmp} = \arg \min_{\|\boldsymbol{x}-\boldsymbol{x}^{(i)}\| \leq 1} U(L^{(i)}(\boldsymbol{x}), \boldsymbol{F}_{current}(a)) \tag{8}$$

In practice, a is found by solving a separate optimization process, where it is lowered to make sure that both conditions, $F_r \geq F_{r.\min}$ and $D_c \leq D_{c.\max}$, are satisfied for $\boldsymbol{x}^{tmp}$ produced by (8). The latter is an indication that the performance requirements have been relaxed to the extent that makes them attainable from the current design $\boldsymbol{x}^{(i)}$.

It can be observed that $f_{current.k}$ is a convex combination of $f_{c.k}$ and the original target frequency f_k. Small values of a correspond to relaxed requirements. Upon convergence of the optimization algorithm, the conditions $F_r \geq F_{r.\min}$ and $D_c \leq D_{c.\max}$ will hold for $a = 1$ (i.e., the original requirements). This is of course under the assumptions that the original specifications are attainable. If this is not the case, the optimization process will converge upon approaching the targets as closely as possible.

The above procedure describes the adaptation of the design requirements for one iteration of the optimization process. It is executed before each iteration, i.e., at all vectors $\boldsymbol{x}^{(i)}$, $i = 0, 1, \ldots$ As a result, the target frequencies are being continuously altered throughout the optimization run. An important feature of this technique is that it does not incur additional computational costs because the Jacobian matrix required to construct the linear model (cf. (3)) is already available. More specifically, it is generated as a part of the normal operation of the optimization algorithm.

2.3 Reference Algorithm: Trust-Region Gradient Search

The adaptive adjustment of performance requirements can be combined with various optimization algorithms. For the purpose of validation, it is incorporated into the trust-region (TR) framework [27], briefly recalled in the remaining part of this section. We aim at solving the problem (1). Toward this end, the TR procedure yields a series of vectors $\boldsymbol{x}^{(i)}$, $i = 0, 1, \ldots$, being approximations to $\boldsymbol{x}^*$. These are generated as

$$\boldsymbol{x}^{(i+1)} = \arg \min_{\|\boldsymbol{x}-\boldsymbol{x}^{(i)}\| \leq d^{(i)}} U(L^{(i)}(\boldsymbol{x}), \boldsymbol{F}_{current}) \tag{9}$$

In (9), the linear model $L^{(i)}$ is constructed using (3), whereas $\boldsymbol{F}_{current}$ stands for the current performance specifications (target operating frequencies). The TR radius $d^{(i)}$ is updated at each iteration based on the gain ratio r, defined as

$$r = \frac{U(\boldsymbol{S}(\boldsymbol{x}^{(i+1)}), \boldsymbol{F}_{current}) - U(\boldsymbol{S}(\boldsymbol{x}^{(i)}), \boldsymbol{F}_{current})}{U(L^{(i)}(\boldsymbol{x}^{(i+1)}), \boldsymbol{F}_{current}) - U(L^{(i)}(\boldsymbol{x}^{(i)}), \boldsymbol{F}_{current})} \tag{10}$$

In particular, if $r > 0$, the candidate design $\boldsymbol{x}^{(i+1)}$ is accepted. In addition, if r is sufficiently large (e.g., $r > 0.75$), $d^{(i+1)}$ is set to $2d^{(i)}$; otherwise, if r is too low (e.g., $r < 0.25$), $d^{(i+1)}$ is diminished to $d^{(i)}/3$. If no objective function improvement is observed, i.e., $r < 0$, the candidate design is rejected, and the iteration is repeated with a reduced trust region radius.

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2.4 Optimization Framework

Figure 3 shows the pseudocode of the optimization procedure combining the trust-region algorithm and the procedure for adaptive adjustment of performance requirements discussed in Sections 2.1 and 2.2. The termination condition is convergence in argument $||\boldsymbol{x}^{(i+1)} - \boldsymbol{x}^{(i)}|| < \varepsilon$, or reduction of the trust region radius below the same threshold, i.e., $d^{(i)} < \varepsilon$. In our numerical experiments (cf. Section 3), we set $\varepsilon = 10^{-3}$. More details about the TR algorithms can be found in the literature (e.g., [27]).

3 Verification Examples

This section demonstrates the operation and performance of the procedure for adaptive adjustment of performance specifications introduced in Section 2. We consider two test cases, a miniaturized branch-line coupler, and a dual-band power divider. In both cases, poor-quality initial designs are employed to emphasize the benefits of the proposed adjustment strategy, and to corroborate the efficacy of the method under challenging design scenarios.

<u>Input arguments</u>:

1. $\boldsymbol{x}^{(0)}$ – initial design;
2. $\boldsymbol{F}$ – target operating frequency/band vector;
3. U_R – primary objective function encoding design goals;

<u>Algorithm operating flow</u>:

1. Set the iteration index $i = 0$;
2. Find the scalar a to determine current specification vector $\boldsymbol{F}_{currentr}(a)$ (cf. Section 2.2);
3. Perform TR iteration (9) to find the new iteration point $\boldsymbol{x}^{(i+1)}$ according to $\boldsymbol{F}_{current}$;
4. Update the TR radius $d^{(i)}$;
5. If the termination condition is satisfied, go to 7;
6. **If** $U(\boldsymbol{R}(\boldsymbol{x}^{(i+1)}),\boldsymbol{F}_{current}) < U(\boldsymbol{R}(\boldsymbol{x}^{(i)}),\boldsymbol{F}_{current})$
   Set $i = i + 1$;
   Go to 2;
   else
   Go to 3;
   end
7. END

Fig. 3. Operating flow of the trust-region optimization algorithm incorporating adaptive adjustment of performance specifications.

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3.1 Compact Branch-Line Coupler

Consider a compact branch-line coupler (BLC) [28] shown in Fig. 4. The circuit is implemented on RO4003 substrate (ε_r = 3.5, h = 0.76 mm) and described by ten independent parameters $\boldsymbol{x} = [g\ l_{1r}\ l_a\ l_b\ w_1\ w_{2r}\ w_{3r}\ w_{4r}\ w_a\ w_b]^T$; we also have $L = 2dL + L_s$, $L_s = 4w_1 + 4g + s + l_a + l_b$, $W = 2dL + W_s$, $W_s = 4w_1 + 4g + s + 2w_a$, $l_1 = l_b l_{1r}$, $w_2 = w_a w_{2r}$, $w_3 = w_{3r} w_a$, and $w_4 = w_{4r} w_a$. The computational model is evaluated using frequency-domain solver of CST Microwave Studio (~60,000 mesh cells, simulation time 5 min).

The design objective is to make the circuit operate at the centre frequency of f_0 = 1 GHz. The matching $|S_{11}|$, and isolation $|S_{41}|$ should be minimized, and the circuit should provide equal power split, i.e., $|S_{21}| = |S_{31}|$, all at f_0. We use the objective function (2). The initial design and the final design rendered using the technique proposed in this work are shown in Fig. 5 using grey and black lines, respectively. Note that the operating frequency at $\boldsymbol{x}^{(0)}$ is approximately 2.2 GHz. Consequently, re-designing the structure to 1 GHz using local procedures is virtually impossible. In particular, the conventional TR routine fails to identify a satisfactory solution. In contrast to that, the approach introduced in this paper works yields the design $\boldsymbol{x}^*$ = [1.00 0.81 6.91 11.94 0.75 0.99 0.89 0.65 4.05 0.53]^T, which satisfies the original requirements (cf. Fig. 5). Figure 6 shows the evolution of the performance specifications (target operating frequency). It can be observed that the requirements had to be significantly altered at the early stages of the optimization process, then gradually adjusted back to the original value of 1 GHz. Figure 7 shows selected intermediate designs obtained in the course of the optimization run.

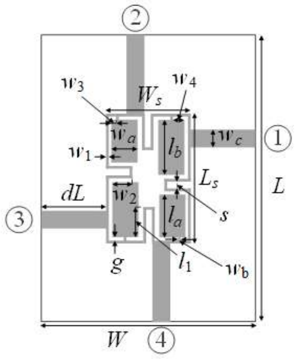

Fig. 4. Miniaturized branch-line coupler (BLC) [28]. The circuit ports marked using numbered circles.

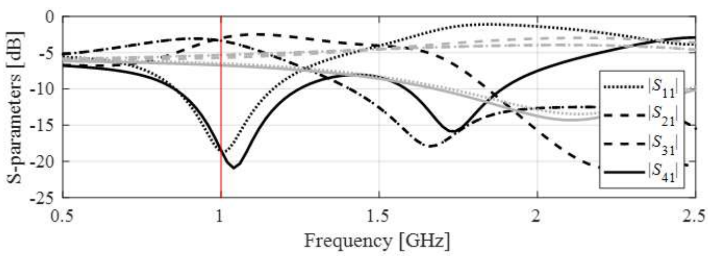

Fig. 5. Branch-line coupler: frequency characteristics of the circuit at the initial (grey) and the final design (black) obtained using the proposed procedure for adaptive adjustment of performance specifications. The target operating frequency is marked using the vertical line.

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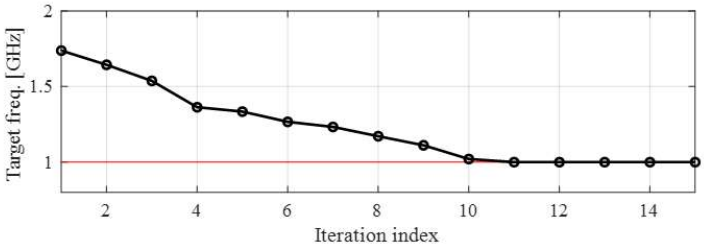

Fig. 6. Branch-line coupler: evolution of the target operating frequency versus iteration index of the optimization algorithm. Original target frequency marked using a horizontal line.

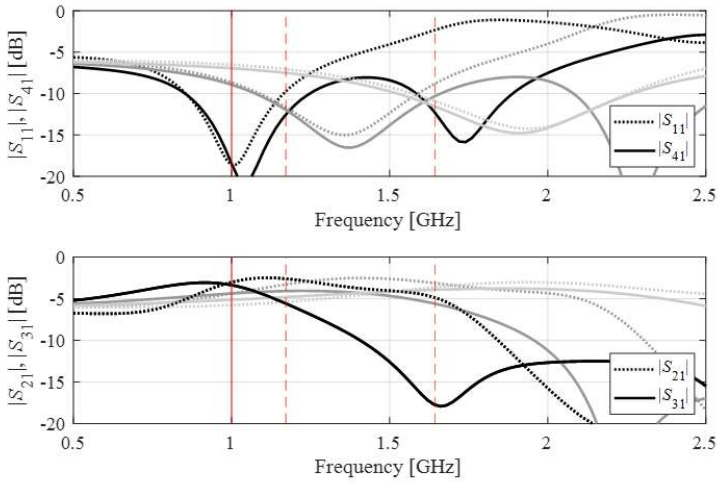

Fig. 7. Branch-line coupler: frequency characteristics of the circuit at three intermediate designs, marked using the light-grey, dark-grey, and black colors (optimum), along with the corresponding target frequencies. For the sake of clarity, the matching/isolation characteristics are shown separate from the transmission characteristics.

3.2 Dual-Band Power Divider

The second verification example is a dual-band power divider [29], shown in Fig. 8, implemented on AD250 substrate ($\varepsilon_r = 2.5$, $h = 0.81$ mm). The design parameters are $\boldsymbol{x} = [l_1\ l_2\ l_3\ l_4\ l_5\ s\ w_2]^T$; $w_1 = 2.2$ and $g = 1$ are fixed (all dimensions in mm). The computational model is evaluated in the time-domain solver of CST Microwave Studio (~200,000 mesh cells, simulation time 2 min).

In this case, the circuit parameters are optimized to make the circuit operate at $f_1 = 2.4$ GHz and $f_2 = 3.8$ GHz. More specifically, the input matching $|S_{11}|$, and the output matching $|S_{22}|$, $|S_{33}|$, as well as isolation $|S_{23}|$ are to be simultaneously minimized at both f_1 and f_2. Note that equal power split is ensured by the symmetry of the structure; therefore, it does not have to be explicitly handled within the objective function. Figure 9 shows the initial and the optimized designs (top and bottom panels, respectively). It can be observed that the operating frequencies at the initial design are severely misaligned with the targets. Conventional TR algorithm fails to identify

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the optimum design. On the other hand, TR procedure combined with adaptive adjustment of performance specifications produces the design $\boldsymbol{x}^* = [26.86\ 2.18\ 21.92\ 2.00\ 3.82\ 0.50\ 4.56]^T$, which satisfied the design requirements (cf. Fig. 9). Figure 10 shows the evolution of the target operating frequencies, which is consistent with what was observed for the first example. Some of the intermediate designs produced in the course of the optimization run along with the corresponding target operating frequencies are shown in Fig. 11.

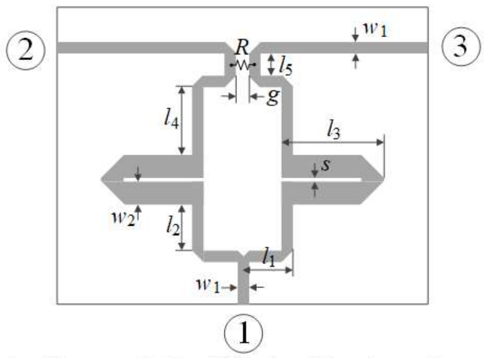

Fig. 8. Dual-band equal split power divider [29]: circuit topology; the ports marked using numbers in circles. The lumped resistor denoted as R.

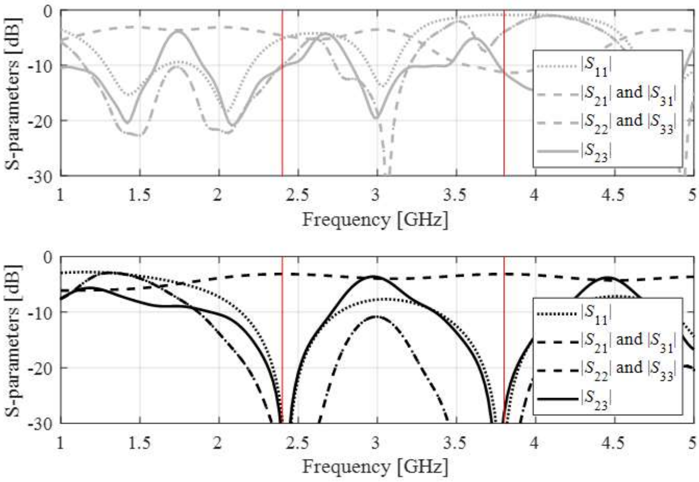

Fig. 9. Dual-band power divider: frequency characteristics of the circuit at the initial (top) and the final design (bottom) obtained using the proposed procedure for adaptive adjustment of performance specifications. The target operating frequencies are marked using the vertical lines.

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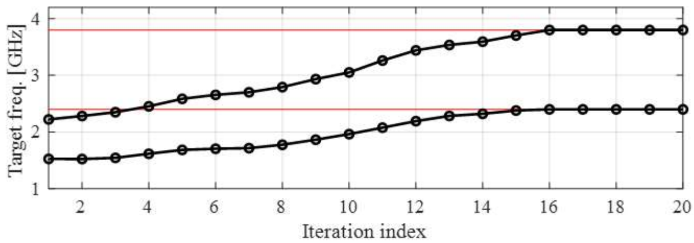

Fig. 10. Dual-band power divider: evolution of the target operating frequencies versus iteration index of the optimization algorithm. Original target frequencies marked using horizontal lines.

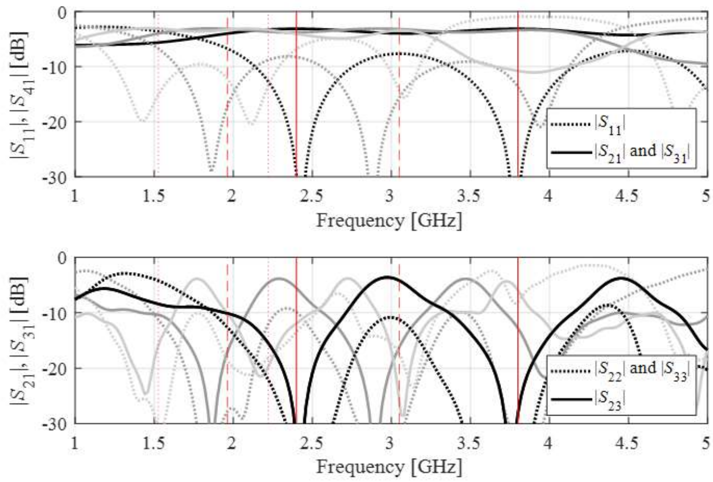

Fig. 11. Dual-band power divider: frequency characteristics of the circuit at the three intermediate designs, marked using the light-gray, dark-gray, and black colors (optimum), along with the corresponding target frequencies. For clarity, the input matching and transmission responses, as well as the output matching and isolation responses are shown in separate panels.

4 Conclusions

This paper proposed a procedure for adaptive adjustment of performance requirements as a tool for improving the reliability of simulation-based design closure of compact microwave circuits. The procedure is intended to work with local iterative search routines (in particular, the gradient-based ones). Its goal is to facilitate identification of the optimum design under demanding scenarios, especially in terms of the lack of quality starting points. Toward this end, the target operating frequencies are automatically relocated before each iteration of the optimization process to become attainable using local search. The necessary adjustment is quantified using rigorous criteria involving the analysis of the system response at the current design. Our methodology has been validated through the optimization of two microstrip circuits, a miniaturized branch-line coupler, and a dual-band power divider. In both cases, satisfactory designs were identified despite of poor starting points. The fundamental advantage of the adaptive adjustment of performance requirements is that it considerably reduces the sensitivity

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of the optimization algorithm to the initial design quality. Among others, this feature enables dimension scaling of microwave components within broad ranges of operating conditions using local procedures, but also eliminates the need for global optimization routines, normally required to handle more challenging design closure tasks. The future work will include generalization of the presented approach for other types of operating conditions (i.e., not necessarily operating frequencies), as well as its application to other classes of high-frequency structures (e.g., antenna systems).

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References

1. Feng, F., Zhang, C., Na, W., Zhang, J., Zhang, W., Zhang, Q.: Adaptive feature zero assisted surrogate-based EM optimization for microwave filter design. IEEE Microwave Wireless Comp. Lett., **29**(1), 2–4 (2019)
2. Bao, C., Wang, X., Ma, Z., Chen, C.P., Lu, G.: An optimization algorithm in ultrawideband bandpass Wilkinson power divider for controllable equal-ripple level. IEEE Microwave Wireless Comp. Lett., **30**(9), 861–864 (2020)
3. Abdolrazzaghi, M., Daneshmand, M.: A phase-noise reduced microwave oscillator sensor with enhanced limit of detection using active filter: IEEE Microwave Wireless Comp. Lett., **28**(9), 837–839 (2018)
4. Wang, Y., Zhang, J., Peng, F., Wu. S.: A glasses frame antenna for the applications in internet of things. IEEE Internet of Things J., **6**(5), 8911–8918 (2019)
5. Ali, M.M.M., Sebak, A.: Compact printed ridge gap waveguide crossover for future 5G wireless communication system. IEEE Microwave Wireless Comp. Lett., **28**(7), 549–551 (2018)
6. Kim, M., Kim, S.: Design and fabrication of 77-GHz radar absorbing materials using frequency-selective surfaces for autonomous vehicles application. IEEE Microwave Wireless Comp. Lett., **29**(12), 779–782 (2019)
7. Gómez-García, R., Yang, L., Muñoz-Ferreras, J., Psychogiou, D.: Single/multi-band coupled-multi-line filtering section and its application to RF diplexers, bandpass/bandstop filters, and filtering couplers. IEEE Trans. Microwave Theory Techn., **67**(10), 3959-3972 (2019)
8. Tan, X., Sun, J., Lin, F.: A compact frequency-reconfigurable rat-race coupler. IEEE Microwave Wireless Comp. Lett., **30**(7), 665–668 (2020)
9. Chen, S., Guo, M., Xu, K., Zhao, P., Dong, L., Wang, G.: A frequency synthesizer based microwave permittivity sensor using CMRC structure. IEEE Access, **6**, 8556–8563 (2018)
10. Qin, W., Xue, Q.: Elliptic response bandpass filter based on complementary CMRC. Electr. Lett., **49**(15), 945–947 (2013)
11. Sen, S., Moyra, T.: Compact microstrip low-pass filtering power divider with wide harmonic suppression. IET Microwaves, Ant. Propag., **13**(12), 2026–2031 (2019)

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To cite this paper please use the final published version:
DOI: 10.1007/978-3-030-77970-2_15

12. Sabbagh, M. A. E., Bakr, M. H., Bandler, J. W.: Adjoint higher order sensitivities for fast full-wave optimization of microwave filters. IEEE Trans. Microwave Theory Techn., **54**(8), 3339–3351 (2006)
13. Pietrenko-Dabrowska, A., Koziel, S., Expedited antenna optimization with numerical derivatives and gradient change tracking. Eng. Comp., **37**(4), 1179–1193 (2019)
14. Zhang, Z., Cheng, Q. S., Chen, H., Jiang, F.: An efficient hybrid sampling method for neural network-based microwave component modeling and optimization. IEEE Microwave Wireless Comp. Lett., **30**(7), 625–628 (2020)
15. Van Nechel, E., Ferranti, F., Rolain, Y., Lataire, J.: Model-driven design of microwave filters based on scalable circuit models. IEEE Trans. Microwave Theory Techn., **66**(10), 4390–4396 (2018)
16. Li, Y., Xiao, S., Rotaru, M., Sykulski, J. K.: A dual kriging approach with improved points selection algorithm for memory efficient surrogate optimization in electromagnetics. IEEE Trans. Magn., **52**(3), 1–4, Art 7000504 (2016)
17. Cai, J., King, J., Yu, C., Liu, J., Sun, L.: Support vector regression-based behavioral modeling technique for RF power transistors. IEEE Microwave and Wireless Comp. Lett., **28**(5), 428–430 (2018)
18. Petrocchi, A., Kaintura, A., Avolio, G., Spina, D., Dhaene, T., Raffo, A., Schreurs, D.M.P.-P.: Measurement uncertainty propagation in transistor model parameters via polynomial chaos expansion. IEEE Microwave Wireless Comp. Lett., **27**(6) 572–574 (2017)
19. Feng, F., Na, W., Liu, W., Yan, S., Zhu, L., Ma, J., Zhang, Q.J.: Multifeature-assisted neuro-transfer function surrogate-based EM optimization exploiting trust-region algorithms for microwave filter design. IEEE Trans. Microwave Theory Techn., **68**(2), 531–542 (2020)
20. Li, S., Fan, X., Laforge, P. D., Cheng, Q. S.: Surrogate model-based space mapping in postfabrication bandpass filters' tuning. IEEE Trans. Microwave Theory Tech., **68**(6), 2172–2182 (2020)
21. Koziel, S.: Shape-preserving response prediction for microwave design optimization. IEEE Trans. Microwave Theory and Tech., **58**(11), 2829–2837 (2010)
22. Pietrenko-Dabrowska, A., Koziel, S.: Surrogate modeling of impedance matching transformers by means of variable-fidelity EM simulations and nested co-kriging. Int. J. RF and Microwave CAE, **30**(8), e22268 (2020)
23. Xiao, L., Shao, W., Ding, X., Wang, B., Joines, W. T., Liu, Q. H.: Parametric modeling of microwave components based on semi-supervised learning. IEEE Access, **7**, 35890–35897 (2019)
24. Toktas, A., Ustun, D., Tekbas, M.: Multi-objective design of multi-layer radar absorber using surrogate-based optimization. IEEE Trans. Microwave Theory Techn., **67**(8), 3318–3329 (2019)
25. Lim, D.K., Yi, K.P., Jung, S.Y., Jung, H.K., Ro, J.S.: Optimal design of an interior permanent magnet synchronous motor by using a new surrogate-assisted multi-objective optimization. IEEE Trans. Magn., **51**(11), 8207504 (2015)
26. Luo, X., Yang, B., Qian, H. J.: Adaptive synthesis for resonator-coupled filters based on particle swarm optimization. IEEE Trans. Microwave Theory Techn., **67**(2), 712–725 (2019)
27. Conn, A.R., Gould, N.I.M., Toint, P.L.: Trust Region Methods, MPS-SIAM Series on Optimization (2000)
28. Tseng, C., Chang, C.: A rigorous design methodology for compact planar branch-line and rat-race couplers with asymmetrical T-structures. IEEE Trans. Microwave Theory Techn., **60**(7), 2085–2092 (20120
29. Lin, Z., Chu, Q.X.: A novel approach to the design of dual-band power divider with variable power dividing ratio based on coupled-lines. Prog. Electromagn. Res., **103**, 271–284 (2010)

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