

Review

# Optimization-Based High-Frequency Circuit Miniaturization through Implicit and Explicit Constraint Handling: Recent Advances

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**Abstract:** Miniaturization trends in high-frequency electronics have led to accommodation challenges in the integration of the corresponding components. Size reduction thereof has become a practical necessity. At the same time, the increasing performance demands imposed on electronic systems remain in conflict with component miniaturization. On the practical side, the challenges related to handling design constraints are aggravated by the high cost of system evaluation, normally requiring full-wave electromagnetic (EM) analysis. Some of these issues can be alleviated by implicit constraint handling using the penalty function approach. Yet, its performance depends on the arrangement of the penalty factors, necessitating a costly trial-and-error procedure to identify their optimum setup. A workaround is offered by the recently proposed algorithms with automatic adaptation of the penalty factors using different adjustment schemes. However, these intricate strategies require a continuous problem-dependent adaptation of the penalty function throughout the entire optimization process. Alternative methodologies have been proposed by taking an explicit approach to handle the inequality constraints, along with correction-based control over equality conditions, the combination of which proves to be demonstrably competitive for some miniaturization tasks. Nevertheless, optimization-based miniaturization, whether using implicit or explicit constraint handling, remains a computationally expensive task. A reliable way of reducing the aforementioned costs is the incorporation of multi-resolution EM fidelity models into the miniaturization procedure. Therein, the principal operation is based on the simultaneous monitoring of factors such as quality of the constraint satisfaction, as well as algorithm convergence status. This paper provides an overview of the abovementioned size-reduction algorithms, in which theoretical considerations are illustrated using a number of antenna and microwave circuit case studies.

**Keywords:** miniaturization; EM-driven design; constrained optimization; implicit constraint handling; explicit constraint handling; penalty function approach; variable-fidelity models

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## 1. Introduction

The emerging system integration technologies, resulting from the miniaturization trends in contemporary electronic systems, have led to size restrictions on the comprising components, in applications such as integrated system-on-chip (SoP) wireless communication modules, internet of things (IoT), or integrated passive components [1] in RF ICs. Some of the essential passive components occupying considerable space in these systems include microstrip filters [2], capacitors/inductors [3], couplers/dividers [4], and antenna arrays [5]. Various alterations in conventional structures have been proposed to minimize their footprints. These are typically based on the techniques incorporating electromagnetic wave theory along with additional degrees of freedom provided by topological modifications. Some of the popular methods include the use of metamaterial-based

(MTM) composite left/right-handed transmission line (CLRH-TL) structures [6–8] the employment of artificial transmission lines (ATL) [9,10] the incorporation of half-mode evanescent-mode cavity resonators [11,12] or the introduction of differential bridged-T coils [13,14]. The scope of this work is an optimization-based size reduction in high-frequency devices and not topology adjustment aimed at footprint reduction. Notwithstanding, the frameworks discussed hereinafter may be applied for parameter tuning of antenna and microwave structures designed with the use of the aforementioned (as well as other) topological modifications.

Although the abovementioned techniques ensure reliability in producing reduced-size structures, they contribute to the design complexity both at the conceptual development stage and the subsequent handling of additional geometry parameters. Identification of the optimal design in the sense of resolving the conflict between miniaturization and satisfaction of the design constraints imposed on electrical characteristics can be dealt with through local parameter tuning [15–27] (in particular, through genuine multi-objective design [28–30]), or global search methods [31–33]. Still, there are only a few works on optimization-related miniaturization of antenna and microwave structures: some examples can be found in [34–38]. Nevertheless, in these approaches, an optimization algorithm of choice (e.g., firefly optimizer [34] or genetic algorithm [35]) is employed in the last stage of the design process for parameter tuning of geometry parameters aimed at obtaining the required electrical properties of the component under design rather than size reduction. Furthermore, no constraint on the component size is imposed in the optimization procedure, so, in some cases, the footprint of the optimized structure may be actually larger than that of the initial non-optimal design. Regardless of the specific optimization technique, handling of the design constraints tends to be impeded by algorithmic complexity as well as costly and repetitive system evaluations involved in the process. The penalty function approach [39] offers the alleviation of these issues by providing an implicit way of controlling the constraints. Nevertheless, the performance of this approach is strongly based upon the setup of the penalty factors, conventionally adjusted through laborious guesswork and repeated trials. The recently proposed automatic adaptation of the penalty function [40,41] attempts to mitigate this problem by eliminating the trial-and-error stage. Therein, the penalty factors are continuously adjusted based on a concept of sufficient constraint violation improvement for single and multiple design constraints. The automated procedure exercises precise control over the design constraints thereby allowing to obtain competitive miniaturization rates. Yet, another adaptation scheme has been reported in [42], where a continuous observation of a properly quantified combination of the convergence status, and the constraint violation levels has been carried out throughout the entire optimization process. The resulting miniaturization rates are comparable to those obtained using the optimum arrangement of the penalty factors. At the same time, a precise control over the design constraints was achieved.

The abovementioned strategies have been successful in resolving the conflict between miniaturized size and satisfactory system performance levels. However, algorithmic complexities arise due to the multiplicity of the adjustment rules that require continuous monitoring of the optimization procedure. Moreover, the entire adjustment procedure is problem-dependent and needs to be readjusted accordingly. A workaround has been proposed by implementing an explicit method of handling constraints [43,44] using the trust-region (TR) framework as the optimization engine. Therein, the TR search radius is adjusted based on a cheap linear approximation of the design constraints rather than based on the quality of the objective function. This results in a virtual elimination of the challenge of the problem-dependent penalty function adjustment as compared to the implicit approach.

An alternative methodology has been developed as well, based on a separate treatment of equality and inequality constraints [45]. The specific geometry of the feasible regions corresponding to equality constraints (i.e., being thin sets in a set-theory sense) calls

for a special treatment to control the design quality in a satisfactory manner. Consequently, in the technique of [45], the equality constraints are treated using a correction-based scheme launched before each iteration of the core algorithm, whereas the inequality constraints are dealt with implicitly using the previously mentioned penalty function approach.

Regardless of the constraint handling approach (in particular, implicit or explicit), optimization-based miniaturization tends to remain a highly expensive task in terms of both computational time and resources. The employment of variable-fidelity EM models [46] has proved to be efficient in reducing the aforementioned costs. The operation of the scheme considered in [46] exploits meticulously defined performance indicators including the quality of the constraint satisfaction, as well as the convergence status of the algorithm. This allows for the precise control of the constraints as well as obtaining satisfactory miniaturization rates at a reduced cost.

This paper provides a review of the aforementioned recent advancements in optimization-based miniaturization of high-frequency components. In particular, we discuss both the implicit and explicit approaches, along with the relevant algorithmic strategies, including acceleration methods. Our considerations are illustrated using a number of specific case studies, including both antenna and microwave passive structures. Recommendations concerning the investigated algorithms are also given. The authors believe that this work may be useful for those readers interested in EM-driven design, automation of size-reduction procedures of high-frequency systems, but also improving their computational efficiency.

## 2. Optimization-Based Size Reduction

This section recalls a formulation of the optimization-based high-frequency circuit miniaturization task. The relevant recent algorithmic developments will be discussed in subsequent sections: the adaptive penalty function approach in Section 3, explicit constraint handling in Section 4 separate treatment of equality and inequality constraints in Section 5, and multi-resolution adaptive penalty functions in Section 6.

The involved interrelationships between geometrical dimensions and the electrical and field properties of high-frequency structures make their size reduction a challenging problem. This is especially pertinent to miniaturized components, in which topological alterations have been introduced to reduce their footprint (e.g., [47–52]). Although these properties may vary to some extent depending on the nature and applications of the specific structure, they are normally evaluated using EM simulations of the corresponding structural dimensions. The latter are expressed as a vector  $\mathbf{x} = [x_1 \dots x_n]^T$ , containing  $n$  independently adjustable geometry parameters of the structure. It should be emphasized that all of the algorithmic frameworks discussed in this work are generic in the sense that they may utilize any simulation software package selected according to the designer's preference. In the presented examples, CST Microwave studio has been employed for evaluating high-frequency verification structures, yet, the considered frameworks may also employ, e.g., Ansys HFSS, Sonnet *em* or dedicated solvers.

The simulation-based high-frequency size reduction problem can be formulated as

$$\mathbf{x}^* = \arg \min_{\mathbf{x} \in X_f} A(\mathbf{x}) \quad (1)$$

where  $A(\mathbf{x})$  is the size of the structure (e.g., a footprint area for planar circuits),  $\mathbf{x}^*$  is the optimum design to be found, whereas  $X_f$  is the feasible space. The latter contains parameter vectors for which all design constraints are satisfied, which may be of inequality or equality type. Formally, the equality constraints are written as

$$S_{eq,k}(\mathbf{x}) = 0, \quad k = 1, \dots, n_{eq} \quad (2)$$

and inequality ones as



$$S_{ineq,k}(\mathbf{x}) \leq s_j, k = 1, \dots, n_{ineq} \quad (3)$$

Thus, the total number of constraints is  $n_c = n_{eq} + n_{ineq}$ . A practical issue is that the constraints, apart from the strictly geometric ones, are expensive, as their evaluation requires EM analysis. Here, are a few examples (below,  $S_{kl}(\mathbf{x}, f)$  denotes the scattering parameter of a considered device for ports  $k$  and  $l$  at the design  $\mathbf{x}$  and frequency  $f$ ):

- The reflection coefficient of the antenna should not exceed  $-10$  dB within the frequency range  $F$ , i.e.,  $|S_{11}(\mathbf{x}, f)| \leq -10$  dB for  $f \in F$  (inequality constraint);
- Axial ratio  $AR$  should not exceed  $3$  dB within the frequency range  $F$ , i.e.,  $|AR(\mathbf{x}, f)| \leq 3$  dB for  $f \in F$  (also an inequality constraint);
- Power split ratio of a coupling structure  $K_P$  should be equal to zero at the center frequency  $f_0$ , i.e.,  $K_P = |S_{31}(\mathbf{x}, f_0)| - |S_{21}(\mathbf{x}, f_0)| = 0$  dB (equality constraint)

Unfortunately, miniaturization is detrimental to the electrical and field performance of high-frequency structures [53]. Consequently, minimum-size designs are normally allocated at the feasible space boundary  $\partial X_f$  as at least one of the constraints is active at the optimum. Explicit treatment of design constraints (2)–(3) is often problematic, due to numerical issues related to the exploration of  $\partial X_f$ . An alternative is implicit handling using a penalty function approach [39]. The design task is then reformulated into

$$\mathbf{x}^* = \arg \min_{\mathbf{x}} U_p(\mathbf{x}) \quad (4)$$

where the objective function is defined as

$$U_p(\mathbf{x}) = A(\mathbf{x}) + \sum_{k=1}^{n_c} \beta_k c_k(\mathbf{x})^2 \quad (5)$$

In (5), minimization of  $A(\mathbf{x})$  is the primary objective, whereas the remaining terms are penalty factors that provide a non-zero contribution if the respective constraints are violated. The penalty function  $c_j(\mathbf{x})$  is typically defined to quantify relative violations. For example, we may define  $c_j(\mathbf{x}) = \max\{0, [S_{ineq,j}(\mathbf{x}) - s_j]/s_j\}$  for the  $j$ th inequality condition (3). Note that problem (4) is formally unconstrained, which facilitates handling of the size reduction task. On the other hand, the choice of the penalty coefficients  $\beta_j$  is instrumental in the success and reliability of solving (4), (5). As mentioned in Section 1, using too low or too high values leads to either the lack of constraint violation control or to numerical issues due to the steepness of the objective function  $U_p$  in the vicinity of the feasible region boundary. The algorithms outlined in the remaining part of this paper attempt to address this and other difficulties of EM-driven miniaturization, both in the explicit and implicit constraint handling regimes.

### 3. Adaptive Penalty Function Methods

In a conventional penalty function approach, appropriate values of the penalty coefficients are adjusted on a trial-and-error basis and kept fixed throughout the entire optimization run. As mentioned on several occasions, such a setup is far from optimal, as it leads to obtaining inferior solutions, either in terms of an insufficient constraint control, or degraded values of the primary objective. In contrast, the adaptive penalty function methods monitor the levels of current constraint violations during the optimization run and adjust the values of the penalty coefficients accordingly. This allows for improving the reliability of the optimization process, as well as the precise control of constraints violation. This section outlines two versions of the algorithms exploiting an adaptive adjustment of penalty factors. In the first one, the penalty factor values are adjusted based on an appropriately quantified combination of the algorithm convergence status and the constraint violation level [42]. Whereas the second technique takes into account the improvement of constraint violation between consecutive algorithm iterations as well as solution feasibility [41].

### 3.1. Adaptive Scheme I. Convergence Status and Constraint Violation Levels

The algorithm with automated adjustment of the penalty factors [42] adheres to the following assumptions: (i) the optimization process is initiated with low values of the penalty terms and increased tolerance thresholds for constraint violations to facilitate exploration of the design space, (ii) in the subsequent stages of the optimization run, the penalty coefficients are gradually increased, (iii) near convergence, the constraint violation tolerances are made more rigid to ensure the target levels of the constraint violations.

Overall, throughout the algorithm run, adaptive adjustment of both constraint violation tolerance thresholds and the penalty coefficient values is carried out, which are briefly explained in Figures 1 and 2, respectively. A detailed exposition of the adaptive penalty factors adjustment, along with the discussion of the suggested setup of the algorithm control parameters can be found in [42].

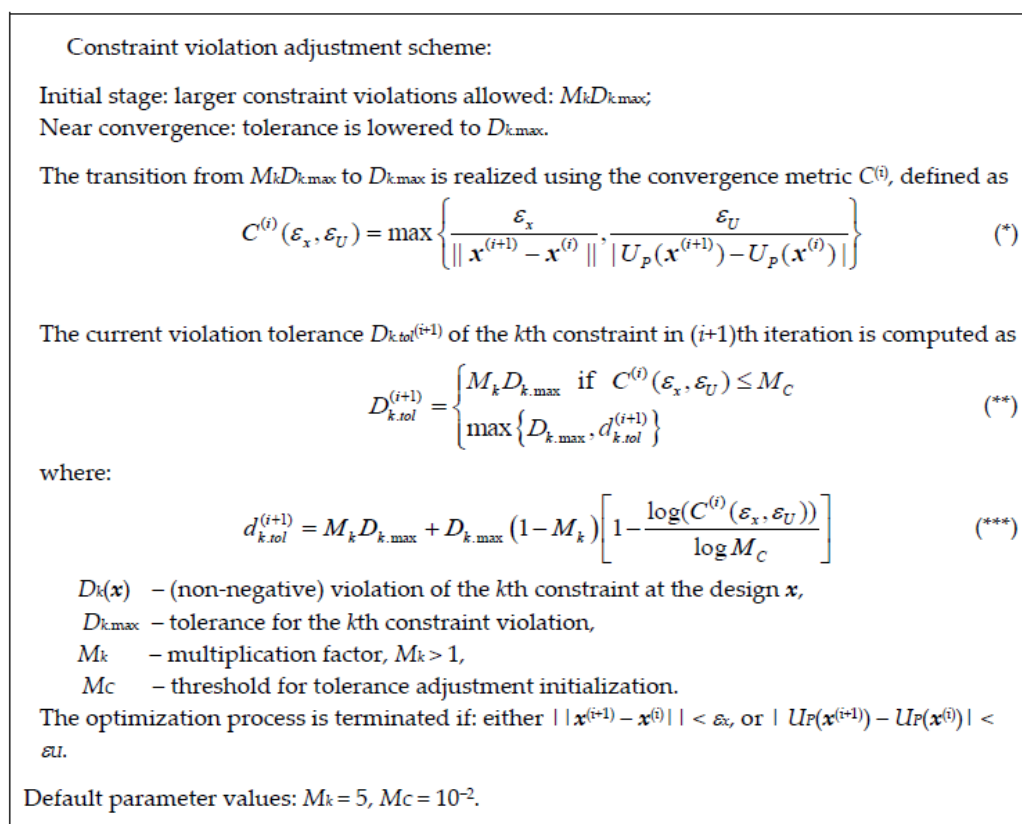
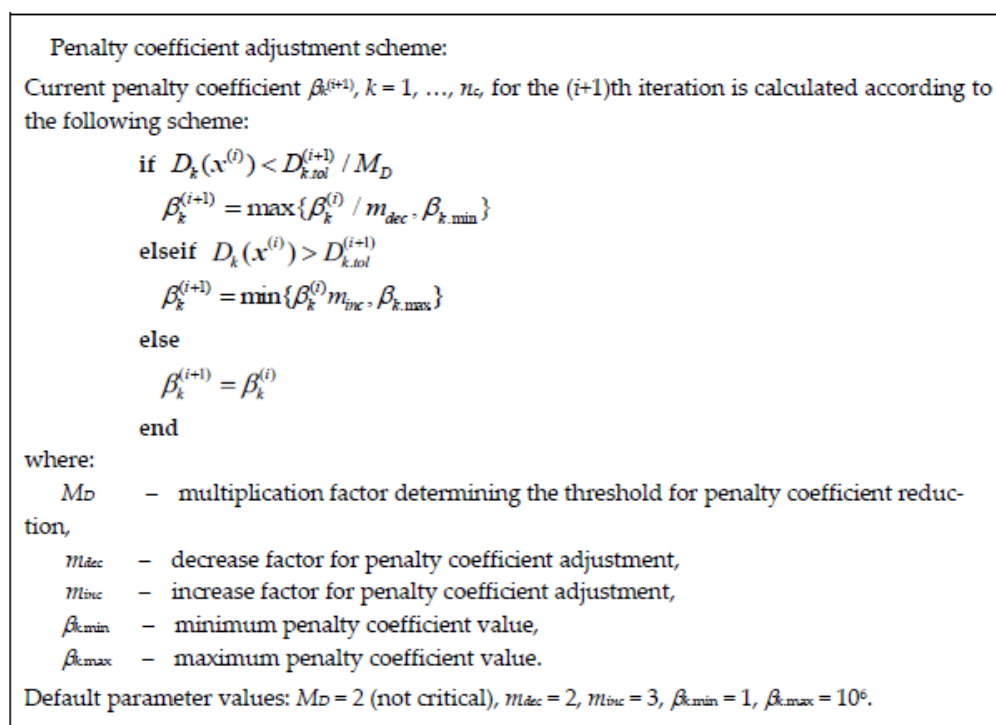


Figure 1. Adaptive constraint violation adjustment according to the methodology of [42].



**Figure 2.** Penalty coefficient setup according to the methodology of [42].

### 3.1.1. Trust-Region Gradient-Based Algorithm

The approach of [42], as well as all other optimization procedures outlined in this paper, are embedded in the trust-region (TR) framework [54], which, for the convenience of the reader, is briefly outlined in this section. Let us recall that the TR algorithm yields a series of approximations  $\mathbf{x}^{(i)}$ ,  $i = 0, 1, \dots$ , to the optimum design  $\mathbf{x}^*$  of (1), where  $\mathbf{x}^{(i)}$  is found as

$$\mathbf{x}^{(i+1)} = \arg \min_{\mathbf{x}; \|\mathbf{x} - \mathbf{x}^{(i)}\| \leq d^{(i)}} U_L^{(i)}(\mathbf{x}) \quad (6)$$

Here,  $U_L^{(i)}$  is the local (usually linear) model of the objective function  $U_p$  at  $\mathbf{x}^{(i)}$ . The problem is subject to constraints (2) and (3), although for notational simplicity we only assume inequality constraints here. The adjustment of the trust-region size  $d^{(i)}$  is addressed below.

Denoting by  $\mathbf{r}(\mathbf{x})$  the aggregated vector of EM-simulated system responses, consider a local expansion model  $L^{(i)}(\mathbf{x})$  of  $\mathbf{r}(\mathbf{x})$  set up at  $\mathbf{x}^{(i)}$

$$L^{(i)}(\mathbf{x}) = \mathbf{r}(\mathbf{x}^{(i)}) + \mathbf{J}(\mathbf{x}^{(i)}) \cdot (\mathbf{x} - \mathbf{x}^{(i)}) \quad (7)$$

The Jacobian matrix  $\mathbf{J}(\mathbf{x}^{(i)})$  of  $\mathbf{r}$  is estimated using finite differentiation. When considering individual components, the merit function can be expressed as

$$U_L^{(i)}(\mathbf{x}) = A(\mathbf{x}) + \sum_{k=1}^{n_c} \beta_k^{(i)} c_{L,k}(\mathbf{x}) \quad (8)$$

where  $c_{L,k}$  refers to constraint functions of the same form as  $c_k$  of (4); yet, they are evaluated using the linear model  $L^{(i)}$  of the component responses instead of directly from  $\mathbf{r}$ .

The interval  $[\mathbf{x}^{(i)} - \mathbf{d}^{(i)}, \mathbf{x}^{(i)} + \mathbf{d}^{(i)}]$  of (6) is referred to as the trust region. Typically, its size is made proportional to the design space size, and its value in each algorithm iteration is decided upon using the standard TR rules [54] based on the gain ratio defined as

$$\rho = \frac{U_P(\mathbf{x}^{(i+1)}) - U_P(\mathbf{x}^{(i)})}{U_L(\mathbf{x}^{(i+1)}) - U_L(\mathbf{x}^{(i)})} \quad (9)$$

The following rules for updating the TR region size apply: (i) if  $\rho > 0.75$  (i.e., the gain ratio is large enough),  $d^{(i+1)}$  is increased, (ii) if  $\rho < 0.25$  (i.e., the gain ratio is small),  $d^{(i+1)}$  is reduced, (iii) in other cases, it is remained intact. Furthermore, the next design is accepted only for  $\rho > 0$ , otherwise, the iteration is re-launched with a smaller  $d^{(i+1)}$ .

### 3.1.2. Example: Ultrawideband Antenna

Consider an ultrawideband antenna shown in Figure 3a. The structure parameters and design goals along with constraints are provided in Figure 3b. The antenna EM model is evaluated using CST Microwave Studio and incorporates the SMA connector (~1,200,000 mesh cells, simulation time 240 s). All the simulations were performed on Intel Xeon 2.1 GHz dual-core CPU with 128 GB RAM. The results obtained with the use of the algorithm [28] are compared to the fixed setup with different values of penalty factors. The procedure [42] has been executed with the default values of the control parameters given in Figure 2.

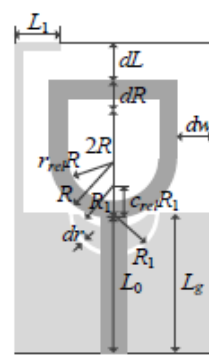
The discussed optimization task is a multimodal one; thus, a statistical assessment of the algorithm [42] is carried out based on ten independent runs, executed using random initial designs. Table 1 provides the optimization results in the form of the average values of antenna size and constraint violations, along with standard variation thereof. Antenna reflection characteristics and the evolution of penalty coefficient values for a representative algorithm run are shown in Figure 4. The results of Table 1 indicate that the miniaturization framework of [42] allows for precise constraint control. In addition, for similar average constraint violation levels, the adaptive penalty factors approach renders antenna designs with improved miniaturization rates.

**Table 1.** Optimization results for antenna of Figure 3.

Optimization Approach	Performance Figure			
	Antenna Footprint $A$ [mm <sup>2</sup> ] <sup>1</sup>	Std( $A$ ) <sup>2</sup>	Constraint Violation $D$ [dB] <sup>3</sup>	Std( $D$ ) [dB] <sup>4</sup>
Penalty function approach	$\beta = 10^2$	113.7	9.07	0.53
	$\beta = 10^3$	250.4	24.0	0.50
	$\beta = 10^4$	318.6	60.0	0.14
	$\beta = 10^5$	331.6	63.4	0.10
	$\beta = 10^6$	367.6	51.9	0.05
Adaptive penalty factors [28]	281.6	37.1	0.23	0.15

<sup>1</sup> Optimized antenna footprint averaged over ten algorithm runs. <sup>2</sup> Standard deviation of the antenna footprint averaged over ten algorithm runs. <sup>3</sup> Average constraint violation  $D = \{3.1 \text{ GHz} \leq f \leq 10.6 \text{ GHz}: \max |S_{11}(f)|\} + 10 \text{ dB}$ . <sup>4</sup> Standard deviation of the constraint violation  $D$ , averaged over ten algorithm runs.



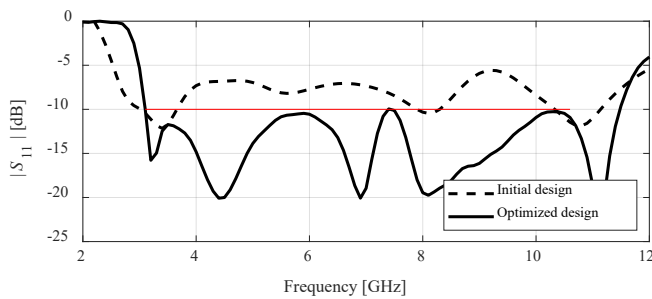


Substrate	RF-35 ( $\epsilon_r = 3.5, h = 0.762 \text{ mm}$ )
Design variables	$x = [L_0 \ dR \ R \ r_{rel} \ dL \ dw \ Lg \ L_1 \ R_1 \ dr \ c_{rel}]^T$
Other variables	$w_0 = 1.7$
Design goals and constraints	<ul style="list-style-type: none"> <li>Minimize footprint area <math>A(x)</math></li> <li>Ensure <math> S_{11}(x, f)  \leq -10 \text{ dB}</math> for <math>3.1 \text{ GHz} \leq f \leq 10.6 \text{ GHz}</math></li> </ul>

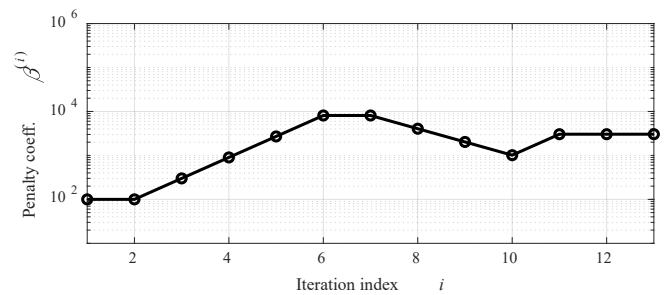
(a)

(b)

Figure 3. Ultrawideband antenna [55]: (a) geometry, (b) essential parameters.



(a)



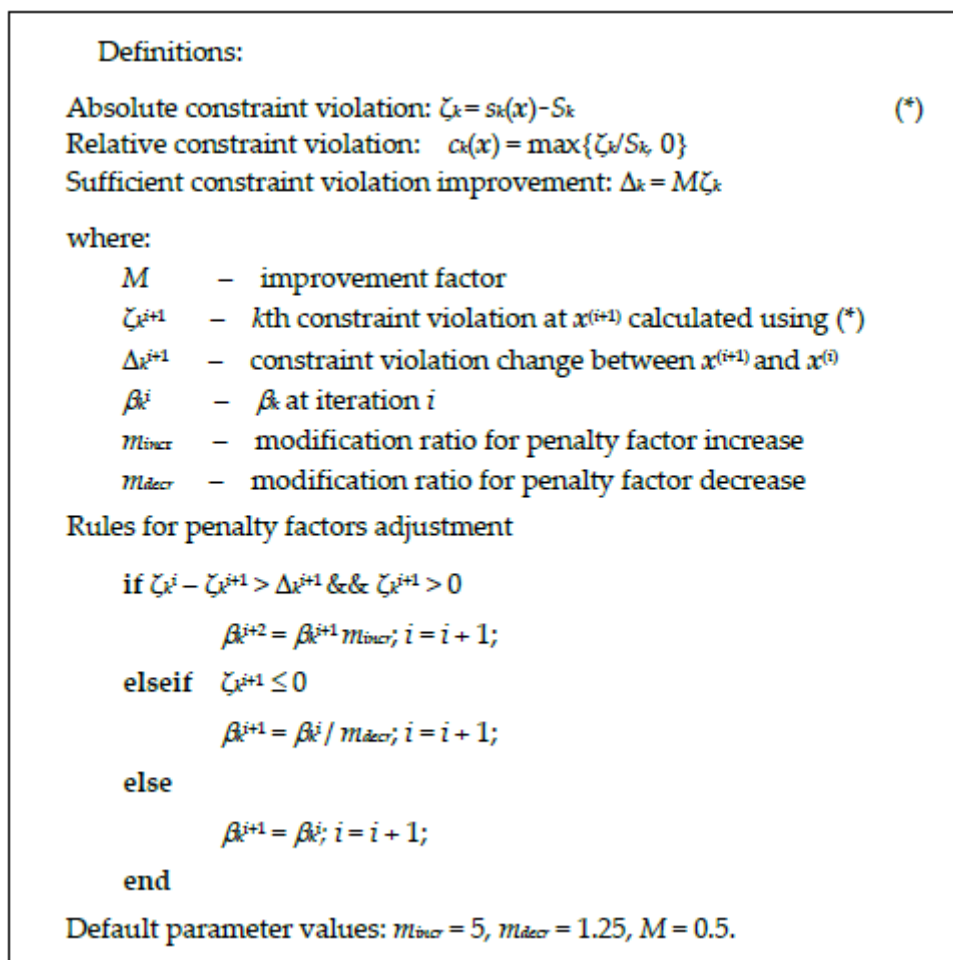
(b)

Figure 4. Representative run of the algorithm [42] optimizing the antenna of Figure 3: (a) antenna reflection characteristics at the initial (---) and optimized design (—), horizontal line marks design specifications; (b) evolution of penalty factor value across optimization course.

### 3.2. Adaptive Scheme II. Sufficient Constraint Violation Improvement

An alternative adaptive penalty coefficient methodology has been proposed in [41]. It exploits a somewhat different approach than the technique delineated in Section 3.1. In [41], the adjustment of the penalty factors is based on monitoring both the feasibility status of the current design and the improvement of the constraint violation between algorithm iterations. The rules for governing the current values of the penalty coefficients, along with basic definitions of the technique [41], are shown in Figure 5.





**Figure 5.** Rules for penalty coefficient adjustment in the methodology of [41].

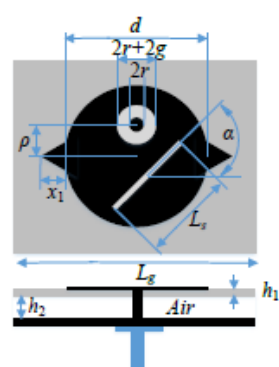
In [41], the penalty functions of (5) quantify relative violations of the constraints, whereas the penalty coefficients serve to commensurate the contribution of the said relative constraints to the primary objective (i.e., footprint area of the component under design). In [41], the inequality constraints take the form

$$s_k(\mathbf{x}) \leq S_k, j = 1, \dots, n_{ineq} \quad (10)$$

In short, the operation of the algorithm [41] may be described as follows. If the current design is feasible with respect to the  $k$ th constraint, the corresponding penalty factor is reduced. If, however, the actual design is infeasible but, at the same time, the constraint violation has been sufficiently improved, the previous value of the penalty coefficient is retained to maintain the optimization process stable. In the case of infeasible current design accompanied by insufficient constraint improvement, the respective penalty factor is increased.

**Example: Circular Patch Antenna**

Figure 6a shows a circularly polarized antenna used as a verification case in [41]. The antenna parameters, substrates and design goals/constraints are given in Figure 6b. The antenna EM model is evaluated using a time-domain solver of CST Microwave Studio (~400,000 mesh cells, simulation time 150 s). The results obtained with the approach of [41] are benchmarked against the fixed setup with different values of penalty factors.



(a)

Substrate I	Arlon ( $\epsilon_r = 2.5, h = 3.8$ mm)
Substrate II	Air ( $\epsilon_r = 1.08, h = 2.0$ mm)
Design variables	$x = [r \ g \ L_g \ d \ \rho \ L_s \ \alpha \ x_1]^T$
Design goals and constraints	<ul style="list-style-type: none"> <li>Minimize footprint area <math>A(x)</math></li> <li>Ensure <math> S_{11}(x, f)  \leq -10</math> dB for <math>8.1 \text{ GHz} \leq f \leq 8.3 \text{ GHz}</math></li> <li>Ensure <math> AR(x, f)  \leq 3</math> dB for <math>8.1 \text{ GHz} \leq f \leq 8.3 \text{ GHz}</math></li> </ul>

(b)

Figure 6. Circular patch antenna [56]: (a) geometry, (b) essential parameters.

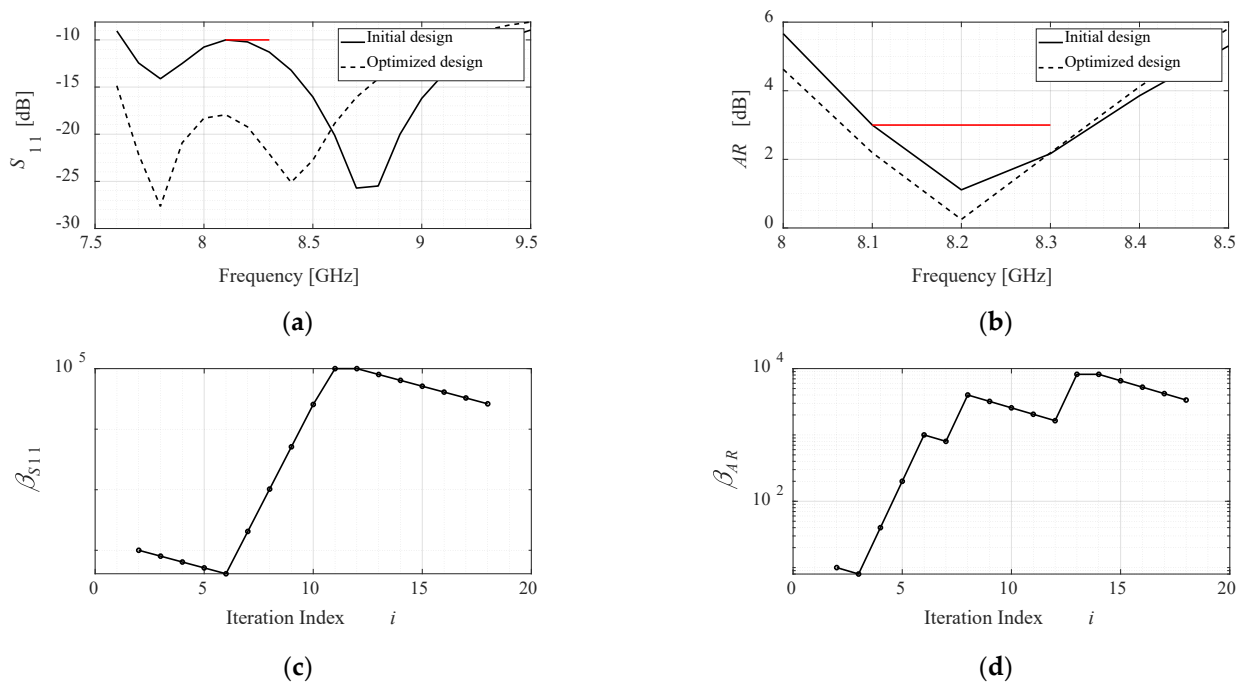
Table 2 shows the optimization results: the antenna footprint, as well as violations of both constraints  $\zeta_{AR}$  and  $\zeta_{S11}$ , imposed on axial ratio and reflection, respectively. Figure 7 shows the antenna outputs, along with the evolution of penalty factors throughout the optimization run. Similarly, as for the algorithm described in Section 3.1, the considered procedure allows for obtaining enhanced miniaturization rates, and, at the same time, a better level of control over constraint violations has been achieved.

Table 2. Optimization results for antenna of Figure 6.

Algorithm with Fixed Penalty Factors		Antenna Footprint $A$ [mm <sup>2</sup> ]	Constraint Violation $\zeta_{S11}$ [dB] <sup>2</sup>	Constraint Violation $\zeta_{AR}$ [dB] <sup>3</sup>
$\beta_{AR}$	$\beta_{S11}$	<sup>1</sup>		
10	10 <sup>2</sup>	374.38	2.77	0
10	10 <sup>3</sup>	323.37	2.24	0.2
10	10 <sup>4</sup>	334.37	2.69	0.01
10	10 <sup>5</sup>	340.24	2.15	0.01
10 <sup>2</sup>	10 <sup>2</sup>	309.99	0.05	3.8
10 <sup>2</sup>	10 <sup>3</sup>	361.73	0.33	0
10 <sup>2</sup>	10 <sup>4</sup>	359.71	0.27	0
10 <sup>2</sup>	10 <sup>5</sup>	356.18	0.20	0
10 <sup>3</sup>	10 <sup>2</sup>	404.58	0.07	0
10 <sup>3</sup>	10 <sup>3</sup>	421.75	0.05	0
10 <sup>3</sup>	10 <sup>4</sup>	421.75	0.05	0
10 <sup>3</sup>	10 <sup>5</sup>	421.75	0.05	0
10 <sup>4</sup>	10 <sup>2</sup>	455.41	0.03	0
10 <sup>4</sup>	10 <sup>3</sup>	455.41	0.03	0
10 <sup>4</sup>	10 <sup>4</sup>	455.41	0.03	0
10 <sup>4</sup>	10 <sup>5</sup>	455.41	0.03	0
Adaptive penalty factors [41]		373.36	0	0

<sup>1</sup> Optimized antenna footprint. <sup>2</sup> Constraint violation  $\zeta_{S11} = \{8.1 \text{ GHz} \leq f \leq 8.3 \text{ GHz}: \max |S_{11}(f)|\} + 10$  dB. <sup>3</sup> Constraint violation  $\zeta_{AR} = \{8.1 \text{ GHz} \leq f \leq 8.3 \text{ GHz}: \max |AR(f)|\} + 3$  dB.





**Figure 7.** Size reduction in the antenna of Figure 6 using algorithm [41]: (a,b) reflection  $S_{11}$  and axial ratio AR, respectively, at the initial (---) and optimized design (—), horizontal lines mark design specifications; (c,d) evolution of the penalty factors corresponding to  $S_{11}$  and AR, respectively, throughout optimization process.

#### 4. Explicit Constraint Handling Approach

The implicit approach can alleviate some of the difficulties pertinent to the handling of computationally expensive design constraints while creating problems of its own. As elaborated in Section 2, the appropriate choice of the penalty coefficients is critical for the performance of the optimization process. Section 3 outlined two strategies for adaptive adjustment of those coefficients, which enable relatively precise control of the constraints while ensuring competitive miniaturization rates. It should be noted, however, that implementation of these strategies is rather complex. Recently, a technique for explicit constraint control in high-frequency design has been presented [44], which operates on entirely different principles while enabling similar benefits as the procedures of [41,42]. This section outlines this approach and illustrates it using two examples.

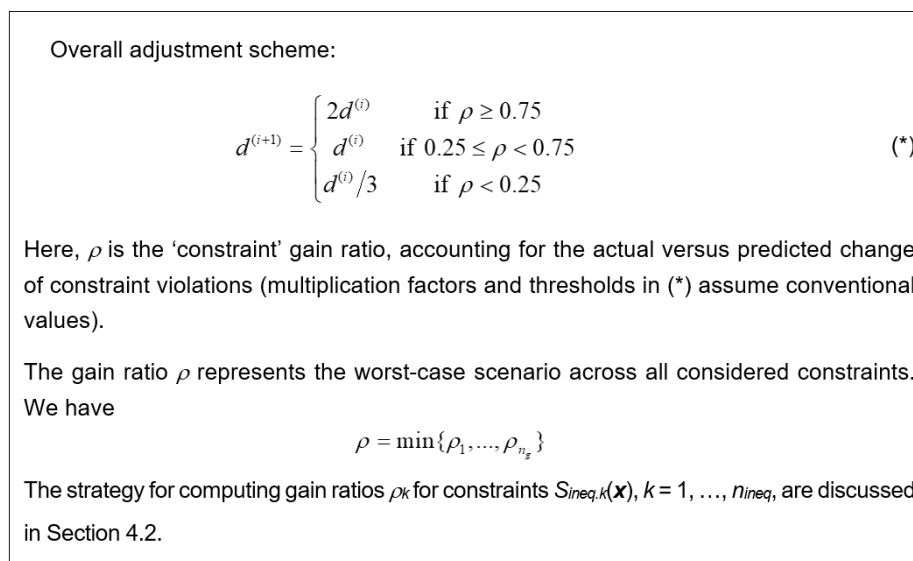
##### 4.1. Explicit Constraint Handling

The approach of [44] is embedded in the trust-region (TR) framework [54] briefly outlined in Section 3.1. In [44], the following model of the  $k$ th constraint  $S_{ineq,k}(\mathbf{r}(\mathbf{x}))$  is used:

$$S_{L,ineq,k}(\mathbf{x}) = S_{ineq,k}(\mathbf{L}^{(i)}(\mathbf{x})) \quad (11)$$

The new point  $\mathbf{x}^{(i)}$  is found using (2) subject to  $S_{L,ineq,k}(\mathbf{x}) \leq 0$ ,  $k = 1, \dots, n_{ineq}$ .

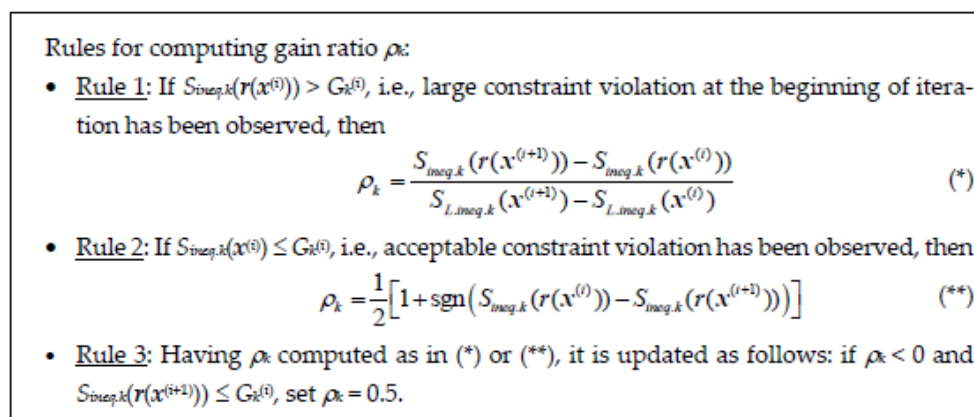
The keystone of the procedure [44] is the updating scheme for the trust-region size  $d^{(i)}$ . It has been explained in Figure 8. Good alignment between the linear-model-predicted constraint value  $S_{L,ineq,k}(\mathbf{x})$  and the actual value  $S_{ineq,k}(\mathbf{r}(\mathbf{x}))$  promotes the increase in  $d^{(i)}$ , whereas poor agreement results in decreasing it.



**Figure 8.** Updating the trust-region size according to the methodology of [44].

#### 4.2. Calculating Gain Ratio

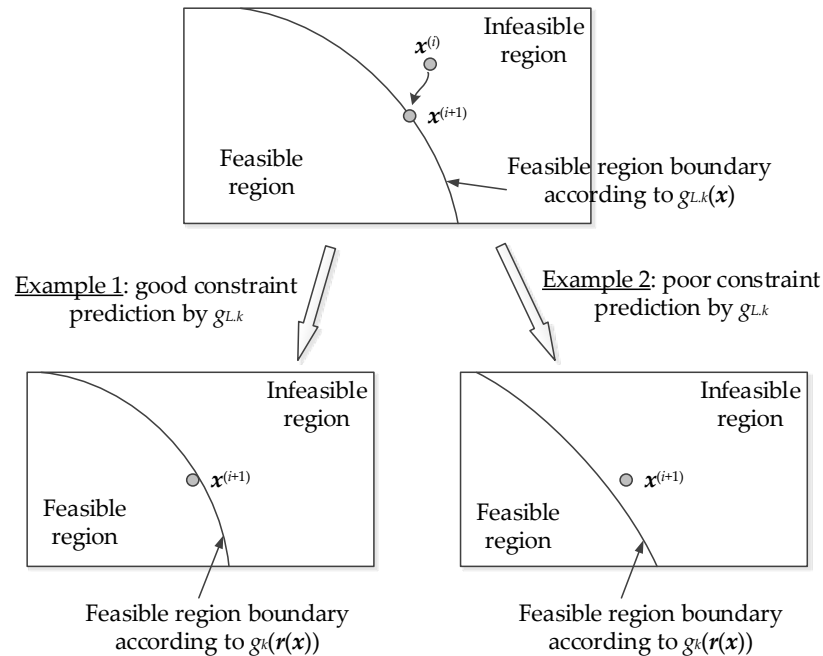
Figure 9 shows the rules for computing the gain ratio considered in Figure 8. Their evaluation is contingent upon the acceptance threshold  $G_k^{(i)}$  set up for the constraint  $k$  at iteration  $i$ . Rules 1 and 2 penalize insufficient prediction of constraints of the linear model  $G_{L,ineq,k}$  for sizeable constraint violations, and no improvement of feasibility status for minor violations, respectively. The same rules promote satisfactory prediction capability, and design shifts towards feasible regions. Rule 3 overrides both Rules 1 and 2 if the actual violation at  $\mathbf{x}^{(i+1)}$  is lower than  $G_k^{(i)}$ . This allows for avoiding erratic behavior in the vicinity of the feasible region boundary [44].



**Figure 9.** Rules for computing gain ratios  $\rho_k$  [44].

Some examples of poor and good constraint prediction can be found in Figure 10. Regarding the thresholds  $G_k^{(i)}$ , to allow more space for infeasible solutions early in the optimization process, the thresholds are associated with the algorithm convergence status, and the maximum acceptable constraint violation  $G_{k,max}$  (user-defined). Given the termination condition  $\|\mathbf{x}^{(i+1)} - \mathbf{x}^{(i)}\| < \varepsilon$  or  $d^{(i)} < \varepsilon$  ( $\varepsilon$  being the user-defined threshold) the convergence status at iteration  $i$  is defined as [44]

$$C^{(i)} = \max \left\{ 1, \frac{\min \{ \| \mathbf{x}^{(i+1)} - \mathbf{x}^{(i)} \|, d^{(i)} \}}{\varepsilon} \right\} \quad (12)$$



**Figure 10.** Prediction of constraints with the use of linear model  $S_{L,ineq,k}$ : **(top)** design shift from  $x^{(i)}$  to  $x^{(i+1)}$  as a result of solving (6), the purpose of the design relocation is to minimize the footprint area and to meet the constraint (as predicted by  $S_{L,ineq,k}$ ); **(bottom-left)** satisfactory prediction of a linear model; **(bottom-right)** poor prediction and infeasible new design (as assessed by the true constraint value rendered by EM analysis), so,  $d^{(i)}$  is to be reduced in the next iteration.

The acceptance threshold for iteration  $i + 1$  is set as

$$G_k^{(i+1)} = G_{k,\max} \min \{ 1, \alpha C^{(i)} \} \quad (13)$$

As  $C^{(i)}$  is initially large, so is  $G_k^{(i+1)}$ . Near convergence, it is reduced to  $\alpha G_{k,\max}$ , where  $\alpha > 0$  is a small number [44].

#### 4.3. Example I: Broadband Antenna

Consider the broadband antenna shown in Figure 11a. The relevant parameters and design goals/constraints are specified in Figure 11b. The EM model is simulated in CST Microwave Studio and incorporates the SMA connector (~380,000 mesh cells, simulation time 100 s).

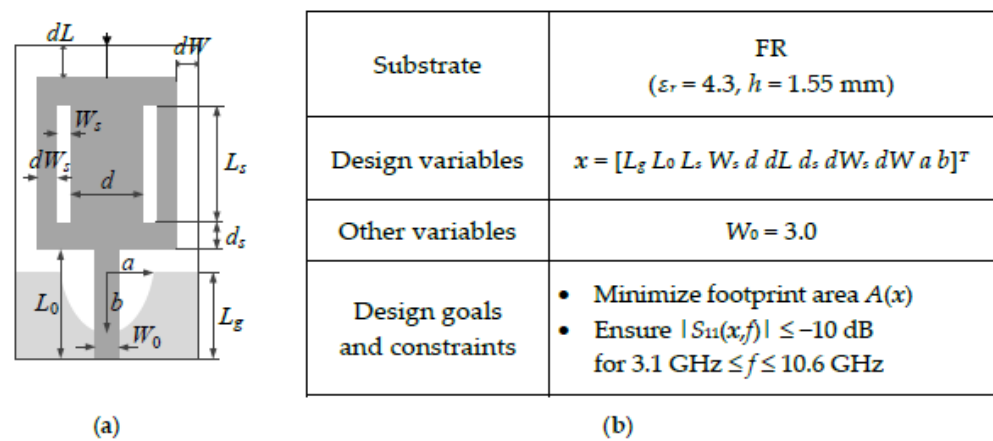


Figure 11. Broadband antenna [57]: (a) geometry, (b) essential parameters.

The algorithm of [44] is compared to several benchmark methods including the penalty function approach with fixed penalty coefficients and the adaptive scheme of [42]. The acceptance threshold is set so  $G_{k,\max} = 1 \text{ dB}$  with  $\alpha = 0.1$ . The results are shown in Table 3 in the form of the average values of performance indicators and their standard deviations. Figure 12 shows the antenna reflection response, the size and constraint violation evolutions for a representative run of the algorithm. As it can be observed, the method of [44] enables the precise control of the design constraint and slightly improves the miniaturization rate in comparison to the penalty function approach (for commensurate average constraint violation levels). Explicit constraint handling is competitive to the adaptive approach of [42] with regard to tackling constraint violations, which leads to slightly increased average antenna sizes.

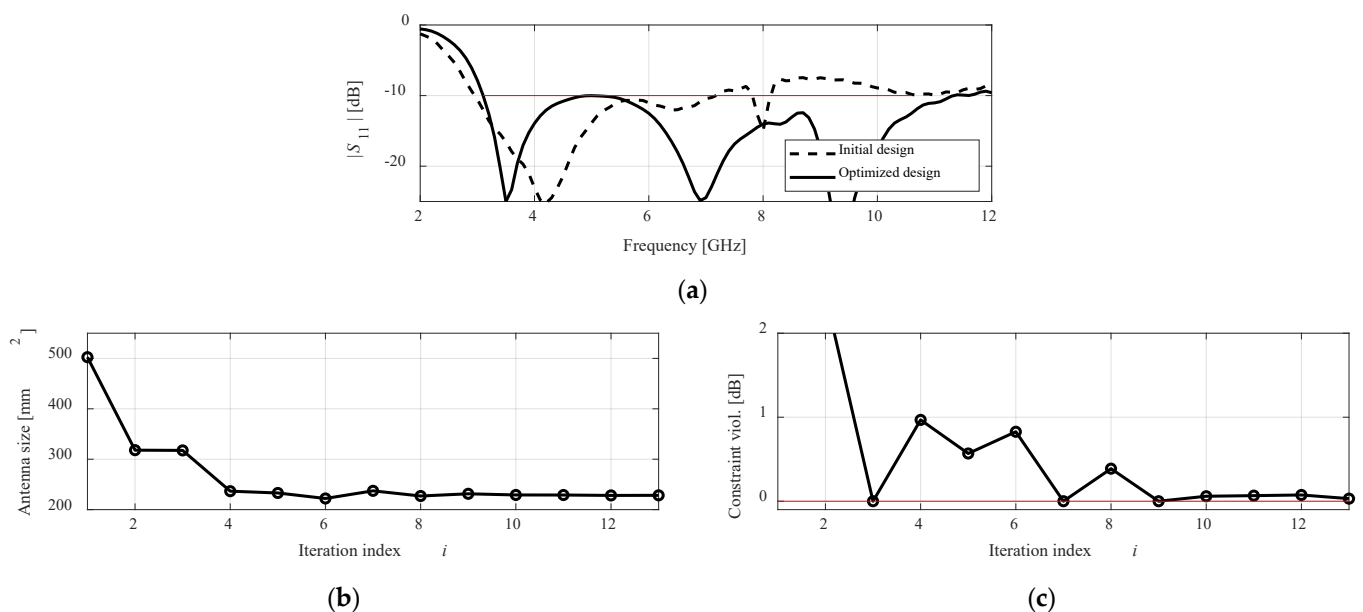


Figure 12. Representative run of the algorithm [44] optimizing the antenna of Figure 11: (a) antenna reflection characteristics at the initial (---) and optimized design (—), (b) evolution of antenna size, (c) evolution of constraint violation.

**Table 3.** Optimization results for antenna of Figure 11.

Optimization Approach	Performance figure				
	Antenna Footprint $A$ [mm <sup>2</sup> ] <sup>1</sup>	Std( $A$ ) <sup>2</sup>	Constraint Violation $D$ [dB] <sup>3</sup>	Std( $D$ ) [dB] <sup>4</sup>	
Penalty function approach	$\beta = 10^2$	56.1	3.8	8.6	0.60
	$\beta = 10^3$	212.8	14.3	1.0	0.40
	$\beta = 10^4$	255.0	25.1	0.15	0.10
	$\beta = 10^5$	280.1	47.4	0.05	0.07
	$\beta = 10^6$	285.8	29.6	0.00	0.01
Adaptive penalty factors [28]	215.6	3.6	0.25	0.14	
Explicit constraint handling [30]	224.4	6.7	0.10	0.21	

<sup>1</sup> Optimized antenna footprint averaged over ten algorithm runs. <sup>2</sup> Standard deviation of the antenna footprint averaged over ten algorithm runs. <sup>3</sup> Average constraint violation  $D = \{3.1 \text{ GHz} \leq f \leq 10.6 \text{ GHz}: \max |S_{11}(f)|\} + 10 \text{ dB}$ . <sup>4</sup> Standard deviation of the constraint violation  $D$ , averaged over ten algorithm runs.

#### 4.4. Example II: Rat-Race Coupler

Consider a rat-race coupler shown in Figure 13. Its EM model is simulated in CST Microwave Studio (~40,000 mesh cells, simulation time 180 s). The main objective is a reduction in the circuit footprint area. There are two design constraints:  $S_{eq,1}(\mathbf{x}) = |S_{31}(\mathbf{x}, f_0) - S_{21}(\mathbf{x}, f_0)| + 10 \text{ dB}$ , and  $S_{ineq,1}(\mathbf{x}) = \max\{f \in F: \max\{|S_{11}(\mathbf{x}, f)|, |S_{41}(\mathbf{x}, f)|\}\} + 20 \text{ dB}$ , where  $f_0$  is the center frequency, and  $F$  is the intended circuit bandwidth, for which we set up two scenarios as shown in Figure 13b.

Substrate	FR4 ( $\epsilon = 4.4, h = 1.55 \text{ mm}$ )
Design parameters	$\mathbf{x} = [L_1 \ b \ g \ h_f \ s \ l_f]^T$
Other parameters	$L_2 = L_1 - g - w_0, a = (l_f - 17s)/16,$ $b = (h_f - s)b_r, l_f = L_2 l_{fr}, l_v = L_1 - 2g - 2w_0,$ $h_f = s + (w_0 - s)h_{fr}, dW = dL = 10 \text{ mm}$
Operating parameters (design scenario I)	$f_0 = 1.2 \text{ GHz}$ $F = [1.15 \ 1.25] \text{ GHz}$
Operating parameters (design scenario II)	$f_0 = 1.2 \text{ GHz}$ $F = [1.18 \ 1.22] \text{ GHz}$
Initial design <sup>1</sup>	$\mathbf{x}^{(0)} = [31.79 \ 0.67 \ 2.12 \ 0.80 \ 0.49 \ 0.33]^T$

<sup>1</sup> Initial design obtained by optimizing the circuit for best matching/isolation within the frequency range  $F$ , under equal-power-split constraint.

**Figure 13.** Rat-race coupler [58]: (a) geometry, (b) essential parameters.

The circuit size was optimized using the procedure of [43], and the algorithm used the implicit approach with a number of combinations of the penalty coefficients. The termination threshold is set to  $\epsilon = 10^{-3}$ , the acceptance thresholds are chosen to be  $G_{1,\max} = 1 \text{ dB}$ ,  $G_{2,\max} = 0.3 \text{ dB}$ , and  $\alpha = 0.1$ .

Table 4 shows the numerical results, whereas Figure 14 illustrates the circuit responses and the evolution of the footprint area and constraint violations during the optimization run. The algorithm of [43] performs consistently for both design scenarios. It does not only ensure precise control of the constraints (at the level of small fractions of dB) but also yields a design featuring competitive size, which is unlike the implicit ap-

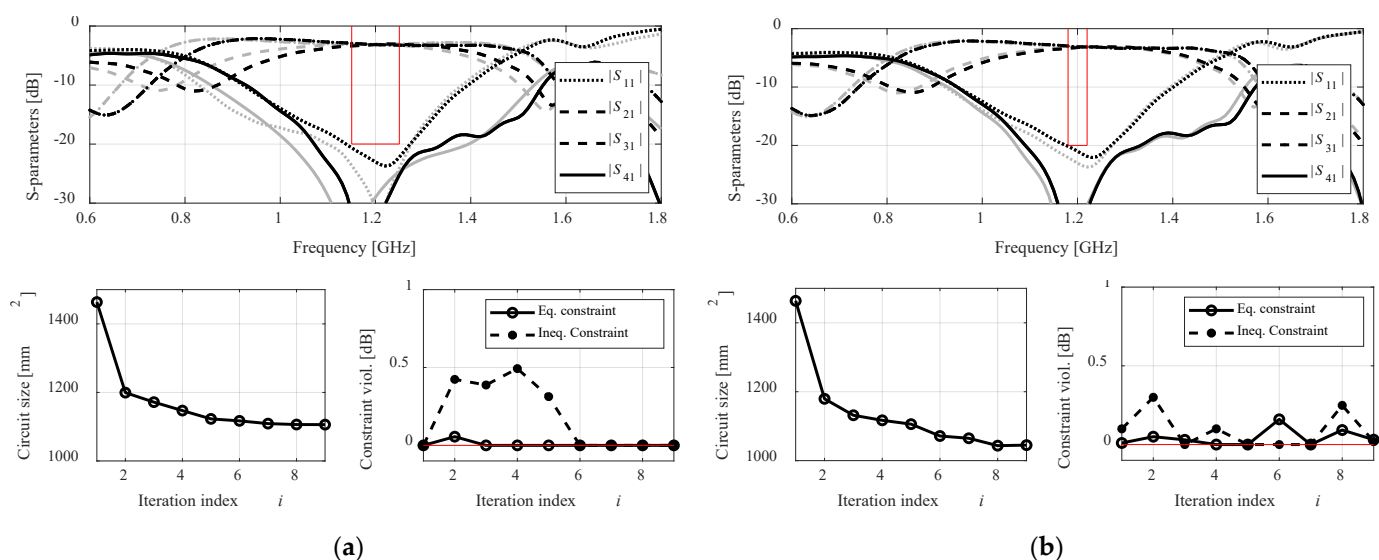
proach with the manual setup of penalty coefficients. Note that if the number of constraints increases, the number of combinations of penalty coefficients increases as well, which makes their proper selection significantly more difficult.

**Table 4.** Optimization results for the circuit of Figure 13.

Optimization Approach		Performance Parameters					
		Design Scenario I ( $F = [1.15 \ 1.25]$ GHz)			Design Scenario II ( $F = [1.18 \ 1.22]$ GHz)		
Method	Setup	Footprint Area A [mm <sup>2</sup> ] <sup>1</sup>	Violation of Equality Constraint $g_1$ [dB] <sup>2</sup>	Violation of Inequality Constraint $g_2$ [dB] <sup>3</sup>	Footprint Area A [mm <sup>2</sup> ] <sup>1</sup>	Violation of Equality Constraint $g_1$ [dB] <sup>3</sup>	Violation of Inequality Constraint $g_2$ [dB] <sup>4</sup>
Implicit constraint handling (penalty function approach)	$\beta_1 = 10^1, \beta_2 = 10^1$	1067	0.17	0.7	1043	0.12	−0.7
	$\beta_1 = 10^1, \beta_2 = 10^2$	681	0.01	10.4	679	0.00	9.4
	$\beta_1 = 10^1, \beta_2 = 10^3$	1063	0.03	0.1	1063	0.03	−1.0
	$\beta_1 = 10^1, \beta_2 = 10^4$	1097	0.02	−0.1	1097	0.02	−1.2
	$\beta_1 = 10^2, \beta_2 = 10^1$	1120	0.04	0.6	1120	0.04	−0.5
	$\beta_1 = 10^2, \beta_2 = 10^2$	1134	0.00	−0.3	1134	0.00	−1.7
	$\beta_1 = 10^2, \beta_2 = 10^3$	1133	0.00	0.1	1133	0.00	−1.2
	$\beta_1 = 10^2, \beta_2 = 10^4$	1038	0.03	1.1	1038	0.03	0.0
	$\beta_1 = 10^3, \beta_2 = 10^1$	1165	0.05	−0.3	1165	0.05	−1.7
	$\beta_1 = 10^3, \beta_2 = 10^2$	1119	0.01	−0.1	1119	0.01	−1.3
	$\beta_1 = 10^3, \beta_2 = 10^3$	1152	0.06	−0.3	1152	0.06	−1.6
	$\beta_1 = 10^3, \beta_2 = 10^4$	1117	0.08	−0.1	1047	0.08	−1.7
	$\beta_1 = 10^4, \beta_2 = 10^1$	1218	0.00	−0.0	1136	0.02	0.2
	$\beta_1 = 10^4, \beta_2 = 10^2$	1208	0.00	−0.2	1132	0.01	−2.1
	$\beta_1 = 10^4, \beta_2 = 10^3$	1152	0.00	−0.5	1152	0.00	−1.7
$\beta_1 = 10^4, \beta_2 = 10^4$	1152	0.02	−0.1	1134	0.00	−2.2	
Explicit constraint handling [43]		1106	0.04	−0.1	1045	0.01	−0.1

<sup>1</sup> Optimized antenna footprint. <sup>2</sup> Constraint violation  $g_1 = ||S_{31}(\mathbf{x}, f_0) - S_{21}(\mathbf{x}, f_0)|| - 0.1$  dB;  $f_0 = 1.2$  GHz. <sup>3</sup> Constraint violation  $g_2 = \max\{f \in F: \max\{|S_{11}(\mathbf{x}, f)|, |S_{41}(\mathbf{x}, f)|\}\} + 20$  dB;  $f_0 = 1.2$  GHz,  $F = 100$  Mhz. <sup>4</sup> Constraint violation  $g_1 = ||S_{31}(\mathbf{x}, f_0) - S_{21}(\mathbf{x}, f_0)|| - 0.1$  dB;  $f_0 = 1.2$  GHz. <sup>5</sup> Constraint violation  $g_2 = \max\{f \in F: \max\{|S_{11}(\mathbf{x}, f)|, |S_{41}(\mathbf{x}, f)|\}\} + 20$  dB;  $f_0 = 1.2$  GHz,  $F = 40$  Mhz.

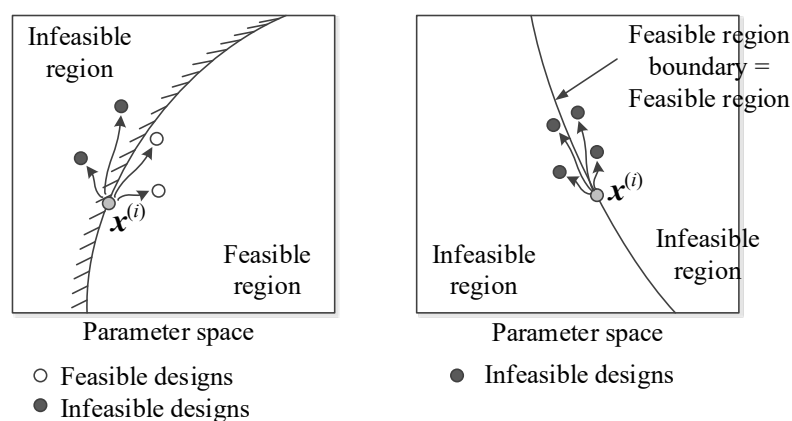




**Figure 14.** Initial (gray) and optimized (black) S-parameters of the circuit of Figure 13. The vertical and horizontal lines mark the target operating bandwidth and the acceptance level for the matching  $|S_{11}|$  and isolation  $|S_{41}|$  responses. Additionally, shown is the evolution of the circuit size and constraint violations (in case of feasibility, violations shown as zero): (a) design scenario I (bandwidth 1.15 GHz to 1.25 GHz), (b) design scenario II (bandwidth 1.18 GHz to 1.22 GHz).

## 5. Equality Constraint Control through Optimization-Based Correction

The handling of equality constraints is more challenging than controlling inequality ones because the feasible region for the former is a thin set (i.e., it is identical to its boundary). Its exploration is difficult because any deviation from the boundary increases the (penalized) objective function, cf. Figure 15. Recently, a strategy for improved handling of equality constraints was proposed in [45], which is briefly outlined and illustrated in this section.



**Figure 15.** Design relocation from feasible region boundary for inequality and equality constraints: (a) inequality constraint: the designs produced from the current design  $x^{(i)}$  may be located in either feasible or infeasible region, (b) equality constraint: essentially all designs produced from  $x^{(i)}$  are infeasible due to feasible region being a thin set. Consequently, exploration of the feasible space is more difficult for the equality constraints than the inequality ones.

### 5.1. Correction Procedure

According to [45], the inequality constraints are handled by means of the adaptive scheme (e.g., [42]), whereas the equality constraints are corrected after each iteration of the optimization process. The correction process has been explained in Figure 16. It should

be noted that the model  $L_A^{(i)}$  therein reuses the Jacobian  $J(\mathbf{x}^{(i)})$  to reduce the cost of its establishment (upon convergence  $J(\mathbf{x}^{(i)}) \rightarrow J(\mathbf{x}^{(i+1)})$ , so that  $L_A^{(i)}$  becomes closer to the true Taylor expansion at  $\mathbf{x}^{(i+1)}$ ). As explained in Figure 17, the corrected design is obtained through possibly small relocation of  $\mathbf{x}^{(i+1)}$  to  $\mathbf{x}_c^{(i+1)}$  aimed at reducing the equality constraint violation in the minimax sense without increasing  $A(\mathbf{x})$  and degrading inequality constraints.

Notation:

- $\mathbf{x}^{(i+1)}$  – new design produced in iteration  $i$ ;
- $\mathbf{r}(\mathbf{x})$  – EM-simulated system responses;
- $\mathbf{J}(\mathbf{x})$  – Jacobian matrix of  $\mathbf{r}(\mathbf{x})$ ;
- $L_A^{(i)}(\mathbf{x}) = \mathbf{r}(\mathbf{x}^{(i+1)}) + \mathbf{J}(\mathbf{x}^{(i)}) \cdot (\mathbf{x} - \mathbf{x}^{(i+1)})$  - linear expansion model of  $\mathbf{r}(\mathbf{x})$  at  $\mathbf{x}^{(i+1)}$  using sensitivity data at  $\mathbf{x}^{(i)}$ ;

Given  $M > 0$ , consider design  $\mathbf{x}_{corr}(M)$  obtained as

$$\mathbf{x}_{corr}(M) = \arg \min_{\mathbf{x}, \|\mathbf{x} - \mathbf{x}^{(i+1)}\| \leq M} \max \{ S_{eq,1}(L_A^{(i+1)}(\mathbf{x})), \dots, S_{eq,n_{eq}}(L_A^{(i+1)}(\mathbf{x})) \}$$

subject to

$$A(\mathbf{x}) \leq A(\mathbf{x}^{(i+1)})$$

$$S_{ineq,j}(\mathbf{x}) \leq S_{ineq,j}(\mathbf{x}^{(i+1)}) \quad j = 1, \dots, n_{ineq}$$

**Remark:** Notation  $S_{eq,k}(L_A^{(i+1)}(\mathbf{x}))$  emphasizes that constraints are evaluated using  $L_A^{(i+1)}$  rather than EM simulation results.

The corrected design is obtained as

$$\mathbf{x}_c^{(i+1)} = \arg \min_M \left\{ \max \left\{ \begin{matrix} h_1(L_A^{(i+1)}(\mathbf{x}_{corr}(M))), \dots \\ h_{n_h}(L_A^{(i+1)}(\mathbf{x}_{corr}(M))) \end{matrix} \right\} \leq \varepsilon_h \right\}$$

where  $\varepsilon_h$  is a small number, e.g.,  $\varepsilon_h = 10^{-3}$ ;  $M \leq M_{max}$ , where the upper bound  $M_{max}$  (e.g.  $M_{max} = 0.1$ ) is set to limit the design relocation  $\|\mathbf{x}^{(i+1)} - \mathbf{x}_c^{(i+1)}\|$ .

Figure 16. Correction of equality constraints according to the methodology presented in [45].

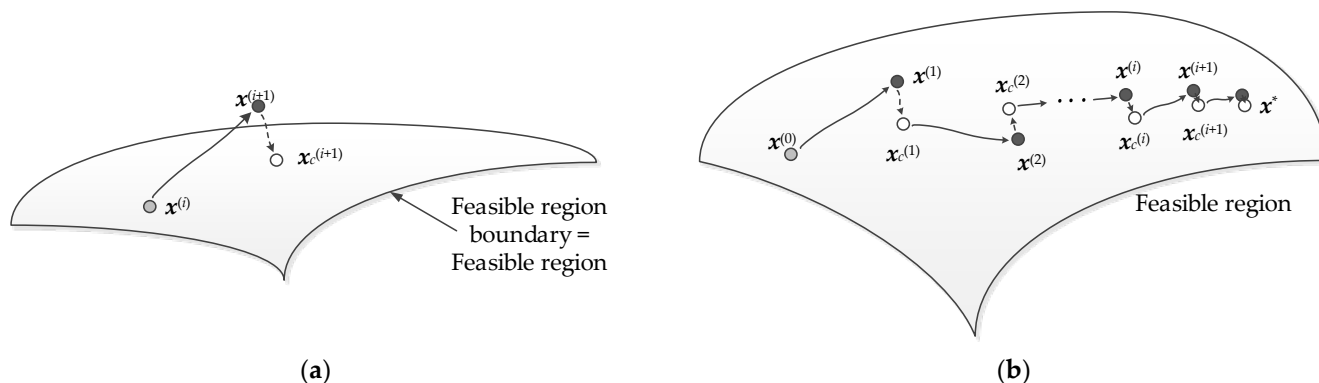


Figure 17. Optimization-based correction scheme for efficient control of equality constraints: (a) the concept: design  $\mathbf{x}^{(i+1)}$  obtained in the  $i$ th iteration of the optimization algorithm, starting from  $\mathbf{x}^{(i)}$ , is infeasible; it is brought closer to a feasible space using the correction procedure [29], without neither degrading inequality constraints nor the circuit area; the corrected design  $\mathbf{x}_c^{(i+1)}$  features reduced equality constraint values  $S_{eq,k}(\mathbf{x}_c^{(i+1)}) < S_{eq,k}(\mathbf{x}^{(i+1)})$ ,  $k = 1, \dots, n_{eq}$ , as well as  $A(\mathbf{x}_c^{(i+1)}) \leq A(\mathbf{x}^{(i+1)})$ , and  $S_{ineq,j}(\mathbf{x}_c^{(i+1)}) \leq S_{ineq,j}(\mathbf{x}^{(i+1)})$ ,  $j = 1, \dots, n_{ineq}$ , (b) graphical illustration of the intermittent equality constraint correction throughout the optimization run.

The overall optimization procedure is embedded in the standard trust-region gradient-based framework with numerical derivatives [54]. For more details, see [45].

5.2. Illustration Examples

Consider two branch line couplers shown in Figure 18, where all the relevant data on both structures are provided. EM models are simulated in CST Microwave Studio (Circuit I: ~450,000 mesh cells, simulation time 300 s; Circuit II: ~112,000 mesh cells, simulation time 160 s). In both cases, the primary objective is a reduction in the circuit footprint  $A(x)$ . Further, we have an inequality constraint for matching and port isolation,  $S_{ineq.1}(x) = \max\{f \in F: \max\{|S_{11}(x, f)|, |S_{41}(x, f)|\} + 20 \text{ dB}\}$ . This corresponds to a condition that both  $|S_{11}(x, f)|$  and  $|S_{41}(x, f)|$  should be not higher than  $-20 \text{ dB}$  over the operating band  $F$ . We also have an equality constraint for the power split ratio:  $S_{eq.1}(x) = ||S_{31}(x, f_0) - S_{21}(x, f_0)|| - K_P$ , where  $K_P$  is the required power split (in dB). Here,  $K_P = 0$  for Circuit I, and 3 dB for Circuit II.

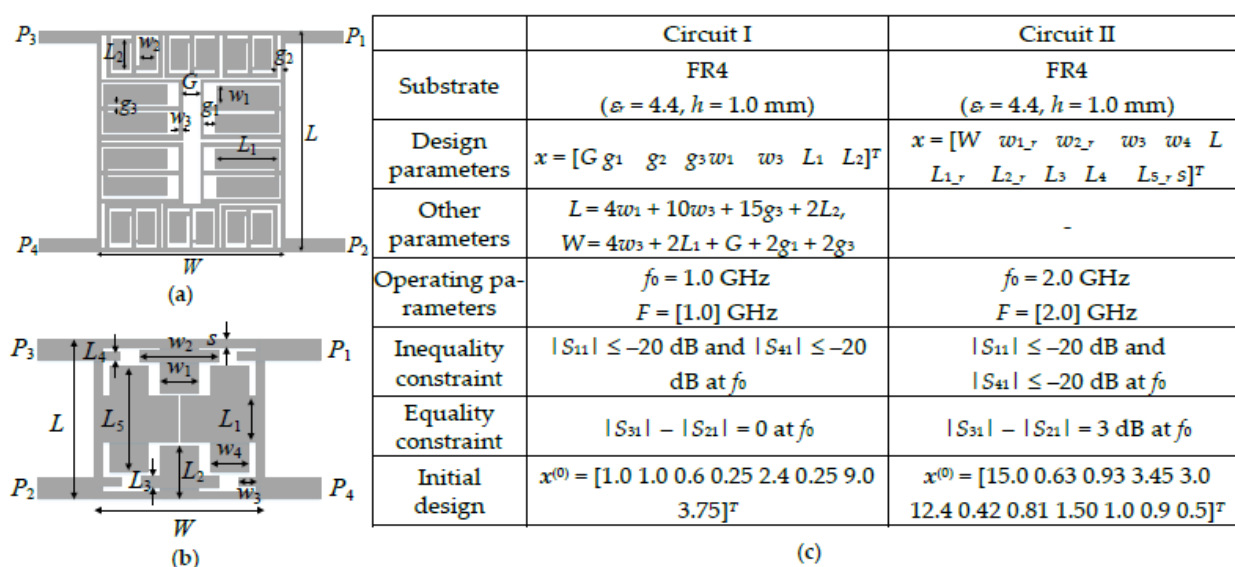


Figure 18. Demonstration case studies for equality constraint correction methodology of [45]: (a) branch-line coupler geometry (Circuit I) [59], (b) branch-line coupler geometry (Circuit II) [60], (c) essential circuit parameters.

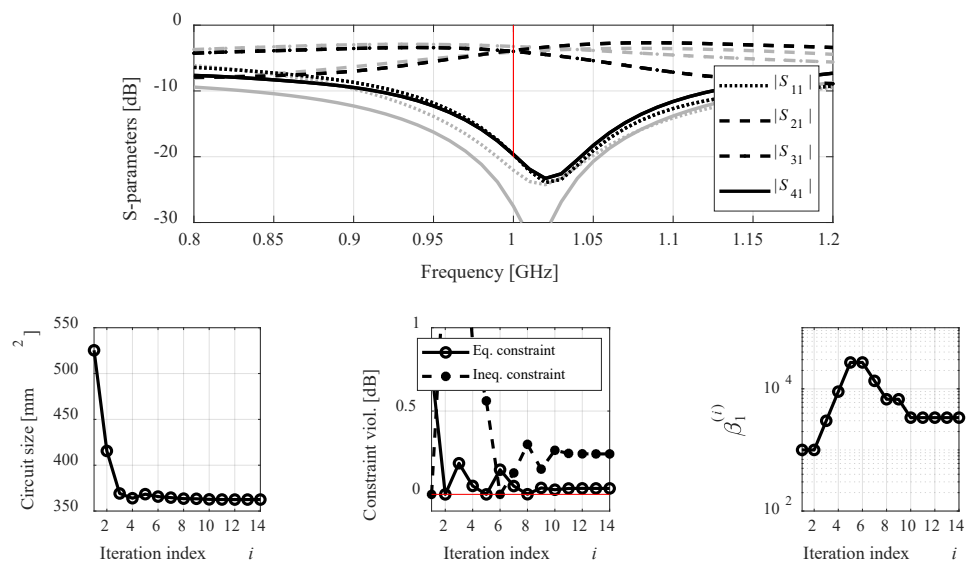
The circuits' size was optimized using the procedure of [44], and the algorithm used the implicit approach with a number of combinations of the penalty coefficients. The numerical results have been gathered in Table 5, whereas Figures 19 and 20 show the frequency characteristics at the initial and optimized designs, along with the evolution of the circuit size and constraint violations

Table 5. Optimization results for Circuit I and Circuit II of Figure 18.

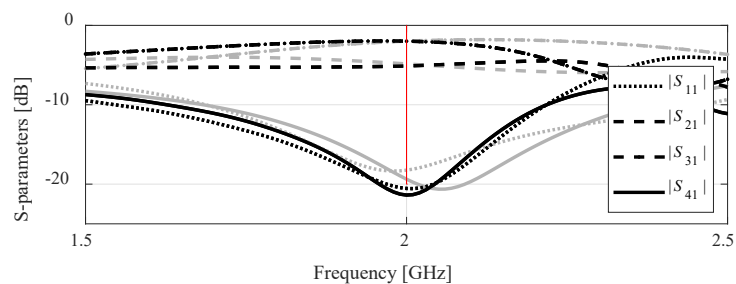
Optimization Approach		Performance Parameters					
		Circuit I ( $f_0 = 1.0 \text{ GHz}$ )			Circuit II ( $f_0 = 2.0 \text{ GHz}$ )		
Method	Setup	Footprint Area $A \text{ [mm}^2\text{]}^1$	Violation of Equality Constraint $g_1 \text{ [dB]}^2$	Violation of Inequality Constraint $g_2 \text{ [dB]}^3$	Footprint Area $A \text{ [mm}^2\text{]}^1$	Violation of Equality Constraint $g_3 \text{ [dB]}^4$	Violation of Inequality Constraint $g_4 \text{ [dB]}^5$
Implicit constraint handling	$\beta_1 = 10^1, \beta_2 = 10^1$	73	0.01	13.8	130	0.03	2.1
	$\beta_1 = 10^1, \beta_2 = 10^2$	75	0.01	13.8	135	0.06	1.8
	$\beta_1 = 10^1, \beta_2 = 10^3$	305	1.12	2.3	121	1.75	0.3
	$\beta_1 = 10^1, \beta_2 = 10^4$	334	1.22	0.2	146	0.02	0.1

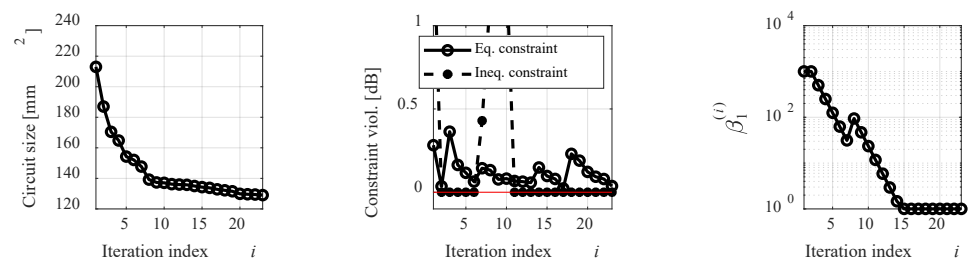
$\beta_1 = 10^2, \beta_2 = 10^1$	73	0.01	13.8	114	0.02	4.7
$\beta_1 = 10^2, \beta_2 = 10^2$	73	0.01	13.8	141	0.04	2.9
$\beta_1 = 10^2, \beta_2 = 10^3$	382	0.20	2.4	135	0.01	0.5
$\beta_1 = 10^2, \beta_2 = 10^4$	428	0.08	0.1	152	0.01	0.1
$\beta_1 = 10^3, \beta_2 = 10^1$	73	0.01	13.8	141	0.00	1.1
$\beta_1 = 10^3, \beta_2 = 10^2$	268	0.03	11.5	140	0.09	1.2
$\beta_1 = 10^3, \beta_2 = 10^3$	324	0.07	3.7	142	0.02	1.3
$\beta_1 = 10^3, \beta_2 = 10^4$	414	0.04	0.2	148	0.01	0.2
$\beta_1 = 10^4, \beta_2 = 10^1$	262	0.00	11.7	164	0.00	1.3
$\beta_1 = 10^4, \beta_2 = 10^2$	303	0.00	9.6	200	0.00	6.1
$\beta_1 = 10^4, \beta_2 = 10^3$	448	0.00	0.0	203	0.01	5.0
$\beta_1 = 10^4, \beta_2 = 10^4$	419	0.01	0.3	207	0.01	0.3
Optimization-based equality constraint correction [44]	362	0.03	0.2	129	0.03	0.4

<sup>1</sup> Optimized antenna footprint. <sup>2</sup> Constraint violation  $g_1 = ||S_{31}(x, f_0) - S_{21}(x, f_0)||$ ;  $f_0 = 1.0$  GHz. <sup>3</sup> Constraint violation  $g_2 = \max\{|S_{11}(x, f_0)|, |S_{41}(x, f_0)|\} + 20$  dB;  $f_0 = 1.0$  GHz. <sup>4</sup> Constraint violation  $g_3 = ||S_{31}(x, f_0) - S_{21}(x, f_0)||$ ;  $f_0 = 2.0$  GHz. <sup>5</sup> Constraint violation  $g_4 = \max\{|S_{11}(x, f_0)|, |S_{41}(x, f_0)|\} + 20$  dB;  $f_0 = 2.0$  GHz.



**Figure 19.** Initial (gray) and optimized (black) S-parameters of Circuit I. The vertical and horizontal lines mark the target operating bandwidth and the acceptance level for the matching  $|S_{11}|$  and isolation  $|S_{41}|$  responses. Additionally, shown is the evolution of the circuit size and constraint violations (in case of feasibility, violations shown as zero), as well as evolution of the penalty coefficient for the inequality constraint. The vertical line shows the target operating frequency of 1.0 GHz.





**Figure 20.** Initial (gray) and optimized (black) S-parameters of Circuit II. The vertical and horizontal lines mark the target operating bandwidth and the acceptance level for the matching  $|S_{11}|$  and isolation  $|S_{41}|$  responses. Additionally, shown is the evolution of the circuit size and constraint violations (in case of feasibility, violations shown as zero), as well as evolution of the penalty coefficient for the inequality constraint. The vertical line shows the target operating frequency of 2.0 GHz.

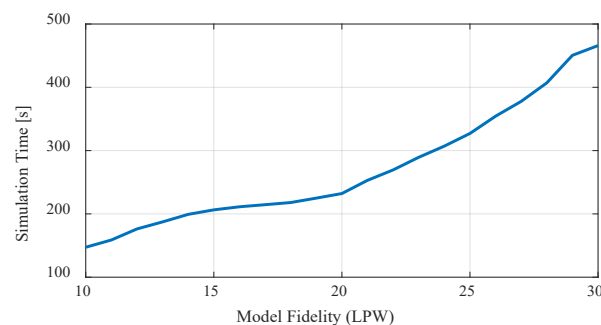
It can be observed that the method of [44] yields consistent results and permits excellent constraint control, especially for the equality condition. As shown in Section 4, the performance of the implicit approach is highly dependent on the setup of penalty coefficients. A combination of adaptive penalty function adjustment for inequality constraints and equality constraint correction effectively eliminates the algorithm setup issue.

## 6. Expedited EM-Driven Size Reduction

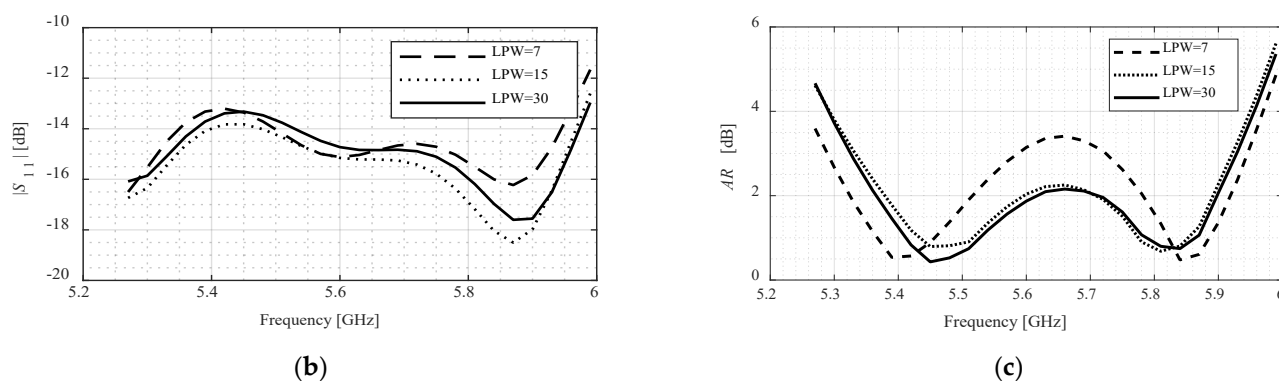
The methods discussed in Sections 3 through 5 considerably improve the treatment of design constraints. As for the other EM-driven design procedures, another practical issue is the high computational cost of the optimization process. In [46], an accelerated size reduction procedure has been proposed, which employs variable fidelity simulation models. It is briefly recalled here and illustrated using an example of a circularly polarized antenna.

### 6.1. Variable-Fidelity EM Models

Figure 21 shows a circularly polarized (CP) patch antenna, as well as the dependence of the simulation time and model fidelity, adjusted using the parameter lines-per wavelength (LPW) in CST Microwave Studio, utilized to control the discretization density of the structure. It can be observed that reducing the number of mesh cells accelerates the simulation process, at the expense of accuracy degradation. For this particular antenna, the high-fidelity model is set up at LPW = 30 (simulation time 236 s), whereas the lowest-fidelity model, which still properly represents antenna characteristics, is set at LPW = 11 (simulation time 82 s). These two levels will be denoted as  $F_{\max}$  and  $F_{\min}$ , respectively.



(a)



**Figure 21.** CP antenna (geometry shown in Figure 25 (a)); EM responses for various model fidelities: (a) dependence of the simulation time on the model discretization density, (b) reflection responses and (c) axial ratio for various fidelity levels.

### 6.2. Model Management Scheme

The model management scheme of [46] adjusts the fidelity of the model, denoted as  $F$ , within the range  $F_{\min} \leq F \leq F_{\max}$  (cf. Section 6.1). The underlying optimization engine is the trust-region gradient-based algorithm [54]. Constraint control follows the adaptive scheme of [41], see also Section 3.2. The decision factors concerning the value of  $F$  have been shown in Figure 22. These can be summarized as follows:

- The fidelity is set to  $F_{\min}$  early in the optimization process, regardless of the solution feasibility;
- Fidelity is set to  $F_{\max}$  upon convergence for reliability reasons;
- In the intermediate phase (i.e., either between infeasible and feasible, or when reaching convergence), the model fidelity depends on both the feasibility and the convergence status.

		Convergence status		
		Away from convergence	➡	Upon convergence
Feasibility status	Feasible	Lowest-fidelity	Increase LPW	High-fidelity
	↑	Lowest-fidelity	Increase LPW with a higher rate	High-fidelity
	Infeasible	Lowest-fidelity	Increase LPW with a lower rate	High-fidelity

**Figure 22.** Decision factors for model fidelity adjustment proposed in [46]. The fidelity control depends on the solution feasibility as well as the convergence status of the optimization process.

The feasibility status is defined as  $e^{-\tau^{(i)}}$ , where  $\tau^{(i)} = \max\{j = 1, \dots, k: \tau_j^{(i)}\}$  is the aggregated constraint violation at the  $i$ th iteration, where  $\tau_j^{(i)} = \zeta_j/\tau_{c_j}$ . The normalization factors  $\tau_{c_j}$  are set to ensure that  $\tau_j^{(i)} = 1$  when constraint violation gets close to a user-defined threshold (constraint-specific [46]). Here, the threshold is set to 2 dB for reflection-related constraints and 1 dB for axial-ratio-related ones. The convergence status has been explained in Figure 23, which also contains the model fidelity updating formula. The dependence between the simulation model fidelity and the convergence status and constraint violation is shown in Figure 24.

Convergence indicators:

- Distance between consecutive vectors  $\| \mathbf{x}^{(i+1)} - \mathbf{x}^{(i)} \| \leq \delta_{arg}$ ,
- difference between consecutive objective function values  $|U_A(\mathbf{R}(\mathbf{x}^{(i+1)})) - U_A(\mathbf{R}(\mathbf{x}^{(i)}))| \leq \delta_{obj}$ ,

where  $\delta_{arg}$  and  $\delta_{obj}$  are the respective termination thresholds.

Define

$$Q^{(i)}(\delta_{arg}, \delta_{obj}) = \max \{ C_{arg}, C_{obj} \}$$

where  $C_{arg}$  and  $C_{obj}$  are relative convergence factors:

$$C_{arg} = \frac{\delta_{arg}}{\| \mathbf{x}^{(i+1)} - \mathbf{x}^{(i)} \|} \quad \text{and} \quad C_{obj} = \frac{\delta_{obj}}{|U_A(\mathbf{R}(\mathbf{x}^{(i+1)})) - U_A(\mathbf{R}(\mathbf{x}^{(i)}))|}$$

Model fidelity updating formula

$$F^{(i+1)} = \begin{cases} F_{\min} & \text{if } Q^{(i)}(\delta_{arg}, \delta_{obj}) \leq \delta_{th} \\ \max \{ F^{(i)}, F_{\min} + (F_{\max} - F_{\min}) e^{-\tau^{(i)} Q_L^{(i)}} \} & \text{otherwise} \end{cases}$$

where  $F^{(i)}$  is model fidelity at the  $i$ th iteration, and  $\delta_{th}$  is a threshold for originating the model fidelity increase; aggregated convergence status defined as

$$Q_L^{(i)} = \left[ 1 - \frac{\log(Q^{(i)}(\delta_{arg}, \delta_{obj}))}{\log \delta_{th}} \right]$$

Figure 23. Definition of the convergence status and the model fidelity updating formula.

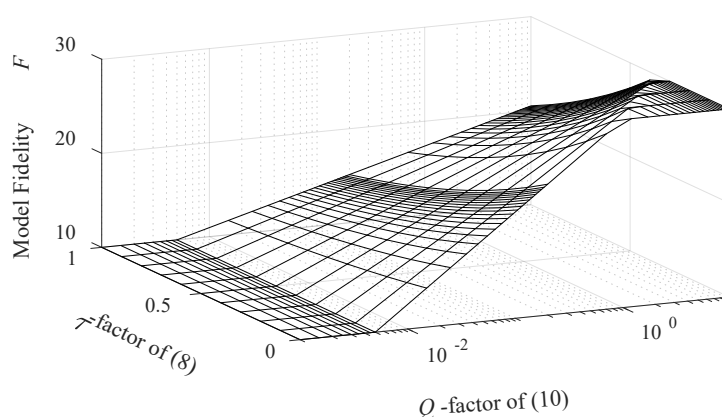


Figure 24. Dependence between the simulation model fidelity and the convergence status  $Q$ , as well as aggregated constraint violation  $\tau$ . The dependence is monotonic with respect to both control factors except from the early stages of the algorithm and when close to convergence. The plot created for exemplary model resolution levels  $F_{\min} = 10$ ,  $F_{\max} = 30$ , assuming  $\delta_{th} = 5 \times 10^{-3}$ .

### 6.3. Illustration Example

Consider a circularly polarized patch antenna shown in Figure 25. The computational model setup has been described in Section 6.1. The goal is to reduce the antenna size subject to constraints listed in Figure 25b. The initial design has been obtained by minimizing the reflection response and axial ratio within the frequency band of interest (cf. Figure 26.

The antenna has been optimized using the algorithm with adaptive adjustment of penalty factors [42], as well as the multi-fidelity procedure (also with adaptive penalty factors) described in this section.

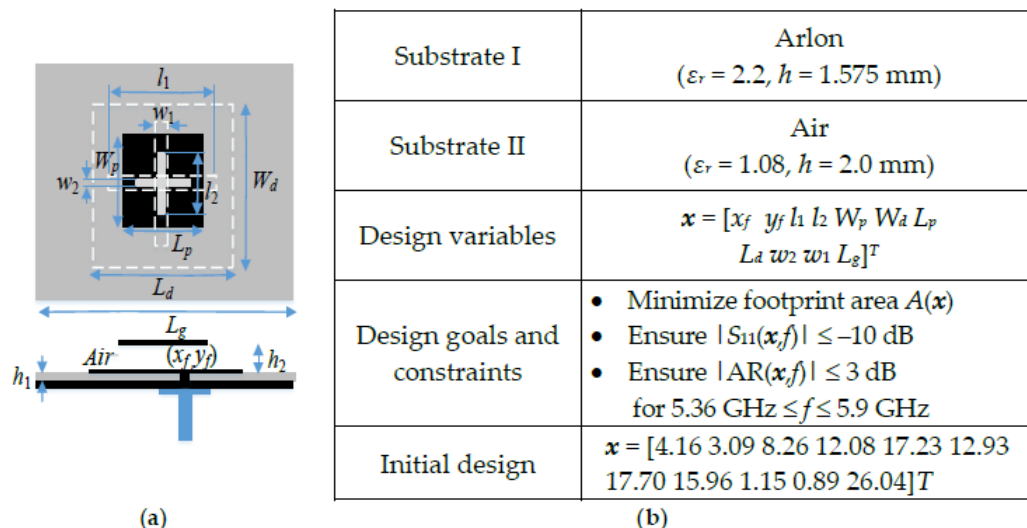


Figure 25. Circular-polarization patch antenna [60]: (a) geometry, (b) essential parameters.

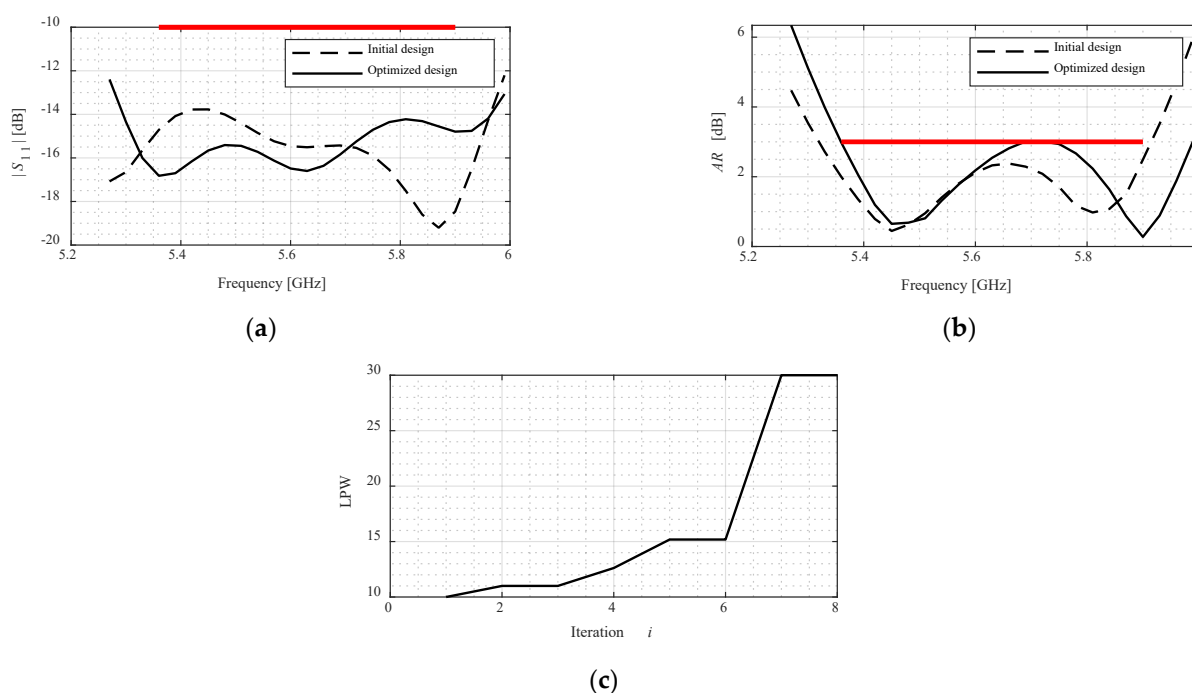


Figure 26. Results for Antenna of Figure 25 using the algorithm [46] incorporating multi-fidelity model management and adaptive penalty coefficients: (a) reflection responses, (b) axial ratio responses, (c) evolution of the model fidelity. The horizontal lines represent the design specifications.

The results shown in Table 6 demonstrate that the employment of variable resolution models considerably expedites the design process (by almost 50 percent), without being detrimental to the design quality. Furthermore, it enables excellent control of both design constraints.



**Table 6.** Optimization results for antenna of Figure 25.

Performance Figures	Optimization method	
	Adaptive Penalty Factors [42]	Variable-Fidelity <sup>4</sup> EM Simulations + Adaptive Penalty Factors [46]
Area $A$ [mm <sup>2</sup> ] <sup>1</sup>	372.7	368
First constraint violation $\zeta_{S11}$ [dB] <sup>2</sup>	0	0.02
Second constraint violation $\zeta_{AR}$ [dB] <sup>3</sup>	0	0
CPU time		
Absolute [h]	8.8	4.7
Relative to $R_f$	135	72
Saving [%]	–	47

<sup>1</sup> Optimized antenna footprint. <sup>2</sup> Constraint violation  $\zeta_{S11} = \{5.36 \text{ GHz} \leq f \leq 5.9 \text{ GHz}: \max |S_{11}(f)|\} + 10$ . <sup>3</sup> Constraint violation  $\zeta_{AR} = \{5.36 \text{ GHz} \leq f \leq 5.9 \text{ GHz}: \max |AR(f)|\} + 3$ . <sup>4</sup> Simulation model fidelity set using LPW parameter of CST Microwave Studio that controls structure density discretization.

## 7. Discussion and Conclusions

This paper presented an overview of the recent techniques for EM-driven size reduction in high-frequency structures. While simulation-based procedures, including numerical optimization, have been playing an increasing role in antenna and microwave design, miniaturization-oriented parameter tuning has been sparsely treated in the literature so far. In this work, we recalled the size reduction task along with its explicit and implicit formulations, as well as reviewed several recent methodologies developed to address its inherent challenges, specifically the need of controlling several performance figures and the presence of expensive constraints. The discussed procedures include implicit approaches with adaptive adjustment of penalty coefficients, an algorithm for a precise explicit constraint control, as well as a dedicated routine for optimization-based correction of equality constraint violation. Accelerated EM-driven miniaturization using variable-resolution models has been discussed as well. The juxtaposition of the discussed miniaturization frameworks is provided in Table 7. Theoretical considerations have been illustrated using a number of real-world examples of broadband and circular polarization antennas, we well as microstrip couplers.

**Table 7.** Main features of the considered miniaturization algorithms.

Approach	Implicit Constraint Handling with Adaptive Penalty Factors (Section 3)	Explicit Constraint Handling (Section 4)	Equality Constraint Control through Optimization-Based Correction (Section 5)	Expedited Optimization-Based Miniaturization Algorithm (Section 6)
Versions	Convergence-based penalty factor adjustment (Section 3.1)	Penalty factor adjustment based on constraint violation improvement (Section 3.2)	–	–
Constraint treatment	Equality Inequality	Implicit Implicit	Explicit Explicit	Explicit Implicit
Simulation model	Implicit	Implicit	Explicit	Implicit
	High-fidelity	High-fidelity	High-fidelity	High-fidelity
				Variable-fidelity

The presented numerical results corroborate the efficacy of both implicit and explicit techniques, especially in terms of the precise control of the design constraints, but also achievable miniaturization rate. The former is instrumental in the appropriate identification of the minimum-size designs: as a reduction in physical dimensions is detrimental to electrical and field performance figures, constrained optima are normally allocated at the feasible region boundary. Consequently, the performance of the optimization process is contingent upon the ability to explore this region. The procedures presented in this paper make it possible while eliminating the need for meticulous tuning of the control parameters in conventional methods. As demonstrated, they can also be accelerated by employing variable-resolution computational models.

While the overall performance of the outlined methods is similar, implicit techniques (i.e., those featuring adaptive adjustment of penalty terms) are conceptually simpler and, therefore, easier to implement. Further, they generally ensure slightly better miniaturization rates, although the difference is minor. On the other hand, explicit methods offer more precise control over the design constraints. From the point of view of a potential user of the aforementioned frameworks, either of them may be considered an attractive alternative to conventional methods. For those reliant on experience-driven parametric studies, the outlined techniques may prove useful tools for achieving size reduction beyond any interactive approaches.

It should be reiterated that the primary purpose of the paper was to provide the reader with a number of alternatives in terms of possible algorithmic approaches for EM-driven size reduction, rather than to compare them against each other. As mentioned earlier, the overall performance of the presented algorithms is similar, whereas the major differences are concerned with the specific ways of handling constraints (which may be preferred for specific applications, as elaborated on in the paper) as well as due to implementation details and complexity.

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