

Performance-Driven Yield Optimization of High-Frequency Structures by Kriging Surrogates

Slawomir Koziel ^{1,2} and Anna Pietrenko-Dabrowska ^{2,*}

¹ Engineering Optimization & Modeling Center, Reykjavik University, 102 Reykjavik, Iceland; koziel@ru.is

² Faculty of Electronics, Telecommunications and Informatics, Gdansk University of Technology, 80-233 Gdansk, Poland

* Correspondence: anna.dabrowska@pg.edu.pl

Abstract: Uncertainty quantification is an important aspect of engineering design, as manufacturing tolerances may affect the characteristics of the structure. Therefore, the quantification of these effects is indispensable for an adequate assessment of design quality. Toward this end, statistical analysis is performed, for reliability reasons, using full-wave electromagnetic (EM) simulations. Still, the computational expenditures associated with EM-driven statistical analysis often turn out to be unendurable. Recently, a performance-driven modeling technique has been proposed that may be employed for uncertainty quantification purposes and can enable circumventing the aforementioned difficulties. Capitalizing on this idea, this paper discusses a procedure for fast and simple surrogate-based yield optimization of high-frequency structures. The main concept of the approach is a tailored definition of the surrogate domain, which is based on a couple of pre-optimized designs that reflect the directions featuring maximum variability of the circuit responses with respect to its dimensions. A compact size of such a domain allows for the construction of an accurate metamodel therein using moderate numbers of training samples, and subsequently, it is employed to enhance the yield. The implementation details are dedicated to a particular type of device. Results obtained for a ring-slot antenna and a miniaturized rat-race coupler imply that the cost of yield optimization process can be reduced to few dozens of EM analyses.

Keywords: statistical analysis; yield optimization; metamodeling; performance-driven modeling; domain confinement

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1. Introduction

High-frequency systems are normally designed in the nominal sense, with possible deviations of geometry and material parameters (e.g., due to fabrication inaccuracies) being generally neglected. Yet, uncertainties may have detrimental effects on the performance. As a consequence, it is important to develop procedures for their evaluation. Among possible types of uncertainties, those pertinent to imperfect manufacturing [1,2] play the most important role in practice. They are stochastic, which makes statistical analysis imperative for their evaluation [3–5]. Diminishing the impact of parameter deviations requires a maximization of appropriately defined figures of merit such as response variance or the yield [6–8]. In the case of high-frequency systems, yield seems to be more suitable because performance specifications are often expressed in a minimax form, particularly for lower/upper acceptance thresholds for *S*-parameters, etc. [9–12].

As mentioned earlier, the evaluation of the effects of parameter tolerances involves statistical analysis [13,14]. For reliability, it is normally carried out using full-wave electromagnetic (EM) analysis, which is associated with significant computational costs. Nevertheless, it is mandatory whenever simpler models (e.g., equivalent circuits) fail insufficiently to account for cross-coupling and similar effects [15–18]. Improving the computational efficiency of statistical analysis can be achieved using simplistic yet

inaccurate methods (e.g., worst-case analysis [19–21]) or surrogate-assisted techniques [22,23], where repetitive EM simulations are replaced by an evaluation of a fast replacement model, usually prepared beforehand. Popular modeling methods include polynomial approximation [24], neural networks (NNs) [25,26], or polynomial chaos expansion (PCE) [27–33]. Despite their advantages, surrogate-based methods are affected by the curse of dimensionality, resulting in excessive costs of model rendition for more complex systems. The alleviation of these difficulties is partially possible by the employment of hybrid techniques (e.g., PC kriging [6], [34,35]), dimensionality reduction [36], multi-resolution methods (space mapping [37–40] and co-kriging [41,42]), or model order reduction [43].

Reducing the effects of manufacturing tolerances is even more essential than their evaluation. The relevant procedures are often referred to as robust design (also yield-driven design, tolerance-aware optimization, etc.) [1,44–47]. In practical terms, this can be accomplished by improving the statistical merit functions of choice, such as the yield. Unfortunately, yield maximization is a CPU-heavy task to the extent of being prohibitive when directly executed at the level of EM simulation models. Surrogate-assisted procedures offer viable workarounds [6,24–28]. Some of the most popular modeling methods utilized in this context are polynomial approximations [24], space mapping [48], NNs [49], and PCE [50]. As for statistical analysis, the bottleneck is a potentially high cost of the surrogate model setup, related to the dimensionality of the parameter space and parameter ranges. A partial mitigation has been offered by sequential approximation optimization (SAO) [51], where the metamodel is rendered along the optimization path, within the limited-volume domains centered at the current design produced by the robust design procedure. Another option is to employ response-feature technology [52]. This method capitalizes on the reduced nonlinearity of the relationship between the appropriately selected characteristic points of the system's responses and geometry parameters of the structure under design. The latter enables the construction of accurate metamodels using small training datasets [53].

In this work, we discuss a method for reduced-expense yield maximization of antenna and microwave components. Our approach involves the recently introduced performance-driven (or constrained) modeling [54–56], which addresses the surrogate construction task from the perspective of the model domain. More specifically, the model is only rendered in the vicinity of the region containing high-quality designs, which prevents wasting computational resources in parameter space regions containing uninteresting designs. This approach enables the construction of reliable metamodels over broad ranges of parameters and operating conditions using limited numbers of training data points [57–59]. Here, this paradigm is employed to construct surrogate models for robust design purposes. In particular, the domain of such a surrogate is extended along the directions possessing a major impact on the system's yield (the directions are found using a separate optimization sub-problems) and restricted along the remaining directions. Low domain volumes allow us to construct reliable surrogates, which are sufficient for conducting the yield maximization process without the necessity to rebuild the model. Our methodology is demonstrated using a ring-slot antenna and a microstrip coupler. In both cases, the robust design process is accomplished at a cost corresponding to less than a hundred of EM simulations. Reliability is corroborated by using EM-driven Monte Carlo analysis.

2. Yield Optimization Problem and Benchmark Algorithms

This section recalls the yield optimization problem statement, illustrated using two specific cases, multi-band antennas, and equal power split coupler. Subsequently, two basic state-of-the-art surrogate-assisted yield optimization algorithms are described. These will be used as benchmark methods in Section 4.

2.1. Yield Optimization Problem

In antenna and microwave designs, performance requirements are frequently formulated in a minimax form, i.e., by setting upper/lower acceptance levels on the electrical characteristics of the device at hand. These may include maximum in-band reflection (antennas) or maximum power split error within the operating band (couplers) [9]. As a consequence, a commonly utilized figure of merit is the yield [4], i.e., the percentage of designs for which the target specifications are met given the assumed deviations of the parameters. Figures 1 and 2 show two examples of the design optimization tasks of high-frequency devices: a multi-band antenna and a microwave coupler. The figures provide the design specifications, as well as the formulations of the respective objective functions. For the antenna, the nominal design has to ensure the best possible matching within the operating bands of interest, whereas in the case of the coupler, the aim is to ensure equal power split and to improve the bandwidth. Typically, the nominal designs serve as a starting point for yield optimization.

Design task: Ensure that the antenna impedance matching at the design $\mathbf{x}$ is not worse than $S_{\max}$ within all target fractional bandwidths:

$$\max \left\{ f \in \bigcup_{k=1}^N \left[\left(1 - \frac{B}{2} \right) f_{0k}, \left(1 + \frac{B}{2} \right) f_{0k} \right] : |S_{11}(\mathbf{x}, f)| \leq S_{\max} \right\} \quad (\text{E1.1})$$

where: $\mathbf{x}$ – vector of designable variables,

f_{0k} , $k = 1, \dots, N$ – target operating frequencies,

B – target fractional bandwidth,

$S_{\max}$ – maximum in-band reflection level, typically set to -10 dB,

f – frequency.

Nominal design $\mathbf{x}^{(0)}$ is obtained by solving:

$$\mathbf{x}^{(0)} = \arg \min_{\mathbf{x}} \left\{ \max \left\{ f \in \bigcup_{k=1}^N \left[\left(1 - \frac{B}{2} \right) f_{0k}, \left(1 + \frac{B}{2} \right) f_{0k} \right] : |S_{11}(\mathbf{x}, f)| \right\} \right\} \quad (\text{E1.2})$$

Figure 1. Example I: Multiple-band antenna optimized for best in-band matching.

Performance figures: Power split error $dS(\mathbf{x}) = ||S_{21}(\mathbf{x}, f)| - |S_{31}(\mathbf{x}, f)||$ and -20 dB $B(\mathbf{x})$, symmetric bandwidth w.r.t f_0 , defined as

$$B(\mathbf{x}) = 2 \min\{f_0 - \max\{f_{11,L}(\mathbf{x}), f_{41,L}(\mathbf{x})\}, \min\{f_{11,H}(\mathbf{x}), f_{41,H}(\mathbf{x})\} - f_0\} \quad (\text{E2.1})$$

where: $\mathbf{x}$ – vector of designable variables,

$S_{ki}(\mathbf{x}, f)$, $k = 1, \dots, 4$ – scattering parameters of the coupler,

f_0 – coupler operating frequency,

$f_{11,L}, f_{11,H}$ – lower and upper frequencies for which $|S_{11}(\mathbf{x}, f)| = -20$ dB,

$f_{41,L}, f_{41,H}$ – lower and upper frequencies for which $|S_{41}(\mathbf{x}, f)| = -20$ dB,

f – frequency.

Design specifications: $dS(\mathbf{x}) \leq dS_{\max}$ and $B(\mathbf{x}) \geq B_{\min}$

Nominal design $\mathbf{x}^{(0)}$ is optimized to obtain equal power split and minimize $|S_{11}|$ and $|S_{41}|$ for $f \in B_{\min}$ and may be obtained by solving:

$$\mathbf{x}^{(0)} = \arg \min_{\mathbf{x}} \left\{ \max \left\{ \begin{array}{l} f_0 - \frac{B_{\min}}{2} \leq f \leq f_0 + \frac{B_{\min}}{2} : \\ \max\{|S_{11}(\mathbf{x}, f)|, |S_{41}(\mathbf{x}, f)|\} \end{array} \right\} + \beta \cdot [dS(\mathbf{x})]^2 \right\} \quad (\text{E2.2})$$

Here, the primary objective is minimization of the maximum of matching and isolation characteristics within the assumed bandwidth, whereas the second component is a penalty factor than enforces equal power split.

Figure 2. Example II: Microwave coupler optimized to ensure the target power split and bandwidth enhancement.

The deviations $d\mathbf{x}$ (e.g., manufacturing tolerances) are characterized by the specified probability distributions (e.g., uniform of maximum deviation $\delta_{\max}$ or joint Gaussian $N(0, \sigma)$). The deviations may be correlated [60], yet we assume here that they are statistically independent. Yield $Y(\mathbf{x})$ at a certain the design $\mathbf{x}$ may be assessed by using Monte Carlo analysis.

$$Y(\mathbf{x}) = \frac{1}{p} \sum_{k=1}^p H(\mathbf{x}^{(k)}) \quad (1)$$

In (1), $\mathbf{x}^{(k)} = \mathbf{x} + d\mathbf{x}^{(k)}$, $k = 1, \dots, p$, denote the observables, $d\mathbf{x}^{(k)}$ are the random deviations, and $H(\mathbf{x})$ is given by the following.

$$H(\mathbf{x}) = \begin{cases} 1 & \text{if design specifications are satisfied} \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

We employ the following formulation of the yield optimization task.

$$\mathbf{x}^* = \arg \min_{\mathbf{x}} \{-Y(\mathbf{x})\} \quad (3)$$

Commonly, nominal design $\mathbf{x}^{(0)}$ is used as a starting point for solving (3), which, in turn, is rendered by solving, e.g., problem (E1.2) (for the example of the multi-band antenna) or (E2.2) (for the example of the microwave coupler).

2.2. Yield Optimization. Benchmark Surrogate-Assisted Algorithms

This section delineates the benchmark surrogate-assisted techniques: one-shot approach (Algorithm 1) and sequential approximate optimization SAO (Algorithm 2), the main features of which are juxtaposed in Table 1. Algorithms 1 and 2 exploit kriging data-driven surrogates [61], yet the actual choice of metamodeling technique is of secondary importance (other possibilities are, e.g., RBF [62] or PCE [29]).

Table 1. Surrogate-assisted yield optimization: one-shot approach and sequential approximate optimization.

Algorithm	Algorithm 1	Algorithm 2
Method	One-shot approach	Sequential approximate optimization
Solving optimization task	Solve a single task $\mathbf{x}^* = \operatorname{argmin}\{\mathbf{x} \in X_s : -Y(\mathbf{x})\}$ within the surrogate domain X_s	Render series $\mathbf{x}^{(i)}, i = 0, 1, \dots$, of approximations to $\mathbf{x}^*$ by solving $\mathbf{x}^{(i+1)} = \operatorname{argmin}\{\mathbf{x} \in X_{s,i} : -Y_{s,i}(\mathbf{x})\}$
Yield estimation	$Y(\mathbf{x})$ evaluated once using single surrogate	In each iteration, $Y_{s,i}$ is evaluated using the i th surrogate
Surrogate domain	$X_s = [\mathbf{x}^{(0)} - \boldsymbol{\delta}, \mathbf{x}^{(0)} + \boldsymbol{\delta}]$, $\boldsymbol{\delta} = [\delta_1 \dots \delta_n]^T$, $\delta_k = 10\delta_{\max}^\#, k = 1, \dots, n$	$X_{s,i} = [\mathbf{x}^{(i)} - \boldsymbol{\delta}, \mathbf{x}^{(i)} + \boldsymbol{\delta}]$, $\boldsymbol{\delta} = [\delta_1 \dots \delta_n]^T$, $\delta_k = 3\delta_{\max}^\#, k = 1, \dots, n$
Pros	Simple to apply	Reduced cost of setting up the surrogate (smaller domain)
Cons	Expected high cost of surrogate construction in a larger domain	Iterative process involving domain relocation and constructing several surrogates

[#] $\delta_{\max}$ —maximum deviation for uniform distribution (or 3σ for Gaussian distribution of variance σ).

The overall idea of Algorithm 1 is to build a single surrogate for which its domain is spread over an ample neighborhood of the nominal design solution, within which the yield may be estimated in a reliable manner. This method is unsophisticated; however, the training data acquisition cost may be sizeable (proportional to the domain size). On the other hand, in Algorithm 2, yield estimation is replaced by an iterative process. Here, the aim is to set up the metamodel over a domain of a lower size, and then reposition it from iteration to iteration. Consequently, the CPU cost of the surrogate setup is reduced (as compared to Algorithm 1); however, the optimization process typically takes several iterations to converge.

3. Surrogate-Based Yield Optimization with Domain Confinement

This section discusses the main components of the considered optimization framework that preserves the simplicity of the one-shot approach (Algorithm 1), while keeping the surrogate setup cost at a reasonable level. This is achieved by exploiting the performance-driven modeling paradigm [54,55]. The employed procedure for locating the directions that span the metamodel domain is introduced in the context of multi-band antenna designs (Section 3.1) and microwave coupler designs (Section 3.2), along with the respective domain definitions. These two methods share the same underlying idea, yet they are tailored to the particular sets of performance specifications, as delineated in Section 2.1.

3.1. Yield Optimization of Multi-Band Antennas

The directions that affect the antenna characteristics to the highest degree are selected by pre-optimizing two supplementary designs: (i) the design that maximizes the antenna symmetrical fractional bandwidths, and (ii) the design that minimizes the antenna reflection at $f_{0,k}$, $k = 1, \dots, N$, (i.e., the resonant frequencies). These designs are rendered by solving the following [63].

$$\mathbf{x}^{(1)} = \operatorname{argmin}_{\mathbf{x}} \left\{ -\min \{ B_1(\mathbf{x}), \dots, B_N(\mathbf{x}) \} \right\} \quad (4)$$

$$\mathbf{x}^{(2)} = \arg \min_{\mathbf{x}} \left\{ \max \left\{ |S_{11}(\mathbf{x}, f_{01})|, \dots, |S_{11}(\mathbf{x}, f_{0N})| \right\} \right\} \quad (5)$$

In (4), $B_k(\mathbf{x}) = 2\min\{f_{0k} - f_{1k}(\mathbf{x}), f_{2k}(\mathbf{x}) - f_{0k}\}$, $k = 1, \dots, N$, (symmetric portion of the bandwidth), whereas f_{1k} and f_{2k} denote the frequencies for which $|S_{11}|$ assumes -10 dB level (the lower and higher frequencies around the k th resonance). The trust-region gradient algorithm [64] is employed to solve problems (4) and (5), and the antenna response sensitivities are updated by applying the Broyden formula [65]. Consequently, the optimization cost equals approximately $1.5n$ EM analyses (n being the number of designable parameters).

Figure 3 describes surrogate domain X_s and its establishment with the use of the reference designs, whereas Figure 4 illustrates this process graphically. The surrogate domain X_s is small; still, it encompasses the most consequential directions of antenna response variations that directly affect the yield, thereby allowing for significant cost reductions. The yield is optimized directly by solving (3) (i.e., the surrogate is used instead of EM simulations), similarly as in Algorithm 1.

Let $\mathbf{s}(t) = [s_1(t) \dots s_n(t)]^T$ be a t -parameterized curve such that the following is the case:

$$s_j(t) = a_{j0} + a_{j1}t + a_{j2}t^2$$

for $0 \leq t \leq 1$, so that $\mathbf{s}(0) = \mathbf{x}^{(1)}$, $\mathbf{s}(0.5) = \mathbf{x}^{(0)}$, and $\mathbf{s}(1) = \mathbf{x}^{(2)}$.

The model coefficients can be found as follows.

$$\begin{bmatrix} a_{10} & L & a_{n0} \\ a_{11} & L & a_{n1} \\ a_{12} & L & a_{n2} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 0.5 & 0.25 \\ 1 & 1 & 1 \end{bmatrix}^{-1} \begin{bmatrix} (\mathbf{x}^{(1)})^T \\ (\mathbf{x}^{(0)})^T \\ (\mathbf{x}^{(2)})^T \end{bmatrix}$$

Let $S(t)$ be the interval with the center at $\mathbf{s}(t)$ and the size $\delta_c = [\delta_{c1} \dots \delta_{cn}]^T$, where δ_{cj} is a small multiplicity of the maximum design deviation $\delta_{\max}$, e.g., $2\delta_{\max}$.

Surrogate model domain X_s is defined as the set-theory union of the intervals $S(t)$ for $0 \leq t \leq 1$.

$$X_s = \bigcup_{0 \leq t \leq 1} S(t)$$

X_s contains the reference designs $\mathbf{x}^{(0)}$, $\mathbf{x}^{(1)}$, and $\mathbf{x}^{(2)}$ and a vicinity of the entire curve $\mathbf{s}(t)$ of size δ .

Figure 3. Surrogate domain definition using the reference designs. Multi-band antennas case.

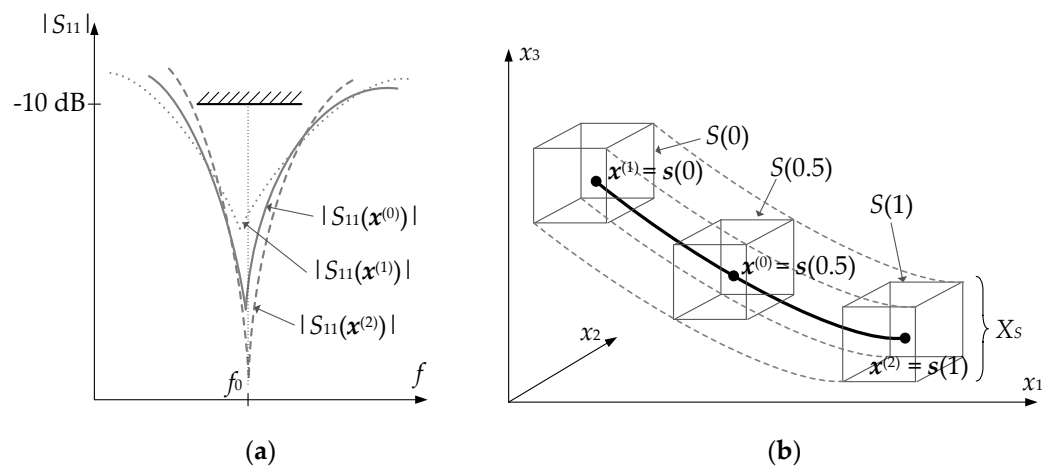


Figure 4. Yield optimization of multi-band antennas using performance-driven surrogates: (a) reflection responses of an exemplary narrow-band antenna at the nominal design $\mathbf{x}^{(0)}$, maximum bandwidth design $\mathbf{x}^{(1)}$, and best matching (at f_0) design $\mathbf{x}^{(2)}$. These designs determine the directions of the most significant response changes (from the point of view of the target operating bandwidth); (b) The reference designs $\mathbf{x}^{(0)}$ through $\mathbf{x}^{(2)}$ form a path (a parameterized curve $\mathbf{s}(t)$). The union of intervals $S(t)$ (cf. (15)) form the surrogate model domain X_s .

3.2. Yield Optimization of Microwave Couplers

In this case, the design requirements include the power split error and the bandwidth. We define $f_{11.L}(\mathbf{x})$, $f_{11.H}(\mathbf{x})$, $f_{41.L}(\mathbf{x})$, and $f_{41.H}(\mathbf{x})$ (the frequencies that are bandwidth boundaries) and also $l_1(\mathbf{x}) = |S_{21}(\mathbf{x}, f_0)|$ and $l_2(\mathbf{x}) = |S_{31}(\mathbf{x}, f_0)|$ (the levels of the respective coupler responses at its operating frequency). These, in turn, are gathered in the vector $\mathbf{F}(\mathbf{x}) = [f_{11.L}(\mathbf{x}), f_{11.H}(\mathbf{x}), f_{41.L}(\mathbf{x}), f_{41.H}(\mathbf{x}), l_1(\mathbf{x}), l_2(\mathbf{x})]^T$, for which Jacobian $\mathbf{J}_F$ can be derived from the Jacobian $\mathbf{J}_S$ of the circuit response (evaluated through finite differentiation). The linear expansion model of $\mathbf{F}$ at the nominal design $\mathbf{x}^{(0)}$ is as follows [66].

$$\mathbf{L}_F(\mathbf{x}) = [\mathbf{L}_1(\mathbf{x}) \ \mathbf{L}_2(\mathbf{x}) \ \dots \ \mathbf{L}_6(\mathbf{x})]^T = \mathbf{F}(\mathbf{x}^{(0)}) + \mathbf{J}_F(\mathbf{x}^{(0)}) \cdot (\mathbf{x} - \mathbf{x}^{(0)}) \quad (6)$$

As before, we also have two supplementary designs $\mathbf{x}^{(1)}$ and $\mathbf{x}^{(2)}$ yielded by solving the following.

$$\mathbf{x}^{(1)} = \arg \min_{\mathbf{x}} \left\{ L_5(\mathbf{x}) - L_6(\mathbf{x}) + \beta_2 \left\| \begin{bmatrix} \mathbf{L}_1(\mathbf{x}) \\ \vdots \\ \mathbf{L}_4(\mathbf{x}) \end{bmatrix} - \begin{bmatrix} \mathbf{L}_1(\mathbf{x}^{(0)}) \\ \vdots \\ \mathbf{L}_4(\mathbf{x}^{(0)}) \end{bmatrix} \right\|^2 \right\} \quad (7)$$

$$\mathbf{x}^{(2)} = \arg \min_{\mathbf{x}} \left\{ -2 \min \{ f_0 - \max \{ L_1(\mathbf{x}), L_3(\mathbf{x}) \}, \min \{ L_2(\mathbf{x}), L_4(\mathbf{x}) \} - f_0 \} + \beta_1 \cdot [L_5(\mathbf{x}) - L_6(\mathbf{x})]^2 \right\} \quad (8)$$

Both (7) and (8) are subject to $\|\mathbf{x} - \mathbf{x}^{(0)}\| \leq D$ (D being selected by the user; here, we set $D = 0.5$ mm). Solving (7) and (8) requires merely n EM analyses of the coupler (it is the cost of estimating $\mathbf{J}_F$ in (6)). These designs serve to find the directions corresponding to the maximal variations of the coupler power split and bandwidth, respectively. Figure 5 provides a brief description of the surrogate domain definition using these reference designs, whereas a graphical illustration of these procedure is provided in Figure 6.

Surrogate domain X_S is small volume-wise, yet it is ample enough to encompass the directions of essential changes of the coupler responses affecting its yield. As in the previous case (Section 3.1), a small volume of the domain allows a significant reduction in the cost of setting up the surrogate, and also—due to the mentioned coverage of important directions—there is no need to iterate the entire process (as in Algorithm 2). The yield optimization process is conducted by solving (3), i.e., similarly as in the algorithm of Section 3.1.

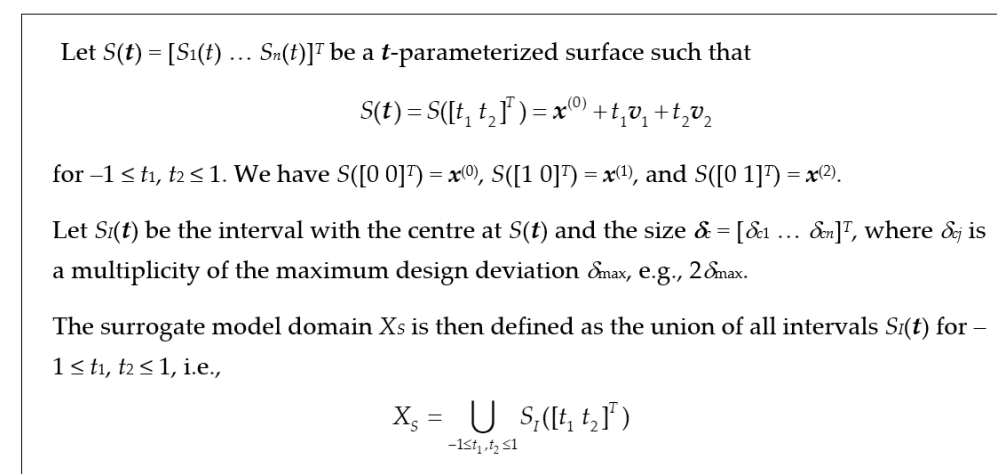


Figure 5. Surrogate domain definition using the reference designs. Microwave couplers case.

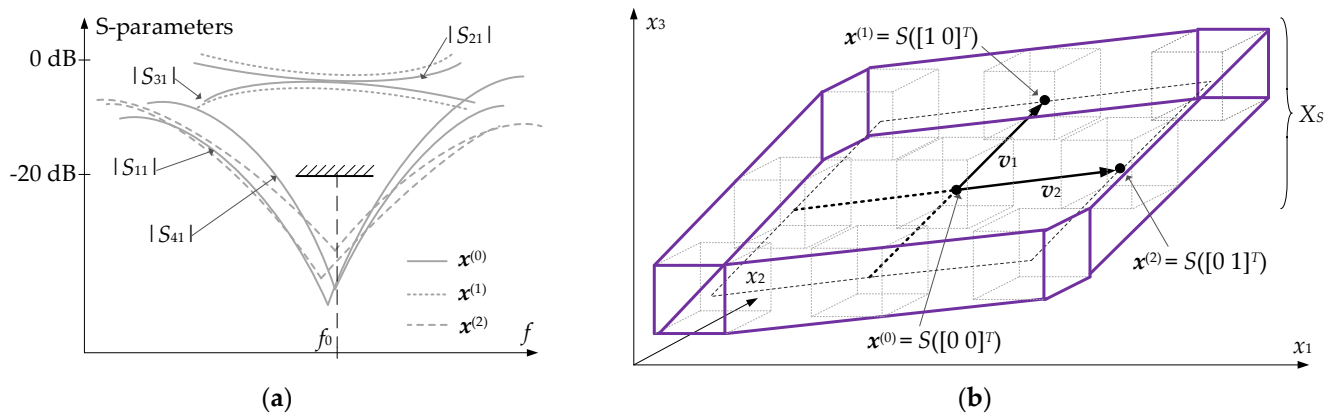


Figure 6. Yield optimization of microwave couplers by means of performance-driven surrogates: (a) scattering parameters of an exemplary coupler at the nominal design $\mathbf{x}^{(0)}$, design $\mathbf{x}^{(1)}$ (spoiled power split), and design $\mathbf{x}^{(2)}$ (improved -20 dB bandwidth); for clarity, only the selected S-parameters are shown for $\mathbf{x}^{(1)}$ ($|S_{21}|$, $|S_{31}|$) and $\mathbf{x}^{(2)}$ ($|S_{11}|$, $|S_{41}|$). These designs determine the directions of the most significant response changes (from the point of view of yield manipulation). (b) The designs $\mathbf{x}^{(0)}$ to $\mathbf{x}^{(2)}$ form a parameterized surface $S(t)$. The union of intervals $S_i(t)$ (cf. (21)) forms surrogate model domain X_S .

4. Demonstration Case Studies

This section provides the results obtained using the algorithms of Sections 3.1 and 3.2 using a ring-slot antenna, and a miniaturized rat-race coupler as verification structures. The procedure is benchmarked against the surrogate-assisted approaches of Section 2. In order to verify the reliability of the considered methodology, a Monte Carlo analysis has been executed at the nominal design and the yield maximizing design.

4.1. Case I: Ring-Slot Antenna

Figure 7 shows our first verification structure: a ring slot antenna, for which its circular ground plane featuring a slot with defected ground structure is excited through a microstrip line [67], whereas all the pertinent details are provided in Figure 8. We assumed independent uniformly distributed parameter deviations with maximum deviation $\delta_{\max} = 0.05$ mm. The yield optimization results are provided in Table 2 for the algorithm of Section 3.1 and the benchmark surrogate-assisted procedures of Table 1. For the discussed approach, the size of the metamodel domain was set to $\delta_{c,k} = 2\delta_{\max}$ (see Figure 3); the training data set for constructing the surrogate contained 35 samples; and its relative RMS error equals 0.5%.

The details pertaining to the benchmark procedures are as follows. For Algorithm 1, the metamodel of relative RMS error 0.7% was constructed using 400 samples within the domain of size $10\delta_{\max}$. For Algorithm 2, the surrogate models were built using 50 training data samples over the domain of size $3\delta_{\max}$. Here, the first metamodel (of the domain focused around $\mathbf{x}^{(0)}$) featured a relative RMS error of 0.4%. In both cases, the aim was to render the metamodels of similar accuracy to less than one percent to ensure the reliability of the yield estimation. The following yield maximizing design was rendered $\mathbf{x}^* = [20.18 \ 6.43 \ 0.21 \ 11.85 \ 2.95 \ 6.78 \ 7.90 \ 2.31]^T$. Figure 9 visualizes the results of Monte Carlo analysis at $\mathbf{x}^{(0)}$ and at $\mathbf{x}^*$ (carried out with the use of 500 samples).

The results of Table 2 may be summarized as follows. The metamodel domain confinement according to the methodology described in Section 3.1. results in dramatic cost savings, which is mainly due to the decreased volume size. Still, as the domain is spanned over the significant directions of the design space (those representing the maximum variations of the antenna response), the yield optimization process may successfully be concluded in one stage.

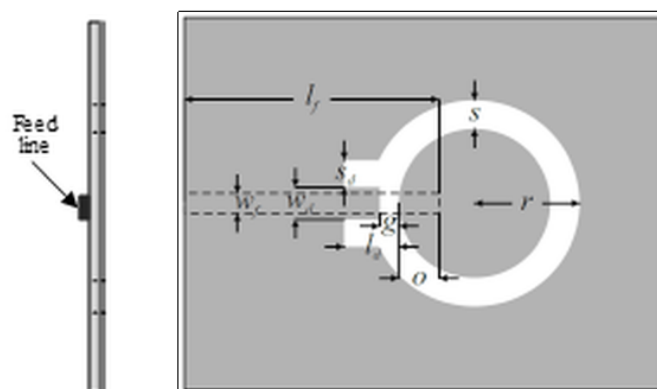


Figure 7. Geometry of the ring slot antenna with a microstrip feed (dashed line) [67].

Ring slot antenna:

Substrate: $h = 0.76$ mm, relative permittivity $\epsilon_r = 2.0$

Geometry parameters: $\mathbf{x} = [l_f \ l_s \ w_c \ r \ s \ s_d \ o \ g]^T$

Design objective: minimization of the in-band reflection for the frequency range 4.15 GHz to 4.85 GHz (center frequency $f_0 = 4.5$ GHz)

The nominal design: $\mathbf{x}^{(0)} = [20.28 \ 6.54 \ 0.24 \ 11.83 \ 2.95 \ 6.77 \ 7.85 \ 2.23]^T$

Reference designs (yielded at the cost of only 13 and 14 EM simulations, respectively):

$\mathbf{x}^{(1)} = [20.03 \ 6.30 \ 0.20 \ 11.84 \ 2.94 \ 6.74 \ 7.89 \ 2.43]^T$ (maximum bandwidth (4))

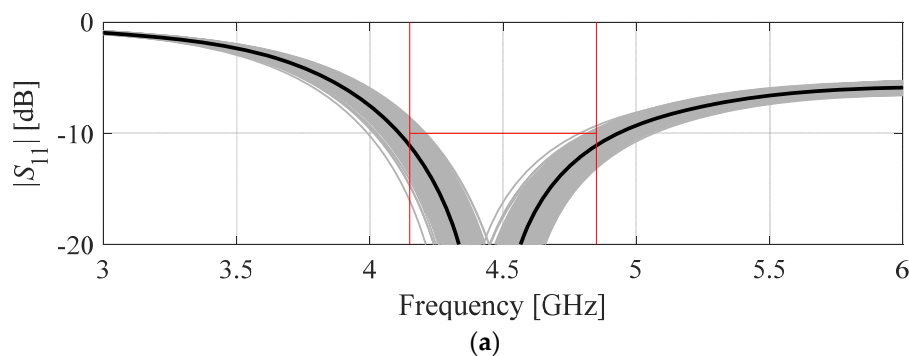
$\mathbf{x}^{(2)} = [20.26 \ 6.51 \ 0.20 \ 11.68 \ 2.92 \ 6.47 \ 7.49 \ 2.24]^T$ (best reflection at $f_0 = 4.5$ GHz (5))

Figure 8. Description of the ring slot antenna of Figure 7 [67].

Table 2. Yield optimization of the ring-slot antenna of Figure 7.

Optimization Algorithm	Initial Yield		Optimized Yield		CPU Cost ^s
	Estimated by Metamodel	EM-Based	Estimated by Metamodel	EM-Based	
Algorithm 1	81%	81%	92%	93%	400
Algorithm 2	81%	81%	91%	91%	150 [#]
Algorithm of Section 3.1	81%	81%	91%	91%	62 ^{&}

^s Optimization cost in number of EM analyses of the antenna structure. [#] The algorithm convergence after four iterations (surrogate setup cost 100 training samples per iteration). [&] The cost includes training data acquisition (35 EM analyzes) and the generation of reference designs $\mathbf{x}^{(1)}$ and $\mathbf{x}^{(2)}$ (27 EM simulations in total).



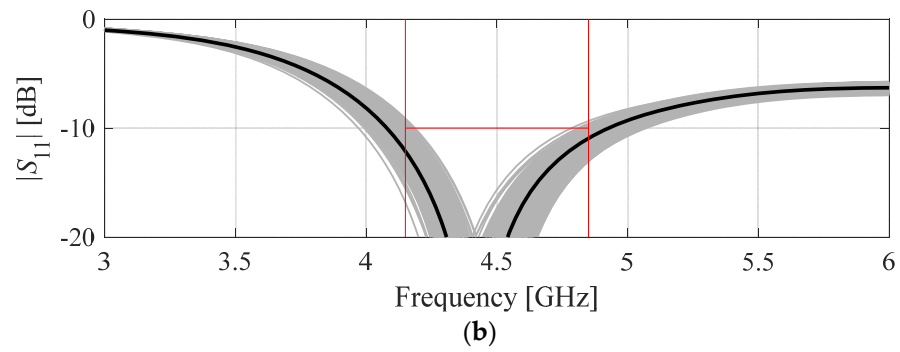


Figure 9. Monte Carlo analysis of antenna of Figure 7 using EM simulations (gray plots): (a) nominal design; (b) yield-optimized design obtained using the algorithm of Section 3.1. Black plots show the antenna response at the nominal and optimized designs, respectively.

4.2. Case IV: Compact Microstrip Rat-Race Coupler

The second verification structure is a miniaturized microstrip rat-race coupler (RRC) presented in Figure 10 and described in Figure 11 [68]. The compact size of the circuit is a result of folding of the transmission lines that constitute its interior.

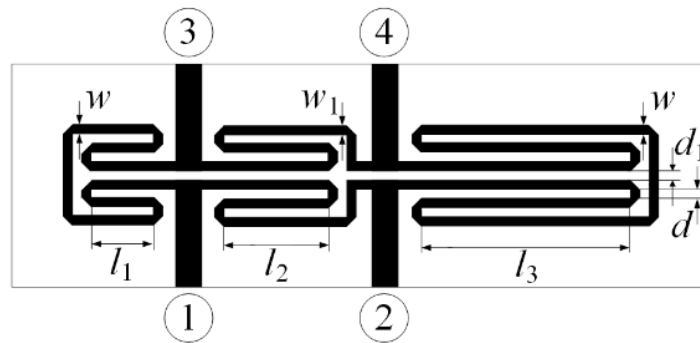


Figure 10. Layout of the miniaturized folded rat-race coupler [68]; the numbered circles (1 through 4) mark the structure ports.

Rat-race coupler:

Substrate: Taconic RF-35 ($\epsilon_r = 3.50$, $h = 0.762$ mm)

Geometry parameters: $\mathbf{x} = [l_1 \ l_2 \ l_3 \ d \ w \ w_1]^T$, $d_1 = d + |w - w_1|$, the input line width and length, $w_0 = 1.7$ and $l_0 = 15$, are fixed (all in mm).

Design objectives:

- maintain equal power split at the operating frequency $f_0 = 1$ GHz,
- minimize the circuit matching and isolation within $f \in (0.9 \text{ GHz}, 1.1 \text{ GHz})$,
- this frequency range is also the minimum acceptable -20 dB bandwidth

The nominal design: $\mathbf{x}^{(0)} = [4.50 \ 11.08 \ 21.80 \ 0.65 \ 0.94 \ 0.85]^T$

Reference designs (yielded at the cost of only 13 and 14 EM simulations, respectively):

$\mathbf{x}^{(1)} = [4.07 \ 11.56 \ 21.48 \ 0.65 \ 0.95 \ 0.86]^T$ (optimized according to (6))

$\mathbf{x}^{(2)} = [4.60 \ 11.18 \ 21.91 \ 0.66 \ 0.95 \ 0.85]^T$ (optimized according to (7))

Figure 11. Description of the rat-race coupler of Figure 10 [68].

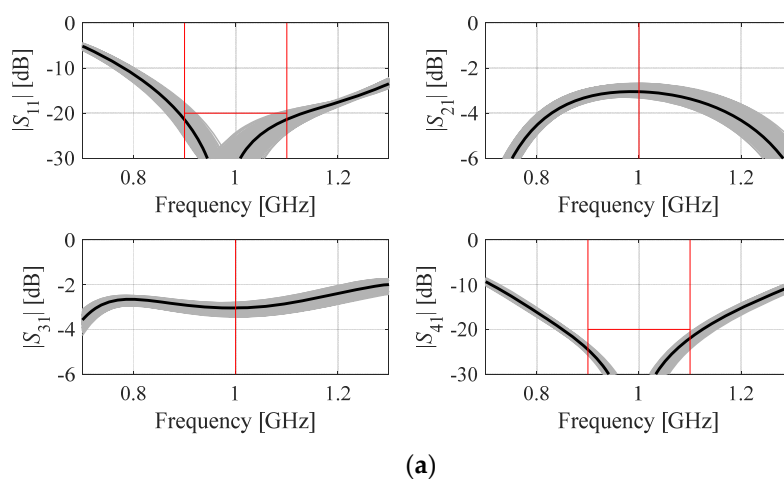
Parameter deviations are assumed to be independently and uniformly distributed with the maximum deviation of $\delta_{\max} = 0.05$ mm. For the discussed algorithm, the metamodel of the relative RMS error of 2.3% was set up within a domain of size $\delta_{x:k} = 2\delta_{\max}$, and the training data set comprised 72 training samples. In the case of Algorithm 1, the surrogate was constructed with 400 samples allocated over the domain of size $10\delta_{\max}$, and the relative RMS error was equal to 3.4%. For Algorithm 2, the first metamodel set up with 50 samples within the domain encompassing $\mathbf{x}^{(0)}$ featured a relative RMS error of 2.2% (the size-defining parameter has been set to $3\delta_{\max}$). Table 3 provides the relevant results for the discussed and benchmark algorithms. The following optimal design was yielded: $\mathbf{x}^* = [4.65 \ 11.10 \ 21.87 \ 0.71 \ 0.95 \ 0.81]^T$.

Table 3. Yield optimization of the compact coupler of Figure 10.

Optimization Algorithm	Initial Yield		Optimized Yield		CPU Cost [§]
	Estimated by Metamodel	EM-Based	Estimated by Metamodel	EM-Based	
Algorithm 1	67%	62%	90%	83%	400
Algorithm 2	66%	62%	86%	83%	200 [#]
Algorithm of Section 3.1	63%	62%	84%	82%	72

[§] Optimization cost in number of EM analyses of the antenna structure. [#] Algorithm convergence after four iterations (surrogate setup cost 100 training samples per iteration).

The results of Monte Carlo analysis at the initial and optimal designs are shown in Figure 12 (500 uniformly distributed samples were used with $\delta_{\max} = 0.05$ mm). In this case, the discussed approach and Algorithm 2 were able to estimate the yield in a reliable manner. As for Algorithm 1, the values of the yield predicted using the surrogate and EM simulations differed considerably. This is because the surrogate rendered across a domain of a larger size featured worse predictive power.



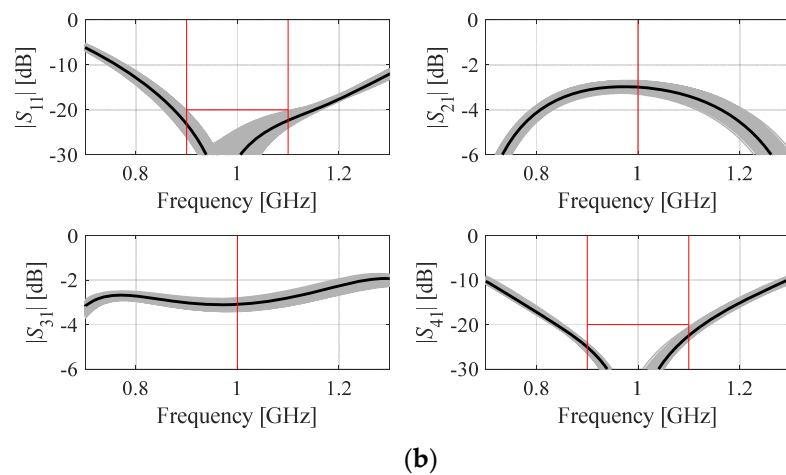


Figure 12. Monte Carlo analysis of the coupler of Figure 10 using EM simulations (gray plots): (a) nominal design; (b) yield-optimized design obtained using the algorithm of Section 3.2. Black plots show the antenna response at the nominal and the optimized designs, respectively.

As in the previous case, it has been verified that the yield optimization within a confined domain enables the obtainment of the benefits of both benchmark procedures. Thus, the entire process may be concluded in one stage due to spanning the domain along the most consequential directions (as opposed to the iterative Algorithm 2). Moreover, as the domain is of reduced size, it was possible to construct the surrogate at a remarkably low cost. The computational savings reached up to 82 and 64 percent (the discussed procedure versus Algorithms 1 and 2, respectively). At the same time, high design quality was maintained in all cases, and the value of the optimized yield is similar for all compared algorithms. Furthermore, the obtained results agree with those of EM-based Monte Carlo analysis.

5. Conclusions

This work discussed the recent techniques for surrogate-based yield maximization of high-frequency components. The main ingredients of the optimization framework are domain-confined metamodels constructed by keeping in mind the parameter-space directions that are the most influential in terms of affecting the system's performance. By maintaining the low overall volume of the domain, it is possible to construct reliable surrogates using a limited number of training data samples, and it is possible to carry out the yield optimization process without the need to rebuild the model. As demonstrated using two microstrip structures (an antenna and a rat-race coupler), the robust design process can be accomplished at remarkably low costs of a few dozens of EM simulations. Thorough benchmarking indicates significant savings, with >80 percent over reference surrogate-based approach and >60 percent over the SAO algorithm. At the same time, reliability has been corroborated using EM-driven Monte Carlo simulations. The optimization techniques considered in the paper offer improved computational efficiency over the state-of-the-art methods without compromising reliability. They are applicable to a variety of antenna and microwave components, and they may be viewed as potential replacements of conventional (also surrogate-assisted) procedures, especially for more complex, e.g., higher-dimensional design scenarios. Since in the considered approach, the surrogate domain is spanned by the directions that influence yield values in the most significant manner, the generalization of the technique would require properly defining these directions so that they reflect the respective design requirements.

In general, the two specific approaches for constructing the domain of the surrogate model (extension along the one-dimensional curve for the antenna example, and along two vectors corresponding to the maximum changes of the considered performance

figures for the coupler example) could be applied to either of the case studies. However, maintaining the domain extension's dimensionality as equal to the number of considered performance figures is recommended, which is to provide sufficient room for yield improvement within the domain.

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