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# Comprehensive Dimension Scaling of Multi-Band Antennas for Operating Frequencies and Substrate Parameters

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***Abstract*—In this paper, low-cost and comprehensive re-design of multi-band antennas with respect to the operating frequencies and material parameters of the substrate is presented. Our approach exploits an inverse surrogate model identified based on a set of reference designs optimized at the level of coarse-discretization EM simulations of the antenna at hand. An iterative correction procedure is also implemented to account for the initial scaling errors (being a result of limited accuracy of the inverse model). The cost of the antenna re-design corresponds to a few high-fidelity EM simulations of the structure. Our considerations are illustrated using a dual-band patch antenna scaled w.r.t. both operating frequencies in the ranges of 1.5 GHz to 2.5 GHz and 5.0 GHz to 6.0 GHz, respectively, as well as the relative permittivity and thickness of the dielectric substrate (within the ranges of 0.7 mm to 1.5 mm, and 2.5 to 3.5, respectively). Several verification cases are provided to confirm correctness of the scaling procedure.**

***Keywords—Antenna design; multi-band antennas; dimension scaling; EM-driven design; inverse modeling; design correction***

## I. Introduction

Design of modern antennas and antenna arrays is a challenging task due to the necessity of handling several performance figures (matching, gain, efficiency, radiation pattern, size, etc.), topological complexity of the structures (thus, a large number of adjustable parameters), as well as necessity of using full-wave electromagnetic (EM) analysis for accurate evaluation of electrical and field properties of the antenna. Particularly the last two factors constitute a fundamental bottleneck for design closure procedures, being it simple parameter sweeping (still an academic and industry standard) or more or less sophisticated numerical optimization algorithms [1]-[4]. In either case, a large number of EM simulations is required. Incorporating engineering experience into hands-on methods may speed up the design optimization process to some extent but only rough approximations of truly optimum designs can be found this way. On the other hand, rigorous optimization using conventional algorithms, both gradient-based [1] and derivative-free [2] may be prohibitively expensive. This is especially pertinent to global search methods such as population-based metaheuristics [5]-[9].

There have been considerable research efforts observed over the recent years towards development of techniques for speeding up EM-driven design of high-frequency structures. Available methods include gradient-based optimization with adjoint sensitivities [10], [11], as well as the entire class of surrogate-based optimization (SBO) algorithms [12]. SBO can utilize data-driven surrogates (e.g., [13], [14]) or physics-based ones, e.g., space mapping [15], manifold mapping [16], various response correction techniques (e.g., shape-preserving response prediction [17]), feature-based optimization [18], or adaptive response scaling [19].

Re-design of antenna structures for various operating conditions (e.g., operating frequencies) or material parameters (e.g., substrate permittivity) is a practically important problem which, in the context of numerical optimization, is just as challenging as finding the original design, i.e., the one from which the re-design process originates. In practice, certain number of designs may be available for a given structure and reusing them may facilitate the process of antenna dimension scaling. A technique based on this idea has been proposed in [20] for dimension scaling of narrow-band antennas with respect to the operating frequency. The method of [20] exploits an inverse surrogate model (constructed using a set of reference designs optimized for a selected set of operating frequencies), and a correction procedure to accommodate the misalignment between the low- and high-fidelity EM models utilized in the process. In [21], the technique of [20] has been extended for handling dual-band antennas, and also applied to microwave components [22].

Here, an inverse surrogate modeling approach is extended to re-design of multi-band antennas with respect to operating frequencies and material parameters of the dielectric substrate (permittivity and thickness). A fundamental challenge that arises due to handling several figures of interest is a limited accuracy of the inverse model which makes it necessary to develop an iterative correction scheme. The proposed approach is illustrated using a dual-band patch antenna scaled with respect to both operating frequencies (in the ranges of 1.5 GHz to 2.5 GHz, and 5.0 GHz to 6.0 GHz, respectively) and substrate parameters (0.7 mm to 1.5 mm for the thickness, and 2.5 to 3.5 for permittivity). Accurate re-design can be accomplished at the cost of a few EM simulations of the structure as demonstrated through comprehensive verification studies.

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## II. Antenna Re-Design for Operating Frequencies and Substrate Parameters

In this section, we formulate the dimension scaling problem, describe the process of inverse surrogate model construction, the scaling procedure, and the iterative correction scheme. Demonstration examples are provided in Section III.

### A. Formulation of Dimension Scaling Problem

Let $\boldsymbol{R}_f(\boldsymbol{x})$ be a response of a high-fidelity EM antenna model, where $\boldsymbol{x} = [x_1 \ldots x_n]^T$ is a vector of geometry parameters. Further, let $h$ and $\varepsilon_r$ be the parameters of the substrate, the antenna is implemented on (thickness and permittivity, respectively). Let $\boldsymbol{x}_f^*(f_{0.1},f_{0.2},\ldots,f_{0.p};h_0,\varepsilon_{r0})$ be the optimum set of antenna dimensions for the operating frequencies $f_{0.1}$, $f_{0.2}$, through $f_{0.p}$ ($p$ is the number of antenna bands) and the substrate parameters $h_0$, $\varepsilon_{r0}$. The scaling (or re-design) problem is formulated as follows: given $\boldsymbol{x}_f^*(f_{0.1},\ldots,f_{0.p};h_0,\varepsilon_{r0})$, find $\boldsymbol{x}_f^*(f_1,\ldots,f_p;h,\varepsilon_r)$, which are the optimum parameter values of the antenna for the required operating frequencies $f_1$, $f_2$, through $f_p$, and implemented on the substrate of thickness $h$ and dielectric permittivity $\varepsilon_r$. Certain (user-defined) ranges for the operating frequencies, $f_{k\min} \leq f_k \leq f_{k\max}$, and substrate parameters, $h_{\min} \leq h \leq h_{\max}$, $\varepsilon_{r\min} \leq \varepsilon_r \leq \varepsilon_{r\max}$, are assumed.

### B. Reference Designs and Inverse Surrogate

The inverse surrogate model is identified based on a set of reference designs, optimized for selected operating frequencies and substrate parameters, allocated within the ranges mentioned in Section II.*A*. We denote these as $\{f_{1.j},f_{2.j},\ldots,f_{p.j},h_j,\varepsilon_{r.j}\}$, $j = 1, \ldots, N_r$. The reference designs are obtained for the coarse-discretization EM antenna model $\boldsymbol{R}_c$.

The inverse surrogate model $\boldsymbol{x}_c(f_1,\ldots,f_p;h,\varepsilon_r)$ is defined as

$$\begin{aligned}&\boldsymbol{x}_c(f_1,\ldots,f_p;h,\varepsilon_r;\boldsymbol{P}) = \\ &= \left[x_{c.1}(f_1,\ldots,f_p;h,\varepsilon_r;\boldsymbol{p}_1) \;\ldots\; x_{c.n}(f_1,\ldots,f_p;h,\varepsilon_r;\boldsymbol{p}_n)\right]^T\end{aligned} \tag{1}$$

where $x_{c.l}(f_1,\ldots,f_p;h,\varepsilon_r,\boldsymbol{p}_l)$ is a model of the $l$th geometry parameter. The overall (aggregated) parameter vector $\boldsymbol{P} = [\boldsymbol{p}_1 \ldots \boldsymbol{p}_n]$. The analytical form of the inverse model is important. On one hand, it needs to be sufficiently flexible and account for interactions between design parameters. On the other hand, the number of model coefficients should be limited in order to focus on the main trends rather than modeling local fluctuations (e.g., due to inaccurate optimization of particular reference designs). Here, the surrogate is selected to be

$$x_{c.l}(f_1,\ldots,f_p;h,\varepsilon_r) = \left[\prod_{l=1}^{p} s_{f.l}(f_l)\right] s_{h.l}(h)s_{\varepsilon_r.l}(\varepsilon_r)q_l(f_0,K,h,\varepsilon_r) \tag{2}$$

where

$$\begin{aligned}s_{f.l}(f_l) &= a_{f.l.1} + a_{f.l.2}\exp(a_{f.l.3}f_l), \quad l = 1,\ldots,p \\ s_{h.l}(h) &= a_{h.1} + a_{h.2}\exp(a_{h.3}h) \\ s_{\varepsilon_r.l}(\varepsilon_r) &= a_{\varepsilon_r.1} + a_{\varepsilon_r.2}\exp(a_{\varepsilon_r.3}\varepsilon_r)\end{aligned} \tag{3}$$

and

$$\begin{aligned}q_l(f_1,\ldots,f_p,h,\varepsilon_r) &= a_{q.0} + a_{q.1}f_1 + \ldots + a_{q.p}f_p + a_{q.p+1}h + a_{q.p+2}\varepsilon_r + \\ &a_{q.p+3}f_1^2 + \ldots + a_{q.2p+2}f_p^2 + a_{q.2p+3}h^2 + a_{q.2p+4}\varepsilon_r^2 + \\ &+a_{q.2p+5}f_1f_2 + \;\ldots\; + a_{q.(p^2+7p+12)/2}h\varepsilon_r\end{aligned} \tag{4}$$

Here, $(p^2 + 7p + 12)/2$ is the total number of parameters of the $q$ model (e.g., it is 15 for a dual-band antenna). It can be observed that the exponential functions of (3) are used to model individual parameter dependence on operating conditions and substrate parameters, whereas the second-order polynomial of (4) accounts for interdependence between the parameters.

The surrogate model is extracted as

$$\boldsymbol{p}_l = \arg\min_{\boldsymbol{p}} \sum_{j=1}^{N_r} (x_{c.l}(f_{1.j},\ldots,f_{2.j};h_j,\varepsilon_{r.j},\boldsymbol{p}) - x_{c.j.l})^2 \tag{5}$$

where, $\boldsymbol{x}_{c.j} = [x_{c.j.1} \;\ldots\; x_{c.j.n}]^T$ is the coarse-discretization reference design corresponding to the operating frequencies $f_{1.j}$, $\ldots$, $f_{p.j}$, and the substrate parameters $h_j$ and $\varepsilon_{r.j}$.

An important remark is that the number of reference designs has to be larger or equal than the number of inverse model parameters, otherwise, the parameter extraction process (5) will lack uniqueness. In practice, it should be considerably larger in order to smoothen out possible fluctuations resulting from non-perfect optimization of the reference designs (cf. [20]). For example, in case of a dual-band antenna we have 27 model parameters in total. If the reference designs are allocated on a 3 × 3 × 3 × 3 grid (with respect to $f_j$, $h$, and $\varepsilon_r$), one has 81 reference designs. Clearly, other allocations are also possible, yet factorial design of experiments schemes are recommended in order to spread the reference designs as far from each other as possible.

### C. Scaling Procedure and Iterative Correction Scheme

Given the inverse model, the dimension scaling, i.e., finding the optimum dimensions of the antenna re-designed to required operating frequencies and substrate parameters only requires one-time evaluation of the surrogate. However, because the model has been constructed at the level of coarse-discretization EM simulations, a correction is needed. This is realized by adding a constant vector $\boldsymbol{x}_f^*(f_{0.1},f_{0.2},\ldots,f_{0.p};h_0,\varepsilon_{r0}) - \boldsymbol{x}_c^*(f_{0.1},f_{0.2},\ldots,f_{0.p};h_0,\varepsilon_{r0})$ that aligns both models at the operating conditions of $\{f_{0.1},f_{0.2},\ldots,f_{0.p},h_0,\varepsilon_{r0}\}$. We have

$$\begin{aligned}&\boldsymbol{x}_f(f_1,\ldots,f_p;h,\varepsilon_r) = \boldsymbol{x}_c(f_1,\ldots,f_p;h,\varepsilon_r,\boldsymbol{P}) + \\ &+\left[\boldsymbol{x}_f^*(f_{0.1},\ldots,f_{0.p};h_0,\varepsilon_{r.0}) - \boldsymbol{x}_c^*(f_{0.1},\ldots,f_{0.p};h_0,\varepsilon_{r.0})\right]\end{aligned} \tag{6}$$

The accuracy of the surrogate model is obviously limited due to the fact that its analytical formulation is rather simple (only a few degrees of freedom per operating condition) and wide range of conditions that needs to be covered in practice. Therefore, scaling errors are unavoidable. Let us denote by $\Delta f_k$ the differences between the required and the actual operating frequencies of the antenna. Correction of these errors can be achieved by using the following iterative procedure

$$\begin{aligned}&\boldsymbol{x}_f(f_1,\ldots,f_p;h,\varepsilon_r) \leftarrow \boldsymbol{x}_c(f_1 - \textstyle\sum_{k=1}^{i}\Delta f_{1.k},\ldots,f_p - \sum_{k=1}^{i}\Delta f_{p.k};h,\varepsilon_r,\boldsymbol{P}) + \\ &+\left[\boldsymbol{x}_f^*(f_{0.1},\ldots,f_{0.p};h_0,\varepsilon_{r.0}) - \boldsymbol{x}_c^*(f_{0.1},\ldots,f_{0.p};h_0,\varepsilon_{r.0})\right]\end{aligned} \tag{7}$$

The procedure (7) incorporates the scaling errors aggregated over the correction iterations into the subsequent evaluation of the surrogate model. According to our experiments, two or three iterations are normally sufficient for the procedure to converge. Also, it should be noted that the computational cost of each iteration is only one high-fidelity EM simulation of the antenna. Thus, the overall re-design cost is very low.

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## III. Case Study and Results

For the sake of demonstration, consider a dual-band planar antenna [23] shown in Fig. 1. The structure consists of two radiating elements in the form of a quasi-microstrip patch with inset feed and a monopole radiator. The independent design variables are $\boldsymbol{x} = [L\ l_1\ l_2\ l_3\ W\ w_1\ w_2\ g]^T$; $o = 7$, $l_0 = 10$ and $s = 0.5$ remain fixed. The feed line width $w_0$ is adjusted for a given substrate permittivity and thickness so as to ensure 50 ohm impedance. The unit for all dimensions is mm. The EM models are implemented in CST Microwave Studio [24]: high-fidelity $\boldsymbol{R}_f$ (~1,200,000 mesh cells, simulation time 6 minutes), and low-fidelity $\boldsymbol{R}_c$ (~130,000 cells, 35 seconds).

Our goal is to perform dimension scaling of the antenna in Fig. 1 for the following ranges of operating frequencies and substrate parameters: 1.5 GHz $\leq f_1 \leq$ 2.5 GHz, 5.0 GHz $\leq f_2 \leq$ 6.0 GHz, 0.7 mm $\leq h \leq$ 1.5 mm, and $2.5 \leq \varepsilon_r \leq 3.5$. As reference designs we consider all the combinations of $f_1 \in \{1.5, 2.0, 2.5\}$, $f_2 \in \{5.0, 5.5, 6.0\}$, $h \in \{0.7, 1.1, 1.5\}$, and $\varepsilon_r \in \{2.5, 3.0, 3.5\}$. The high-fidelity reference design corresponds to the center of the domain, $\boldsymbol{x}_f^*(2.0,5.5;1.1,3.0) = [15.9\ 5.22\ 13.0\ 5.88\ 16.6\ 0.25\ 9.03\ 6.83]^T$; the corresponding low-fidelity design is $\boldsymbol{x}_c^*(2.0,5.5;1.1,3.0) = [15.8\ 5.25\ 12.9\ 5.86\ 16.7\ 0.2\ 9.05\ 6.81]^T$.

Figure 2 shows selected two-dimensional cuts of the inverse surrogate model (cf. Section II.*B* for details). It should be emphasized that the surrogate model is capable of reflecting the main trends (in terms of relationships between the operating conditions and geometry parameters), however, there are certain errors. Due to these, the iterative correction procedure of Section II.*C* is necessary.

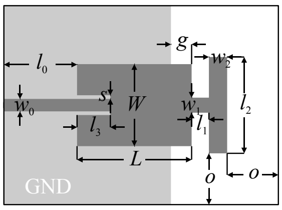


Fig. 1. Geometry of the dual-band patch antenna [23]. Ground plane marked using the lighter shade of gray.

TABLE I Verification Cases for Dual-Band Antenna

| Verification case | | | | Obtained operating conditions | |
|---|---|---|---|---|---|
| Operating conditions | | Substrate parameters | | | |
| $f_1$ [GHz] | $f_2$ [GHz] | $h$ [mm] | $\varepsilon_r$ | $f_1$ [GHz] | $f_2$ [GHz] |
| 1.75 | 5.30 | 1.524 | 3.38 | 1.75 | 5.30 |
| 1.75 | 5.775 | 0.813 | 3.38 | 1.76 | 5.776 |
| 1.75 | 5.65 | 1.524 | 2.97 | 1.75 | 5.65 |
| 1.845 | 5.30 | 1.524 | 3.38 | 1.85 | 5.30 |
| 1.845 | 5.775 | 0.762 | 2.50 | 1.85 | 5.770 |
| 1.845 | 5.65 | 0.813 | 3.38 | 1.85 | 5.65 |
| 2.15 | 5.30 | 1.524 | 2.97 | 2.15 | 5.30 |
| 2.15 | 5.775 | 1.524 | 3.38 | 2.15 | 5.776 |
| 2.15 | 5.65 | 0.813 | 3.38 | 2.16 | 5.65 |
| 2.45 | 5.30 | 1.524 | 3.38 | 2.45 | 5.30 |
| 2.45 | 5.775 | 0.762 | 2.50 | 2.47 | 5.775 |
| 2.45 | 5.65 | 1.524 | 2.97 | 2.45 | 5.65 |

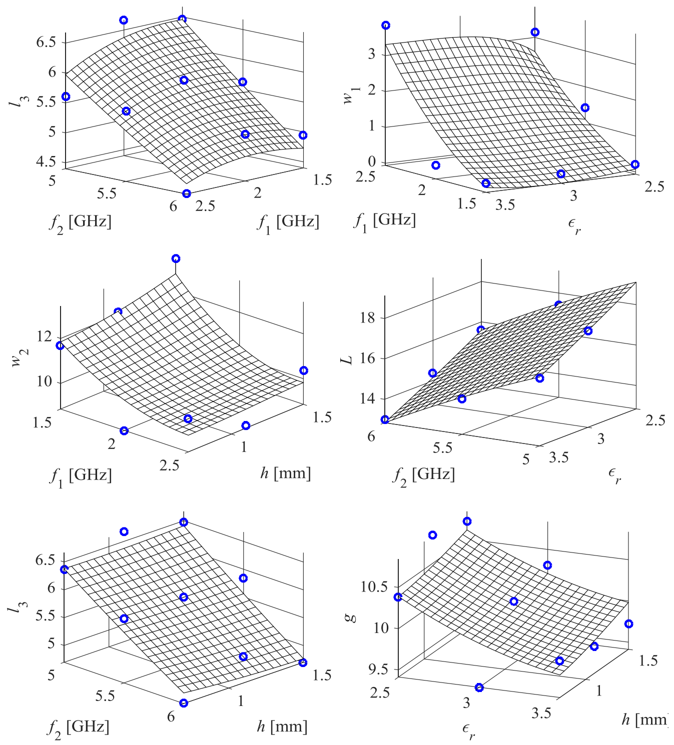


Fig. 2. Compact RRC: selected two-dimensional cuts of the inverse surrogate model for selected geometry parameters. Remaining operating conditions and substrate parameters are set at the domain center (i.e., $f_1$ = 2.0 GHz, $f_2$ = 5.5 GHz, $h$ = 1.1 mm, $\varepsilon_r$ = 3.0).

For the sake of verification, the antenna of Fig. 1 has been re-designed for various operating frequencies and substrate parameters. The detailed data on the verification cases has been gathered in Table I. The selection has been made having in mind practically utilized frequency bands and widely used substrate materials. Note that the scaling procedure works correctly as the allocation of the operating frequencies is nearly perfect. The EM-simulated reflection responses of the re-designed antennas have been shown in Fig. 3 for selected designs (before and after correction (7)). For all cases, the scaling cost is up to three EM simulations of the antenna structure.

## IV. Conclusion

The paper discusses expedited dimension scaling of multi-band antennas with respect to its operating frequencies and the substrate parameters. Utilization of variable-fidelity EM simulations, inverse surrogate model and iterative correction procedure allows for accurate re-design of the antenna structure at the cost of a few full-wave EM analyses of it. Reliability of the proposed methodology has been validated using a dual-band microstrip antenna. Precise allocation of the operating frequencies has been obtained for all verification cases.

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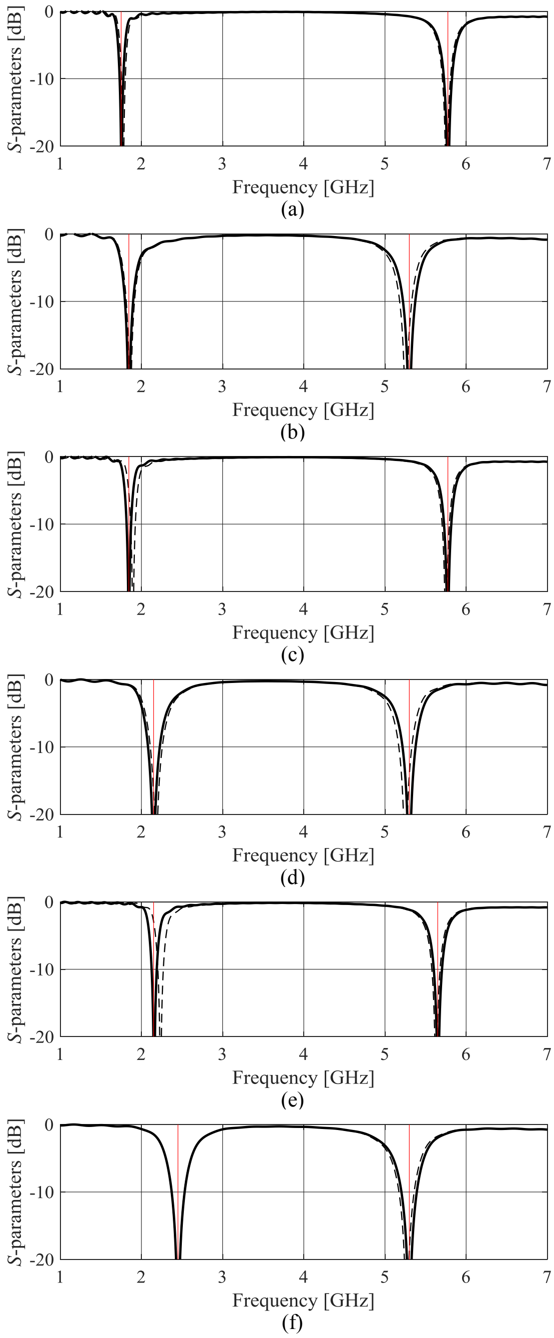


Fig. 3. Verification cases: compact RRC scaled for: (a) [$f_1$ $f_2$ $h$ $\varepsilon_r$] = [1.75 5.775 3.38 0.813], (b) [$f_1$ $f_2$ $h$ $\varepsilon_r$] = [1.845 5.30 3.38 1.524], (c) [$f_1$ $f_2$ $h$ $\varepsilon_r$] = [1.845 5.775 2.50 0.762], (d) [$f_1$ $f_2$ $h$ $\varepsilon_r$] = [2.15 5.30 2.97 1.524], (e) [$f_1$ $f_2$ $h$ $\varepsilon_r$] = [2.15 5.65 3.38 0.813], (f) [$f_1$ $f_2$ $h$ $\varepsilon_r$] = [2.45 5.30 3.38 1.524]; response before iterative correction and the final design marked using thin and thick lines, respectively. Required operating frequencies marked using vertical lines.

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