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ON RAPID RE-DESIGN OF UWB ANTENNAS WITH RESPECT TO SUBSTRATE PERMITTIVITY

Slawomir Koziel, Adrian Bekasiewicz

Reykjavík University, School of Science and Engineering, Menntavegur 1, 101 Reykjavík, Iceland
(✉ koziel@ru.is, +354 599 6376, *bekasiewicz@ru.is)*

Abstract

Re-design of a given antenna structure for various substrates is a practically important issue yet non trivial, particularly for wideband and ultra-wideband antennas. In this work, a technique for expedited redesign of ultra-wideband antennas for various substrates is presented. The proposed approach is based on inverse surrogate modeling with the scaling model constructed for several reference designs that are optimized for selected values of the substrate permittivity. The surrogate is set up at the level of coarse-discretization EM simulation model of the antenna and, subsequently, corrected to provide prediction at the high-fidelity EM model level. The dimensions of the antenna scaled to any substrate permittivity within the region of validity of the surrogate are obtained instantly, without any additional EM simulation necessary. The proposed approach is demonstrated using an ultra-wideband monopole with the permittivity scaling range from 2.2 to 4.5. Numerical validation is supported by physical measurements of the fabricated prototypes of the re-designed antennas.

Keywords: antenna design, geometry scaling, simulation-driven optimization, surrogate modeling, inverse modeling, substrate properties.

1. Introduction

Electromagnetic (EM) simulation is one of the most important tools in the design of contemporary antenna structures. EM analysis is the only way to ensure reliability of performance evaluation, especially for compact structures where additional components (such as connectors) have to be included into the computational model as they affect the antenna operation. Unfortunately, high-fidelity EM simulation at fine discretization of the structure at hand is computationally expensive. This becomes a problem for design automation by means of numerical optimization. Another issue is a large number of geometry parameters typical for modern antennas, which by itself makes simulation-driven design closure a challenging task. Methods such as the gradient-based search with numerical derivatives [1] or population-based metaheuristics (often used for global optimization [2, 3]) may be prohibitively expensive. A possible way of alleviating these difficulties are surrogate-assisted techniques [4, 5] as well as the gradient search with adjoint sensitivities [6, 7]. Surrogate-based methods exploit faster representations of the antenna structure under design, typically constructed from coarse-discretization EM simulation models (faster but less accurate), which are appropriately corrected to be used as prediction tools for finding better designs [4, 5, 8]. Adjoint sensitivities enable to considerable reduce the cost of gradient-based search [9]. However, availability of this technology is still limited in commercial software [10, 11].

A common problem in antenna engineering is re-design of a given structure for various sets of performance requirements (*e.g.*, operating frequencies for narrow-band antennas), but also for various substrates. Normally, such a re-design may be just as expensive and challenging as obtaining the original design (used as a starting point). Therefore, speeding up a re-design

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process by re-using one or more existing designs seems to be an attractive alternative. Notwithstanding, it is a challenging task: due to complexity of contemporary antennas [12], the relationships between geometry parameters [13] and performance figures are normally nonlinear and often counter-intuitive (*e.g.*, some of the parameters may increase, whereas others decrease when the substrate permittivity is increased).

In [14], a surrogate-based technique has been proposed for dimension scaling of narrow-band antennas with respect to the operating frequency. It was utilizing inverse modeling and variable-fidelity EM simulations. In this work, we adopt the approach of [14] to scale *ultra-wideband* (UWB) antennas with respect to the substrate permittivity. The objective is to directly obtain the dimensions of the antenna scaled to any permittivity (within a range of interest) that are optimum in the sense of ensuring the minimum in-band reflection level. Here, we also utilize the inverse model that is constructed based on four reference designs corresponding to various permittivity values distributed along the range of interest and obtained for the coarse-mesh EM simulation model. The appropriate correction enables to elevate the surrogate to the high-fidelity EM simulation model level and to use it for predicting the optimum antenna dimensions corresponding to the required value of the substrate permittivity. Our approach is validated using a UWB monopole antenna scaled in the relative permittivity range from 2.2 to 4.5. Selected designs have been fabricated and measured in order to further confirm the correctness of the proposed scaling methodology.

2. Antenna scaling for substrate parameters

In this section, we outline the procedure for low-cost dimension scaling of UWB antennas with respect to the substrate properties, specifically, the dielectric permittivity. Our technique is comprehensively validated in Section 3 using a compact UWB monopole antenna example.

2.1. Dimension scaling. problem formulation

We denote by $\boldsymbol{x} \in R^n$ a vector of antenna geometry parameters. We also denote by $\boldsymbol{R}_f(\boldsymbol{x})$ the response of the high-fidelity EM simulation model of the structure (here, reflection versus frequency). Let $\boldsymbol{x}_f^*(\varepsilon)$ be the optimized design of the antenna for a substrate of a relative permittivity ε. In this work, we consider UWB antennas and thus the optimized design is understood as the one that ensures the minimum possible reflection level within the UWB frequency range, *i.e.*, from 3.1 GHz to 10.6 GHz.

The scaling problem is formulated as follows. Given the reference design $\boldsymbol{x}_f^*(\varepsilon_0)$ corresponding to a certain relative permittivity value ε_0, find $\boldsymbol{x}_f^*(\varepsilon)$ for given permittivity in the range of interest $\varepsilon_{\min} \le \varepsilon \le \varepsilon_{\max}$. The scaling problem is a non-trivial one in general, but it is particularly challenging for wideband antennas because the relationships between the optimal dimensions and the substrate permittivity cannot be described analytically.

2.2. Inverse model construction

For expedited dimension scaling, we utilize an inverse surrogate model that represents the antenna geometry parameters as a function of the substrate permittivity ε. It is constructed using several antenna designs corresponding to a few values ε_j, $j = 1,\ldots, N$, within the range of interest, and obtained at the level of the coarse-discretization electromagnetic antenna model $\boldsymbol{R}_c$ [14]. The reference designs are found using local optimization, here, by means of the trust-region-based [15] gradient search with finite differentiation.

The surrogate $\boldsymbol{x}_c(\varepsilon)$ is defined as:

$$\boldsymbol{x}_c(\varepsilon,\boldsymbol{P}) = \left[x_{c.1}(\varepsilon,\boldsymbol{p}_1)\ \dots\ x_{c.n}(\varepsilon,\boldsymbol{p}_n)\right]^T, \tag{1}$$

where $x_{c.k}(\varepsilon,\boldsymbol{p}_k)$ is a model of the kth geometry parameter of the antenna with $\boldsymbol{p}_k$ being the model coefficients. $\boldsymbol{P} = [\boldsymbol{p}_1\ \dots\ \boldsymbol{p}_n]$ is the overall coefficient vector for the model.

The models $x_{c.k}$ have an explicit analytical form, determined based on visual inspection of the training data. Initial experiments indicate that a second-order polynomial is sufficient for our purposes. Thus, the surrogate model is:

$$x_{c.k}(\varepsilon,\boldsymbol{p}_k) = p_{k.1} + p_{k.2}\varepsilon + p_{k.3}\varepsilon^2 \tag{2}$$

and its parameters are $\boldsymbol{p}_k = [p_{k.1}\ p_{k.2}\ p_{k.3}]$. The model parameters are identified through curve fitting as:

$$\boldsymbol{p}_k = \arg\min_{\boldsymbol{p}} \sum\nolimits_{j=1}^{N} (x_{c.k}(\varepsilon_j,\boldsymbol{p}) - x_{c.j.k})^2\ . \tag{3}$$

It should be emphasized that in order to smoothen out possible irregularities (*e.g.*, due to imperfect optimization of the reference designs), the surrogate should be a regressive model rather than interpolative one. Therefore, the number of the reference designs should be larger than the number of model parameters. Here, because there are three parameters in the model, four reference designs are used.

2.3. Dimension prediction of scaled design

The surrogate model is created using low-fidelity model reference designs so that it has to be corrected before being used for scaling the antenna dimensions at the high-fidelity model level. This is necessary to account for the low- and high-fidelity model discrepancies. Because both models are evaluated using the same solver, they are well correlated so that it is sufficient to introduce a shift at the level of geometry parameters as described below. The correction requires availability of a reference design $\boldsymbol{x}_f^*(\varepsilon_0)$, but also an optimized coarse-discretization model $\boldsymbol{x}_c^*(\varepsilon_0)$, which is one of the reference designs considered in Section 2.2. The high-fidelity model scaling is then carried out as follows:

$$\boldsymbol{x}_f(\varepsilon) = \boldsymbol{x}_c(\varepsilon,\boldsymbol{P}) + \left[\boldsymbol{x}_f^*(\varepsilon_0) - \boldsymbol{x}_c^*(\varepsilon_0)\right]. \tag{3}$$

The correction $\boldsymbol{x}_f^*(\varepsilon_0) - \boldsymbol{x}_c^*(\varepsilon_0)$ "shifts" the inverse model $\boldsymbol{x}_c$ so that the consistency condition $\boldsymbol{x}_f(f_0) = \boldsymbol{x}_f^*(f_0)$ is satisfied at the reference permittivity ε_0.

3. Verification example: UWB monopole antenna

Here, we provide numerical and experimental verification of the technique introduced in Section 2. We use a UWB monopole antenna scaled within the permittivity range of 2.2 to 4.5.

3.1. Antenna structure

Consider a UWB monopole antenna shown in Fig. 1. The structure is based on a design of [16]. It consists of a rectangular radiator and a ground plane with an L-shaped strip for current path enhancement. The vector of design variables is $\boldsymbol{x} = [l_0\ g\ a\ l_1\ l_2\ w_1\ o]^T$. The parameter $w_0 = 2o + a$, whereas the feeding line width w_i is recalculated based on the substrate permittivity to ensure 50 ohm input impedance. All dimensions are in mm. The EM antenna models are implemented in CST Microwave Studio ($\boldsymbol{R}_f$: ~4,600,000 mesh cells, simulation time 40 minutes, and $\boldsymbol{R}_c$: ~850,000 cells, 2 minutes) [10]. The models include an SMA connector to ensure reliability of antenna evaluation (see Fig. 1b). The target scaling range for the substrate permittivity is from 2.2 to 4.5.

3.2. Inverse model

The inverse surrogate has been prepared using four reference points corresponding to the permittivity values: 2.5, 3.0, 4.1, and 4.5. Fig. 2 shows the optimized low-fidelity model responses at the reference designs, whereas Fig. 3 shows the extracted inverse model for all antenna dimensions. The high-fidelity model reference design is set for a permittivity value of $\varepsilon_0 = 3.0$ and it is $\boldsymbol{x}_f^*(\varepsilon_0) = [4.327\ 1.298\ 10.214\ 14.168\ 5.166\ 3.128\ 3.329]^T$. The corresponding low-fidelity design is $\boldsymbol{x}_c^*(\varepsilon_0) = [4.564\ 1.184\ 10.087\ 13.841\ 5.128\ 3.261\ 3.519]^T$.

3.3. Numerical verification

For the sake of verification, the antenna was scaled to the following substrate permittivity values: 2.2, 2.67, 3.2, 3.5, and 4.3. Fig. 4 shows the high-fidelity model response at the designs obtained using the proposed scaling procedure, whereas Table 1 shows the values of geometry parameters. It can be observed that the simulated antenna performance is excellent in all cases with the maximum in-band reflection around or below –15 dB. Note that the first of the permittivity values is outside the range of the reference designs (*i.e.*, 2.5 to 4.5). This confirms that our inverse model can also be used for extrapolation purposes.

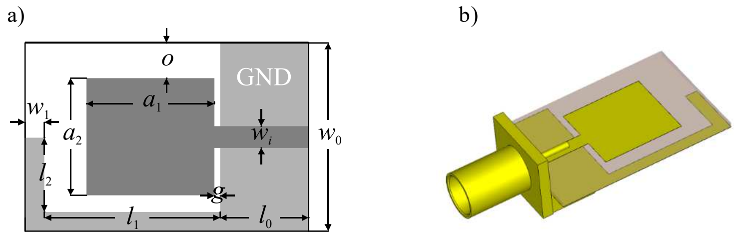

Fig. 1. A UWB monopole antenna: a) the top view with highlighted dimensions; b) 3D visualization.

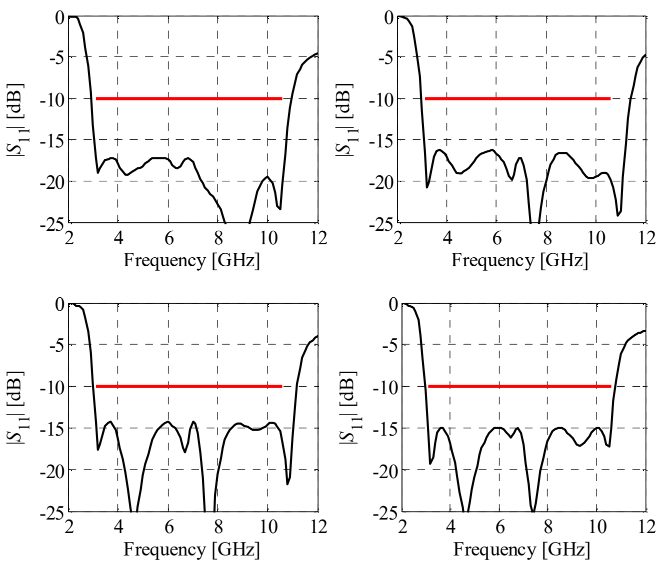

Fig. 2. Responses of the optimized coarse-discretization antenna model at the training designs corresponding to: $\varepsilon = 2.5$, $\varepsilon = 3.0$, $\varepsilon = 4.1$, and $\varepsilon = 4.5$.

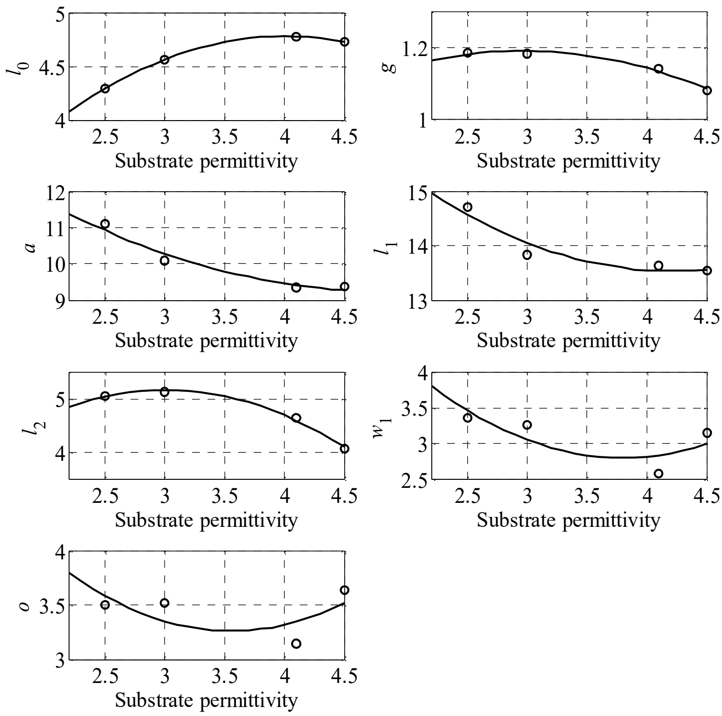

Fig. 3. Dimensions of the four training UWB monopole designs (at the coarse-discretization EM model level) (○) and the extracted inverse surrogate (—).

Table 1. Dimensions of the scaled UWB monopole structure.

Substrate Permittivity	Geometry Parameter						
	l_0	g	a	l_1	l_2	w_1	o
2.2	3.845	1.279	11.515	15.299	4.882	3.669	3.605
2.67	4.161	1.302	10.817	14.704	5.145	3.164	3.297
3.2	4.404	1.304	10.194	14.223	5.185	2.803	3.105
3.5	4.488	1.294	9.919	14.039	5.087	2.697	3.069
4.3	4.524	1.227	9.458	13.862	4.399	2.762	3.231

3.4. Experimental validation

Two of the scaled antennas, especially those re-designed for permittivity values of 2.2 and 3.5 have been fabricated on two different dielectric substrates manufactured by Taconic: TLP-5 (ε_r = 2.2, tanδ = 0.0009; h = 0.78 mm) and RF–35 (ε_r = 3.5, tanδ = 0.0018; h = 0.76 mm). Photographs of the manufactured structures are shown in Fig. 5.

A comparison of the simulated and measured reflection responses of the structure scaled for the TLP-5 substrate is shown in Fig. 6. The obtained results are in good agreement. It should be noted that the maximum simulated and measured in-band reflection levels are –15.8 dB and –13.5 dB, respectively. Thus, the peak difference between responses is 2.3 dB. At the same time the measured $|S_{11}|$ antenna bandwidth (determined at the –10 dB level) is 1.2 GHz broader than the simulated one. Also, it should be mentioned that the electromagnetic model of the antenna was optimized using a substrate with a varied permittivity, yet the loss tangent and thickness were set to 0.0018 and 0.76 mm, respectively. At the same time, these quantities are different for the TLP-5 substrate which is the reason of visible discrepancies between the simulated and measured responses. We would like to reiterate that the structure dimensions for TLP-5 substrate have been obtained by extrapolation of the inverse model parameters, and – from this perspective – the obtained results should be considered as very good.

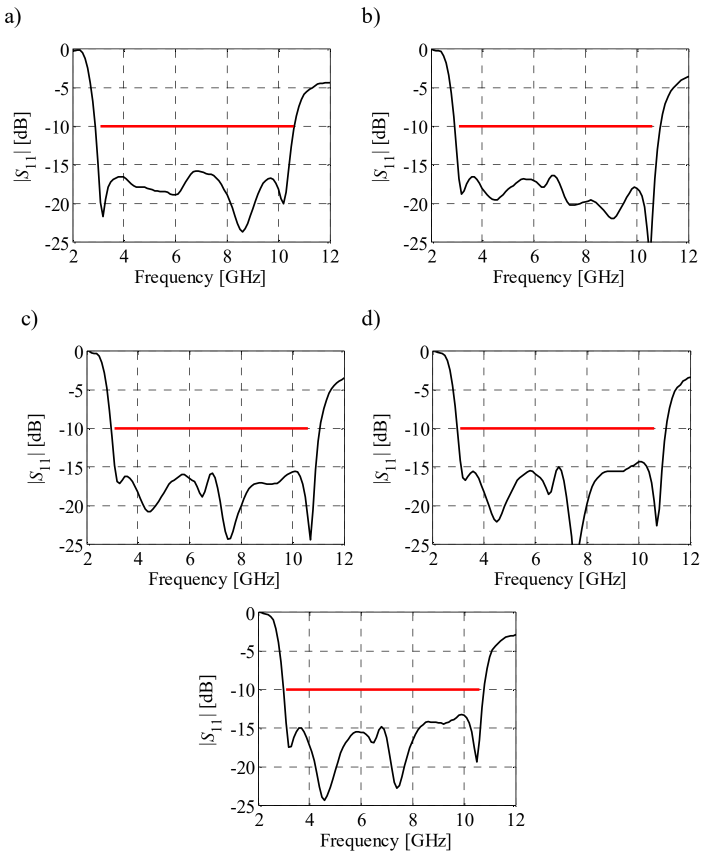

Fig. 4. Responses of the UWB monopole designs scaled to the substrate permittivities: a) $\varepsilon_r = 2.2$; b) $\varepsilon_r = 2.67$; c) $\varepsilon_r = 3.2$; d) $\varepsilon_r = 3.5$; and e) $\varepsilon_r = 4.3$.

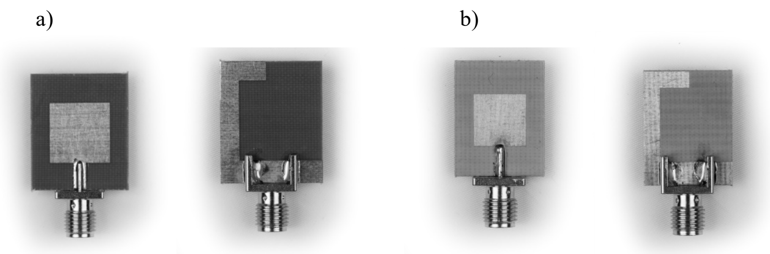

Fig. 5. Photographs of the fabricated UWB monopole antennas: a) $\varepsilon_r = 2.2$ (TLP-5); and b) $\varepsilon_r = 3.5$ (RF-35).

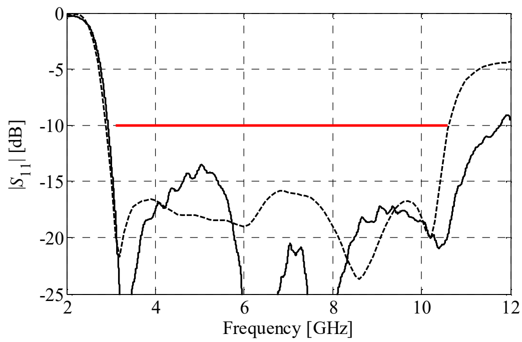

Fig. 6. Comparison of the simulated (– –) and measured (—) reflection responses of the antenna structure scaled to a permittivity of 2.2.

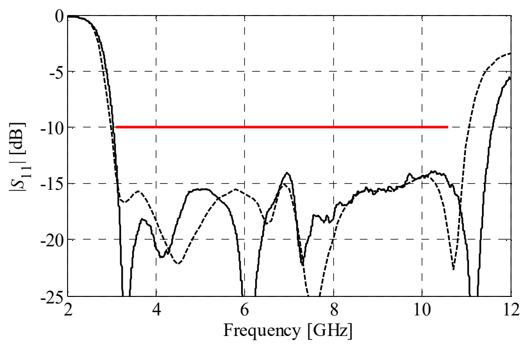

Fig. 7. Comparison of the simulated (– –) and measured (—) reflection responses of the antenna structure scaled to a permittivity of 3.5.

Figure 7 shows a comparison of the reflection responses obtained for the antenna fabricated on the RF-35 substrate. The results are in noticeably better agreement than those obtained for the TLP-5 one. The in-band peak difference between the simulated and measured $|S_{11}|$ responses is only 0.2 dB. On the other hand, the measured antenna bandwidth is 600 MHz broader than the simulated one.

It should be emphasized that both structures are electrically small since their dimensions are only 23.85 × 18.72 = 446 mm^2 and 21.02 × 15.06 = 340 mm^2 for the antenna designed on TLP-5 and RF-35, respectively. The enhanced measured bandwidth is a result of an electrically large measurement setup (cables, fixtures, *etc.*) which affects the antenna's operation.

4. Conclusion

In this work, low-cost dimension scaling of UWB antennas with respect to the substrate permittivity has been examined. Our approach exploits the inverse surrogate model constructed from the reference designs obtained for the coarse-discretization EM model of the antenna of interest, and further corrected using a single reference design at the high-fidelity model level. Once set up, the surrogate permits direct generation of the optimum dimensions of the antenna re-designed for any required value of the substrate permittivity at a negligible computational cost. The proposed procedure has been positively verified using a UWB monopole antenna example for the permittivity range of 2.2 to 4.5. The simulation results have been validated experimentally.

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