Novel Algorithmic Approaches for Simulation-Driven Miniaturization of Antenna Structures

Davíð Órn Jóhannesson

Thesis of 60 ECTS credits
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by

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Thesis of 60 ECTS credits submitted to the School of Science and Engineering at Reykjavík University in partial fulfillment of the requirements for the degree of Master of Science (M.Sc.) in Electrical Engineering

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Abstract

In this thesis, novel approaches to miniaturization of ultra-wideband antennas using trust region method are presented. We investigate the properties of design task formulation as an explicit size-reduction problem, with the footprint area minimization being a primary design objective and a penalty function introduced to control reflection characteristic of the antenna at hand. An alternative approach using the trust region framework with quadratic approximation model is demonstrated to increase control over the maximum in-band reflection level (compared to conventional benchmark method) but it does not decrease the final footprint area size. The second approach, using adaptive adjustment of the maximum acceptable in-band reflection level threshold is proposed and demonstrated to be superior over the conventional (fixed-threshold) setup. Finally, an iterative algorithm for exploring boundary of the feasible region is developed, allowing for efficient identification of a constrained optimum that ensures satisfaction of the prescribed matching requirements for the structure at hand. All methodologies are demonstrated using several case studies of ultra-wideband antennas.
Nýstárleg algrím til lágmörkunar á stærð loftneta með notkun hermilíkana

Davíð Örn Jóhannesson

júní 2017

Útdráttur

Í þessu verkefni eru nýjar aðferðir til bestunar, með tilliti til stærðar, á háttíðni loftnetum þróaðar innan öryggis aðferðafraðið (Trust region methodology). Aðferð, sem notar stærð loftnets sem aðalfall og styrir tíðnisvörun í gegnum refsifall er kynnt sem samanburðaraðferð. Fyrsta aðferð höfunda nýtir annarar-gráðu jöfnu með auka-söfnunarpunktum til að búi til nákvæmari lýsingu á undirlyggjandi falli. Niðurstaða er að með þessu næst betri stýring á tíðnisvörun en engin smækkn á loftneti, sbr. samanburðaraðferð. Önnur aðferð höfunda nýtir breytilegt gildi á viðmiðunarmörkum hámarks leyfilegs speglunargildis(e. reflection) á tíðnisviði. Sýnt er fram á að þessi aðferð standi hefðbundinni aðferðafraði framar þar sem hún finnur minni hönnun fyrir valin loftnet. Síðasta aðferð höfunda flakkar á milli aðgengilega svædisins og óaðgengilega svædisins með tveim mismunandi föllum sem eru nýtt á hvoru svæðinu fyrir sig. Þessi aðferð finnur smærri hönnun á loftneti, sbr. hefðbundin aðferðafraði, á þeim loftetum sem sínd eru hér, ásamt betri stjórnun á tíðnisvörun. Óll loftnet, sem nýtt eru hér til að sýna fram á hæfni nýrra aðferða, eru tekin úr greinasafni fyrir hönnunaraðferðir háttíðni loftneta.
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date

Davíð Órn Jóhannesson
Master of Science
Audur, thanks for tolerating me.
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The author thanks Computer Simulation Technology AG, Darmstad Germany for making CST Microwave Studio available. This work is partially supported by the Icelandic Centre for Research (RANNIS) Grant 163299051. Also Adrian Bekasiewicz for indispensable help in getting models up and running.
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<td>Ultra Wide Band</td>
</tr>
<tr>
<td>EM</td>
<td>Electromagnetic</td>
</tr>
<tr>
<td>CST</td>
<td>Compute Simulated Technologies</td>
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<td>TR</td>
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<td>Radio Frequency</td>
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Chapter 1

Introduction

Antenna structures belong to the fundamental components of wireless communication systems. Contemporary antennas are designed to maintain stringent electrical properties, regarding various performance characteristics, such as frequency response, total efficiency and gain. Furthermore, in many applications, one of important prerequisites are small physical dimensions of the device. However reduction of the physical size can result in degraded performance of the electrical properties. The purpose of this work is investigation of electromagnetic (EM) simulation driven design of compact ultra-wideband (UWB) antennas, trying to improve on currently used approaches. More specifically, several algorithms for improved size-reduction-oriented optimization of UWB antennas are developed and compared to conventional numerical techniques. Operation and performance of the algorithms are illustrated using several representative UWB antenna structures.

This rest of this Chapter is as follows; in Section 1.1 the research goal is define; Section 1.2 presents state of the art for compact ultra-wideband(UWB) antenna designs, and currently used approaches for optimization of complex designs; Section 1.3 explains the scope of this research and how the research progressed; Finally Section 1.4 describes the outline of this thesis.

1.1 Project Scope

Small size has become an important consideration in the design of modern UWB antennas. Systems such as handheld and wearable devices [1] and the internet of things (IoT) [2] depend on the antenna structure having a small footprint. Unfortunately reducing the size can lead to degradation of the electrical properties. Shortening of the current paths can lead to deterioration of matching for lower frequencies. Other issue include reduced gain and efficiency as well as distorted radiation pattern. This makes the design of miniaturized antennas a difficult task.

This research looks for novel methods to improve a currently used approach for design of miniaturized antennas. This is done by introducing changes to a benchmark method, presented in [3]. The objective of these changes is to work around observed drawbacks by creating algorithms that can find a more optimal solution to the design problem. Here, the focus is on the antenna size and reflection characteristics. The reflection is a coefficient describing the antennas capability to reflect a signal through the transmission medium at a certain frequency. This is typically measure using attenuation, a lower reflection coefficient being a better design (cf. [4]).

The optimization problem of designing an antenna, defined as an objective function in Sec-
tion 2.1, is a non-linear problem. The objective function has two parameters to optimize (size, reflection) and here this is approached using penalty function to control the reflection while optimizing the area specifically. The penalty function is used in the benchmark and has proven to be highly efficient.

1.2 Design of UWB Antennas

The design of a compact antenna can be viewed as a two-step process: (i) topology development and (ii) adjustment of structure dimensions. The first step is often realized by introducing changes to basic antenna geometries. Some approaches include adding slits and stubs to enlarge the current paths and improve low frequency antenna reflection performance, e.g. [5], [6], re-shaping of the radiator [7] [8], employing defected ground structures [9], transversal signal interference feed [10], loading with grounded strips [11], extending current paths by meandering radiator edges [12], using high-permittivity dielectric substrate [13], [14], adding ground plane slits [15] or stubs [16], etc. The second step is still often realized by traditional approach based on parameter sweeping involving user experience. However, as the design becomes increasingly more complex and the number of geometric parameter increases, the conventional method becomes impractical because only one or two parameters at a time can be handled this way. When the traditional method is impractical simultaneous, numerical optimization of all relevant geometric parameters can be applied. This can be realized using conventional optimization routines, both local [17],[18], and global [19], [20], as well as surrogate-assisted routines [21].

This work explores a method involving gradient-based search, proposed in [22]. The approach utilizes the antenna footprint area minimization as the primary objective and a penalty function approach for handling the reflection response of the antenna at hand. The penalty function measures a relative violation of the acceptable level of in-band reflection. This approach has been demonstrated successful for practical antenna design cases, see, e.g., [23]. However close analysis of the process suggests that appropriate modifications of the algorithm may result in a smaller final footprint area while maintaining the in-band reflection at acceptance levels. This work focuses on exploring various changes to this gradient-based approach, resulting in novel approaches that might out-perform current methods.

1.3 Specific Approach Methodologies

The first objective, for this research, was identifying potential drawbacks of the reference optimization framework of [3]. More specifically, in the reference framework, implicit handling of design constraints (here, maximum in-band reflection level) results in highly nonlinear functional landscape to be minimized. This is problematic, because minimum-size design is normally located at the boundary of the feasible region of the design space [24]. Because optimization process is conducted at the level of full-wave EM antenna model, certain level of numerical noise is inherent to the simulation results. This may result not finding the true optimum design (typically due to problem with exploring the feasible region boundary).

In the thesis, several approaches are explored in order to alleviate these difficulties. One of them was to improve the generalization capability of the local surrogate model using a second-order polynomial (cf. Section 2.2). Several versions of the second-order polynomial model were tested, including a full quadratic model using all possible additional mixed terms, a model without mixed terms, as well as intermediate models using different number
Another approach was based on introducing an adaptively adjusted acceptance threshold, which is initially more stringent and gradually evolving towards the final value (according to the original design specifications). The idea behind this concept is to keep the intermediate design within the feasible region as long as possible because the major reason for getting stuck in the local optimum is difficulty in getting back to the feasible region once the solution is allocated outside it (upon finishing a particular algorithm iteration). This algorithm is discussed in Section 5.2.

The last technique developed for the purpose of the thesis was based on incorporation of safety procedures, in the form of pushing the design back to a feasible region by optimizing the antenna for best matching instead for minimum size in case the design obtained as a result of the last iteration turned out to be infeasible. This technique seems to be particularly suitable for improving exploration of the feasible region boundary, otherwise difficult due to numerical noise. The proposed procedure iteratively executes two search processes one when in the feasible region, using reduced reflection threshold as an explicit constrain. The other process is applied when in the infeasible region. It is optimizing the antenna for best reflection with constraints imposed on the structure size. The respective algorithm has been described in Section 5.3.

In this thesis, a technique of [3] is used as a reference for numerical comparisons. As mentioned before, numerical studies are based on a set of representative UWB antenna structures. The two main quality criteria are the minimum antenna size obtained as a result of the optimization process as well as the precision of controlling the reflection characteristic of the antenna.

1.4 Thesis Structure

The core part of the thesis is organized as follows.

Chapter 2 describes the formulation of antenna design problem as an optimization task. Important optimization-related nomenclature is introduced, subsequently used throughout the thesis. The specific algorithmic framework of trust-region gradient-search is introduced. The chapter concludes by introducing the basis of the benchmark approach, namely using a penalty function to control the antenna reflection response.

Chapter 3 briefly outlines the software package used to carry out electromagnetic simulations and the computational framework utilized to interface the main programming environment (Matlab) and the EM solver. The chapter concludes by introducing three ultra-wideband antenna structures used as a benchmark set for validation of the developed optimization algorithms.

Chapter 4 introduces the algorithm approaches developed and considered in the thesis. The methods are introduced, in the following order, after a brief introduction of the benchmark approach: Trust-Region with Quadratic Approximation Model (Section 4.2), Adaptive Acceptance Threshold Method (Section 4.3), Feasible Region Boundary Search (Section 4.4). Each method is rigorously described and illustrated by means of a flow diagram and algorithm. The chapter ends by discussing the termination condition for all the algorithms.

Chapter 5 discusses the numerical results obtained for the methods introduced in Chapter 4. On the top of figures of merit directly handled in the design process, other antenna characteristics are also presented, in particular, the total efficiency and radiation patterns, in order to evaluate the effects of antenna miniaturization on its field properties.

Chapter 6 summarizes the work. In particular, a general discussion of the obtained results
is given with the emphasis on advantages and disadvantages of particular optimization techniques considered throughout the thesis. Brief information about publication of the obtained results is also included.
Chapter 2

Antenna Design Using EM-Driven Optimization

In this chapter, we formulate the antenna design task as a nonlinear minimization problem. We introduce necessary notation, discuss typical constraints, give a brief overview of the optimization methodologies when using EM simulation. In particular, a trust-region approach is outlined along with first-order Taylor expansion model and quadratic modelling using linear coefficients.

2.1 Antenna Design Problem Formulation

Let $R(x)$ denote a response of a full-wave EM model. More specifically, $R(x)$ represents relevant electrical and/or field characteristics, e.g., reflection coefficient or antenna gain over certain frequency band of interest. The vector $x = [x_1, x_2, \ldots, x_n]^T$ represents designable geometric parameters to be adjusted for the antenna at hand. The antenna design task can be formulated, following [25], as a nonlinear minimization problem using a generic form

$$x^* = \arg\min_x U_A(R(x))$$  \hspace{1cm} (2.1)

where $U_A$ is the scalar merit function which need to be encoded for the design specification, whereas $x^*$ is the optimum design to be found. The function $U_A$ is implemented so that a better design $x$ corresponds to a smaller value of $U_A(R(x))$. More specifically $U_A$ is implemented as a minimax function with upper (and/or lower) specifications. In practice problem 2.1 is always constrained. Depending on the specific structure of the problem following types of constraints can be considered:

- Lower and upper bounds for design variables, i.e. $l_i \leq x_i \leq u_i$, $i = 1, \ldots, n$
- Inequality of constraints i.e. $c_{ineq,i}(x) \leq 0$, $i = 1, \ldots, N_{ineq}$ where $N_{ineq}$ is the number of constraints
- Equality constraints i.e. $c_{eq,i}(x) \leq 0$, $i = 1, \ldots, N_{eq}$ where $N_{eq}$ is the number of constraints

Geometric constraints are usually introduced to make sure that the antenna structure that is to be evaluated by the EM solver is physically consistent (e.g., certain parts of the structure do not overlap). Design constraints (reflection, efficiency, gain) are introduced through penalty functions (cf Section 2.3).
The constraints create three different regions. The feasible region contains values that are acceptable because they satisfy all constraints. The infeasible region where designs fail one or more constraints and are therefore not be accepted. The cross section of the feasible and the infeasible region is the boundary section.

2.2 Optimization Using Trust Region

The main optimization engine utilized in this work is trust-region gradient search. Utilization of trust regions is convenient for the considered class of problems because handling of multiple optimization goals is arranged here using a penalty function approach and local expansions models (either linear or quadratic) can easily accommodate aggregated objective function as well as alleviate the issue of numerical noise inherent to antenna responses obtained from EM simulations.

Trust-region (TR) methods utilize auxiliary local approximation models (typically, first-order Taylor expansion of the objective function at hand) which are optimized in the vicinity of the current solution, defined by an adaptively adjusted radius. New solutions are only accepted if they lead to reduction of the objective function value [26].

The TR algorithm, (Fig. 2.1), generates a sequence \( x^{(i)} \), \( i = 0, 1, ... \), of approximations to \( x^* \) as

\[
x^{(i+1)} = \arg \min_{||x-x^{(i)}|| \leq \delta^{(i)}} U(F^{(i)}(x))
\]  

Where \( F^{(i)}(x) \) is a local model of \( R(x) \) established at iteration \( i \) and \( \delta^{(i)} \) is the trust region size of the local model at iteration \( i \). The most common choice of the local model is a linear one, specifically, a first order Taylor expansion \( L^{(i)} \) defined as

\[
L^{(i)}(x) = R(x^{(i)}) + (J^{(i)})^T(x - x^{(i)})
\]  

where \( J^{(i)} \) is the Jacobian of \( R(x^{(i)}) \), \( J^{(i)} = [\frac{\partial R}{\partial x_1^{(i)}}, \frac{\partial R}{\partial x_2^{(i)}}, ..., \frac{\partial R}{\partial x_n^{(i)}}]^T \). The model minimizer can be found by

\[
x^* = \arg \min_{x:||x-x^{(i)}|| \leq \delta} R(x^{(i)}) + (J^{(i)})^T(x - x^{(i)})
\]  

A practical point regarding TR methods is the update scheme for the trust region. The update policy, regarding the trust region size, is computed after each iterative step. A gain ratio (\( \rho \)) that compares change in the objective function and change in the local model, i.e., the real change versus the modelled change in going from \( x^{(i)} \) to \( x \), is used to determine the current iteration acceptance. The TR size is also computed based on the gain ratio. The gain ratio is computed as

\[
\rho = \frac{R(x^*) - R(x^{(i)})}{L(x^*) - L(x^{(i)})}
\]  

where \( x^* \) is the approximate minimizer of the model and \( x^{(i)} \) is a previously accepted point.

The trust region is then updated according to policy. Both in this work and the benchmark implement the policy as follows

\[
\begin{align*}
\rho &\leq 0.25; & \delta^{(i+1)} &= 2\delta^{(i)} \\
0.25 < \rho < 0.75; & \delta^{(i+1)} = \delta^{(i)} \\
\rho &\geq 0.75; & \delta^{(i+1)} &= \frac{1}{3}\delta^{(i)}
\end{align*}
\]  

2.3 Objective Function

Due to the fact that there are two objectives that need to be handled, specifically, the antenna size and its maximum in-band reflection level, the objective function for the TR algorithm need to be defined in an appropriate manner. More specifically, size reduction is considered to be a primary objective, whereas matching requirements are handled as a design constraint. From the perspective of TR algorithm it is more convenient to control the latter using a penalty function approach. By handling the matching using this approach the objective function is simpler to optimize, as there are fewer constraints. Consequently, the objective function is defined, using [3], as

$$U(A(x), S(x)) = A(x) + \beta \cdot c \cdot (S(x))^2$$

(2.8)

with $A(x)$ representing the antenna size, $\beta$ is a penalty factor (here $\beta = 1000$) and $S(x) = \max\{|S_{11}(x)|_{3.1 \text{ GHz to 10.6 GHz}}\}$ is the maximum in-band reflection level (here the UWB, 3.1...
GHz to 10.6 GHz). The reflection characteristics, returned from EM simulator, are represented as complex numbers. It is more convenient to represent the value in dB scale using $|S_{11}(x)| = 20 \log_{10}|R^*(x)|$, where $R^*$ is the reflection response from EM simulation.

In 2.8, $c$ is a penalty function defined as

$$c(S(x)) = \frac{\max(S(x)) - S_{\text{max}}}{S_{\text{max}}}$$

where $S_{\text{max}}$ is the threshold value for antenna design (typically -10 dB). This formulation of the penalty function returns a negative value when the maximum in band reflection violates the threshold. Therefore equation 2.8 uses this value squared, as violation of the threshold must increase $U$, not decrease.
Chapter 3

Computational Models of Antennas. Case Studies

In this chapter, we provide basic information about the electromagnetic simulation software utilized for evaluating antenna structures in this work as well as programming environment used to develop optimization routines. All numerical experiments described in this thesis are conducted on a set of benchmark ultra-wideband antennas, outlined in the second part of the chapter.

3.1 Software

Accurate evaluation of electrical and field characteristics of antenna structures required full-wave electromagnetic (EM) simulation. In this work, we are mostly concerned with antenna reflection coefficient. There is a large variety of commercial simulation packaged available, including, JCMsuite, Ansys HFSS, CST, FEKO, or Sonnet em. In this work CST Microwave Studio (CST MWS) is utilized due to its availability as well as convenience (e.g., user-friendly interface). CST is a specialized tool for full 3D EM simulation of high frequency components. The software uses a time domain solver based on Finite Integration Technique by applying Maxwell’s equations in integral form to a set of staggered grids. The time domain solver uses transmission-line matrix method and is classified as a full-wave, volume-meshing technique.\(^{(27)}\).

In our case, CST returns the antenna reflection response, which is necessary in the optimization process because of the design requirement imposed on the antenna, specifically, that the maximum in-band reflection level does not exceed certain value, typically –10 dB. Normally, CST is run in an interactive mode. For the purpose of this work, however, a CST-to-Matlab socket is utilized, which is an in-house code created in Engineering Optimization and Modelling Center at Reykjavik University. The socket creates a Visual Basic script that runs CST in a batch mode, updates geometry parameters of the antenna at hand, and postprocesses the results providing the antenna responses in a particular format for further processing by the optimization algorithm.

All algorithms have been implemented in Matlab, which is a popular high-level programming environment. Figure 3.1 shows the flow of information between Matlab and CST. The process shows that a set of initial parameters and a template antenna project file need to be implemented beforehand. This information is fed to Matlab which updates the CST project using the aforementioned socket, the updated template returns a set of EM simulated responses and any additional postprocesses required for design (Efficiency, gain, etc.).
Once the antenna characteristics have been returned, Matlab uses the information to run the optimization algorithms that either repeat the process or return a final optimized design.

Figure 3.1: Evaluation of antenna structures using Matlab-CST socket: original CST project containing the antenna structure at hand is modified to update the geometry parameters according to the input vector $x$; CST solver is run in a batch mode; results obtained from the EM simulation are postprocessed and returned in a form of a cell array containing frequency characteristics (reflection response, gain, efficiency, etc.).

### 3.2 Test Antenna Designs

Numerical experiments performed under this work have been conducted using a set of compact ultra-wideband antennas taken from the literature. All the structures are briefly characterized in this section.

Antenna I [28], a microstrip-fed hexagonal wide slot monopole antenna (Fig. 3.2), and Antenna II [29] (Fig. 3.3), a circular slot antenna with a rectangular patch, are implemented on Taconic RF-35 substrate ($h = 0.76$ mm, $\epsilon_r = 3.5$); Antenna III [30] (Fig. 3.4), is implemented on 1.55 mm thick FR-4 substrate ($\epsilon_r = 4.4$). Computational models for all structures were implemented in CST Microwave Studio and evaluated using its time-domain solver. The design variables for Antenna I are $x_I = [L_2, L_3, L_4, L_5, w_2, w_3, w_4, w_5, w_6, w_7]^T$. $w_1 = 1.95$, $L_1 = 7.0$, and $L_6 = 1$, all in mm, are fixed. The EM model consist of 940,000 mesh cells (average simulation time about 11 minutes). The design variables for Antenna II are $x_{II} = [r_l, r_s, l, m, a, h]^T$. The EM model contains 900,000 cells (average simulation time 7 min). The design variables for Antenna III are $x_{III} = [L_1, L_2, L_3, r_1, w_1, w_2]$, $d = 0.60$, $w_3 = 4.4$ mm are fixed to keep the feedline impedance close to 50-ohm. The EM model contains 560,000 cells (average simulation time of 4 min).
3.2. TEST ANTENNA DESIGNS

Figure 3.2: Antenna I, a microstrip-fed hexagonal wide slot monopole antenna.

Figure 3.3: Antenna II, a circular slot antenna with a rectangular patch.
Figure 3.4: Antenna III, An asymmetric coplanar strip feedline with an octagon and patch cut along the feedline and a lateral ground plane patch.
Chapter 4

Algorithms for Simulation-Driven Miniaturization of Antenna Structures

In this section we describe novel approaches to explicit size reduction of antenna structures. All presented methods exploit appropriate formulation of the design problem and optimization routines involving trust-region framework. For convenience, the mathematical notation is reintroduced and a reference method is recalled. This approach is used for comparison with the new methods. As mentioned in the introduction, the primary motivation behind the proposed techniques is addressing the difficulties related to the benchmark method. The last section of this chapter discusses the termination conditions utilized by the optimization algorithms. The comparative numerical studies are presented in Chapter 5.

4.1 Benchmark Optimization Method

The objective function is formulated using equation 2.8, where the antenna size, $A(x)$, is the primary objective, whereas $c$ is a penalty function defined as 2.9 and $\beta$ is a penalty factor (here, $\beta = 1000$, selected from experience).

The benchmark algorithm, [3], generates a sequence $x^{(i)}$, $i = 0, 1, \ldots$, of approximations to $x^*$ as shown in (2.2), using TR approach. The local model, used is a first-order Taylor approximation, as (2.3). The trust region search size, $\delta^{(i)}$, is adjusted using the standard rules [31].

---

**Algorithm 1 Benchmark**

1: procedure BM($x^{(0)}$, lb, ub)
2: $i = 0$
3: while Termination conditions not satisfied do
4: Create approximation model, around $x^{(i)}$, using 2.3
5: Find approximation minimizer, $x^*$, using Eq. (2.2)
6: Compute gain ratio $\rho$, using 2.5
7: Update TR using 2.6
8: if $\rho > 0$ then
9: $i = i + 1$
10: $x^{(i)} = x^*$
11: Check termination conditions (cf. Section 4.5)
CHAPTER 4. ALGORITHMS FOR SIMULATION-DRIVEN MINIATURIZATION OF ANTENNA STRUCTURES

A practical issue concerning the penalty function, when using (2.8), is that once the threshold, \( S(x) \leq S_{\text{max}} \), is violated at certain iteration, the benchmark algorithm may have problems locating the optimum. This is because the active penalty term makes the functional landscape being optimized very steep (in the directions perpendicular to the boundary of the region that is feasible w.r.t. the constraint \( S(x) \leq S_{\text{max}} \)). The remainder of this chapter introduces novel methods that attempt to address these shortcomings. The flow diagram of the algorithm is described using the same flow diagram as the trust region approach, as this method is created using said approach, see Figure 2.1.

4.2 Trust-Region with Quadratic Approximation Model

The purpose of this method was to improve the generalization capability of the local surrogate model utilized to approximate the reflection response of the antenna within the trust-region optimization framework. By having a more accurate model, the functional landscape can be represented in a more reliable manner (compared to the linear approach) resulting in a better control in the context of exploring the research space while searching for the optimum design. Here, the approach generates a sequence \( x^{(i)}, i = 0, 1, \ldots \), of approximations to \( x^* \) as

\[
x^{(i+1)} = \arg \min_{x:||x-x^{(i)}||\leq\delta(i)} U(Q^{(i)}(x))
\]

(4.1)

where the local model is a second-order polynomial of the form

\[
Q(x) = \lambda_0 + \sum_{k=1}^{N} \lambda_k x_k + \sum_{l=1}^{N} \lambda_l (x_l)^2 + \sum_{(j,q)\in P} \lambda_{jq} x_j x_q
\]

(4.2)

The last term of the polynomial, in (4.2), is a set of mixed terms that represent additional points to represent the approximation model. It is assumed that more sampled values used to create an approximation model will result in a better generalization of the functional landscape. Without the mixed term the samples used for the polynomial are selected using a star distribution, the size defined by the trust region size. The mixed terms are selected from the corner of the trust region. The number of mixed terms were subject to inspection. A full model, using all possible additional mixed terms was tested; no mixed terms using only the quadratic approach; a partial set of mixed terms selected by user. In equation 4.2 \( \sum_{(j,q)\in P} \lambda_{jq} x_j x_q \) are the mixed terms, the number of selected mixed terms are \( M \), with \( 0 \leq M \leq \frac{(N-1)N}{2} \). The set \( P \) of the indices representing the mixed terms is a subset of all possible pairs of distinct indices, i.e., \( P \subseteq \{j,q\}; \ j = 1, \ldots, M; \ q = 1, \ldots, M; \ j \neq q \) In case \( M = 0 \), there are no mixed terms, if \( M = \frac{(N-1)N}{2} \), we have a full quadratic model. For simplicity, the conditions defining the model coefficients can be rewritten in matrix form as

\[
Y(x) = A\lambda
\]

(4.3)

where

\[
Y(x) = \begin{bmatrix} R(x^{(0)}), R(x^{(1)}), & \ldots, & R(x^{(N)}), R(x^{(N+1)}), & \ldots, & R(x^{(q,j_1)}), & \ldots, & R(x^{(jqqu)}) \end{bmatrix}^T
\]

(4.4)
are the EM responses for model points.

\[
A = \begin{bmatrix}
1 & x_1^{(0)} & \cdots & x_N^{(0)} & (x_1^{(0)})^2 & \cdots & (x_N^{(0)})^2 & x_{(j_1,q_1)}^{(0)} & \cdots & x_{(j_M,q_M)}^{(0)} \\
1 & x_1^{(1)} & \cdots & x_N^{(1)} & (x_1^{(1)})^2 & \cdots & (x_N^{(1)})^2 & x_{(j_1,q_1)}^{(1)} & \cdots & x_{(j_M,q_M)}^{(1)} \\
\vdots & \ddots & \ddots & \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots \\
1 & x_1^{(2N+M)} & \cdots & x_N^{(2N+M)} & (x_1^{(2N+M)})^2 & \cdots & (x_N^{(2N+M)})^2 & x_{(j_1,q_1)}^{(2N+M)} & \cdots & x_{(j_M,q_M)}^{(2N+M)} 
\end{bmatrix}
\]

(4.5)

is the combined set of initial design points, used to create the approximation model, using star distribution and auxiliary point allocated at the corners of the design space. The model is recreated at each iteration,

\[
\lambda = \begin{bmatrix} \lambda_0, \lambda_1, \ldots, \lambda_N, \lambda_{N+1}, \ldots, \lambda_{2N}, \lambda_{j_1,q_1}, \ldots, \lambda_{j_M,q_M} \end{bmatrix}^T
\]

(4.6)

are the model coefficients. Using 4.3, and assuming that the number of the training points is equal to the number of model coefficients (in which case the matrix \(A\) is square and non-singular), the coefficients can be found as

\[
\lambda = A^{-1}Y(x)
\]

(4.7)

**Algorithm 2** Trust-Region with Quadratic Approximation Model

1: \textbf{procedure} TRQAM(\(x^{(0)}\), lb, ub)
2: \hspace{1em} \(i = 0\)
3: \hspace{1em} \textbf{while} Termination conditions not satisfied \textbf{do}
4: \hspace{2em} Create approximation model, around \(x^{(i)}\), using 4.2
5: \hspace{2em} Find approximation minimizer, \(x^*\), using Eq. 4.1
6: \hspace{2em} Compute gain ratio \(\rho\), using 2.5
7: \hspace{2em} Update TR using 2.6
8: \hspace{2em} \textbf{if} \(\rho > 0\) \textbf{then}
9: \hspace{3em} \(i = i + 1\)
10: \hspace{3em} \(x^{(i)} = x^*\)
11: \hspace{1em} \textbf{end if}
12: \hspace{1em} \textbf{end while}
13: \hspace{1em} Check termination conditions (cf. Section 4.5)

It should be mentioned that a practical issue, regarding the quadratic approximation, is a considerably larger number of objective function evaluations required for the algorithm to converge. The benchmark method uses fewer evaluations per iteration to get close to the minima. Given that the advantage of the quadratic approximation approach is improved accuracy, the maximum benefit of using this method would be to utilize it as a supplement of the reference technique for the last few iterations of the algorithm run.

The design flow of the method is the same as for the standard trust-region framework with linear approximation model (cf. Fig. 2.1), with the difference being the trust-region quadratic approximation model is used instead of the linear one, \(L(x) = Q(x)\).

## 4.3 Adaptive Acceptance Threshold Method

This approach is a modification of the reference optimization method where the acceptable threshold concerning the maximum in-band reflection level is adaptively adjusted and gradually converges towards the final threshold value (referred to as \(S_{\text{max,ref}}\)). This arrangement
allows for maintaining (in most iterations) feasibility of the designs thus facilitating identification of the optimum. A flow diagram can be seen in Figure 4.1.

The practical difference between this approach and the reference is the definition of the penalty function, it is formulated as

\[
c^{(i)}(S(x)) = \max \left\{ \frac{(S(x) + S^{(i)}_{\text{max}})}{(S^{(i)}_{\text{max}})}, 0 \right\}; \tag{4.8}
\]

where

\[
S^{(i)}_{\text{max}} = \frac{S(x^{(i)}) + S_{\text{max, ref}}}{2}; \tag{4.9}
\]

The reference threshold value (typically -10dB) is initially pushed lower (e.g., -12 dB, assuming the initial point has the highest in-band reflection of -14dB), reducing the number available results. This ensures that the method returns, as possible, results in the feasible region away from the threshold boundary.

The algorithm is as follows:

**Algorithm 3** Adaptive Acceptance Threshold Method

1: procedure AATM(x\(^{(0)}\), lb, ub)
2: Initialize threshold, \(S^{(i)}_{\text{max}}\)
3: \(i = 0\)
4: while Termination conditions not satisfied do
5: Create approximation model, around \(x^{(i)}\), using 2.3
6: Find approximation minimizer, \(x^*\), using Eq. 4.8
7: Compute gain ratio \(\rho\), using 2.5
8: Update TR using 2.6
9: if \(\rho > 0\) then
10: Update threshold using 4.8
11: \(i = i + 1\)
12: \(x^{(i)} = x^*\)
13: Check termination conditions (cf. Section 4.5)
4.4 Feasible Region Boundary Search

Feasible region boundary search is a novel procedure that iteratively executes two search processes, both on non-linear functions. Depending on whether, at a certain iteration, the design point \( x^{(i)} \) is in the feasible region or slightly violates the boundary and is in the infeasible region. If the current design \( x^{(i)} \) is feasible, explicit minimization of the area \( A(x) \) is carried out with the constraints on the reflection based on the threshold value \( S_{\max} \) and a violation parameter \( \epsilon \) (here \( \epsilon = -1 \) dB) effectively relaxing the threshold to \( S_{\max}^* = S_{\max} + \epsilon \).

The optimization is realized as

\[
    x^* = \arg \min_{|x-x^{(i)}| \leq \delta^{(i)}} A(x)
\]

Subject to:

\[
    S(x) \leq S_{\max}^*
\]

(4.10)
CHAPTER 4. ALGORITHMS FOR SIMULATION-DRIVEN MINIATURIZATION OF ANTENNA STRUCTURES

If, at a certain iteration, $x^{(i)}$ is infeasible (i.e., it violates the reflection requirements), minimization of the reflection $S(x)$ is carried out with the explicit constraint on the area $A(x)$

$$x^* = \arg \min_{||x-x^{(i)}|| \leq \delta^{(i)}} S(x)$$

Subject to:

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

(4.11)

where $0 \leq \alpha \leq 1$ is adjusted adaptively (see below). If (4.11) returns a point in the infeasible region, most likely due to $\delta_s \leq \delta_a$, the algorithm will converge in the infeasible region. For this reason the relaxation parameter, $\epsilon$, must be within an expectable final range, as the final design can slightly violate the threshold. However, the constraint tries to ensure that the returned design minimizer has a size between the previous design (in the feasible region) and the optimized area design.

Both in 4.10 and 4.11, $S$ is replaced by its linear model $L$ as described under equation 2.3. The algorithm description is as follows:

Algorithm 4 Feasible Region Border Search

1: procedure FRBS($x, lb, ub$)
2: $i = 0$
3: while Termination conditions not satisfied do
4: Create approximation, around $x^{(i)}$, model using 2.3
5: if $S(x^{(i)}) \leq S_{\text{max}}$ then:
6: Find approximation minimizer, $x^*$, using 4.10
7: Compute gain ratio $\rho$, using 2.5
8: Update $\delta_a$, using 2.6
9: if $\rho > 0$ then
10: $i = i + 1$
11: $x^{(i)} = x^*$
12: else if $S_{\text{max}} \leq S(x^{(i)}) \leq S_{\text{max}} + \epsilon$ then
13: Find approximation minimizer, $x^*$, using 4.11
14: Compute gain ratio $\rho$, using 2.5
15: Update $\delta_s$, using 2.6
16: if $\rho > 0$ then
17: $i = i + 1$
18: $x^{(i)} = x^*$
19: if $S(x^*) > S_{\text{max}}$ then
20: Check convergence in infeasible region
21: $\alpha = \frac{2}{3}\alpha$ go to 13
22: else
23: $\alpha = \alpha^{(0)}$
24: Check termination conditions (cf. Section 4.5)

The trust region radii $\delta_a$ and $\delta_s$ are independent for size minimization and reflection minimization, respectively. This method is preferred as it allows the TR to work independently in each region, increasing the likelihood of a good final optima.

The proposed algorithm is designed to bounce between feasible and infeasible region which
allows for overcoming the problem of the steep functional landscape faced by the benchmark method, and, at the same time, for practical control of the computationally expensive constraint $S(x) \leq S_{\text{max}}$. The algorithm is illustrated in figure 4.2.

Figure 4.2: Flow diagram for Feasible Region Boundary Search.

Figure 4.3 shows the conceptual illustration of the feasible region boundary search, explaining the process further.
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Figure 4.3: Conceptual illustration of feasible region boundary search. Given an initial point $x^{(0)}$ border search minimizes the antenna size with constrains on the reflection response, cf. equation (4.10). Due to using linear approximation models, the method can return infeasible points, e.g., $x^{(*)}$. These points are rejected and the trust region radius is updated. Point $x^{(1)}$ is a feasible point found subsequently. The algorithm optimizes the antenna for best matching in the vicinity of this point with constrains on the area, cf. equation (4.11). In the example given in the picture, the algorithm is terminated after finding point $x^{(5)}$, which could not be improved. Consequently, the last-found feasible point $x^{(4)}$ is returned at the final outcome of the optimization process.

4.5 Termination Conditions for Optimization Algorithms

A comment is necessary concerning termination conditions of the optimization algorithms discussed in this thesis. There are two conditions utilized, one related to convergence in argument, the other related to reduction of the trust region radius. The first condition is determined by

$$||x^{(i)} - x^{(i-1)}|| \leq \kappa \quad (4.12)$$

where $\kappa$ is a user-defined threshold. Because the optimization is performed at the level of EM-simulated antenna responses, certain level of numerical noise is always present. Consequently, convergence in argument may not be possible in some instances and another termination condition is necessary utilized here as a convergence safeguard. More specifically, the algorithm is terminated upon satisfying

$$|\delta^{(i)}| \leq \gamma \quad (4.13)$$

where $\gamma$ is another user-defined threshold. For all numerical experiments in this work the termination threshold were chosen as $\kappa = \gamma = 10^{-2}$. 

Chapter 5

Numerical Results and Benchmarking

In this chapter we present the numerical studies of the novel trust-region-based methodologies for explicit size reduction of antenna structures. The experiments have been performed using three ultra-wideband antennas as described in Chapter 3. The design objective was to achieve minimum size while maintaining acceptable level of the maximum in-band reflection. The results obtained using the techniques proposed in this work have been compared to the reference method. Other performance figures have also been evaluated at the optimized designs, specifically, total efficiency and radiation patterns (both, H-plane and E-plane). The latter are included mostly to verify that reducing the antenna size does not lead to degradation of the field properties of the respective antenna structures. Further discussion of the results as well as the summary has been provided in Chapter 6

5.1 Trust-Region with Quadratic Approximation Model

The first method to be tested was a trust-region algorithm with quadratic approximation model. Starting from the designs obtained using the benchmark method (as the method considered here was meant to improve over the benchmark, not to compete with it) the final design were found for two out of three antennas, i.e. the algorithm converged. In these two cases (Antenna II & III) the final footprint area (Table 5.1) is insignificantly smaller than for the benchmark approach: 12 mm$^2$ for Antenna II and 12 mm$^2$ for Antenna III. The reflection characteristics at the final designs (Fig. 5.1) suggest that this method can reduce the distance between the actual and acceptable maximum in-band reflection (improved control over reflection compared to the benchmark technique). Comparison between the different number of mixed terms reviewed no improvement, for area reduction or reflection control, when increasing the number of mixed terms. A full model, using all mixed terms, gave the same results as using a simple quadratic model, no mixed terms. The method was not investigated further due to the aforementioned limited improvements concerning the achievable miniaturization rates.
5.2 Adaptive Acceptance Threshold Method

The results, Table 5.1, show that adaptive acceptance threshold allows for obtaining better miniaturization rate than the fixed threshold of the benchmark approach. The additional size reduction is 60 mm$^2$ for Antenna I. and 8 mm$^2$ for Antenna II. Figure 5.2 shows the plots of the reflection responses indicating that the size-optimized designs exhibit maximum in-band reflection at the level close to −10 dB. The efficiency and radiation patterns are very similar for the designs obtained with the benchmark techniques (cf. Fig. 5.3, Fig. 5.4, Fig 5.5) and the proposed method which means that additional size reduction has not been achieved at the expense of performance degradation of the respective structures.
5.2. ADAPTIVE ACCEPTANCE THRESHOLD METHOD

Figure 5.2: Reflection characteristics using adaptive acceptance threshold method, optimization for best matching (···), optimization using fixed acceptance threshold (−−) and optimization using adaptive acceptance threshold (–): (a) Antenna I, (b) Antenna II respectively.

Figure 5.3: Total efficiency of the considered antenna structures, optimization for best matching (···), optimization for size using fixed acceptance threshold (−−) and adaptive acceptance threshold (–): (a) Antenna I, (b) Antenna II.
Figure 5.4: H-plane radiation patterns, optimization for best matching (···), optimization for size using fixed acceptance threshold (−−) and adaptive acceptance threshold (−): (a) Antenna I, and (b) Antenna II. Plots from left- to right-hand-side correspond to frequencies 4 GHz, 6 GHz and 8 GHz, respectively.
Figure 5.5: E-plane radiation patterns, optimization for best matching (···), optimization for size using fixed acceptance threshold (−−) and adaptive acceptance threshold (−): (a) Antenna I, and (b) Antenna II. Plots from left- to right-hand-side correspond to frequencies 4 GHz, 6 GHz, and 8 GHz respectively.
5.3 Feasible Region Boundary Search

The proposed optimization technique allows for better control of the reflection response than the benchmark technique (in particular, the maximum in-band reflection is closer to the required level $S_{\text{max}}$, cf. Fig. 5.6). For Antennas I and III, the proposed approach yields designs that are considerably smaller than those obtained with the benchmark method (520 mm$^2$ versus 580 mm$^2$ for Antenna I, and 255 mm$^2$ versus 287 mm$^2$ for Antenna III cf. Table 5.1). The efficiency and radiation patterns are very similar for the designs obtained with the benchmark techniques (cf. Fig. 5.7, Fig. 5.8, Fig. 5.9) and the proposed method which means that additional size reduction has not been achieved at the expense of performance degradation of the respective structures. It should be noted that the efficiency of Antenna III is considerably worse than for the other structures, which is because it was implemented on a high-loss FR-4 substrate. Nevertheless, this is not relevant for the main point of this work which is reliability of the simulation-driven antenna miniaturization.
Figure 5.6: Reflection characteristics using feasible region boundary search, optimization for best matching (⋯), optimization using fixed acceptance threshold (——) and optimization using feasible boundary search (–): (a) Antenna I, (b) Antenna II, (c) Antenna III.
Figure 5.7: Total efficiency characteristics of the considered antenna structures, optimization for best matching (···), optimization for size using the benchmark method (——) and the proposed approach (−−): (a) Antenna I, (b) Antenna II, (c) Antenna III.
Figure 5.8: H-plane radiation patterns, optimization for best matching (\cdots), optimization for size using fixed acceptance threshold (\ldots) and adaptive acceptance threshold (\ldots): (a) Antenna I, and (b) Antenna II. Plots from left- to right-hand-side correspond to frequencies 4 GHz, 6 GHz and 8 GHz, respectively.
Figure 5.9: E-plane radiation patterns of the considered antenna structures, optimization for best matching (···), optimization for size using the benchmark method (−−) and the proposed approach (−): (a) Antenna I, (b) Antenna II, (c) Antenna III. Left, middle, and right plots correspond to frequencies of 4 GHz, 6 GHz, and 8 GHz.
5.4 Numerical Comparison of Final Antenna Footprint Size

Table 5.1 shows the footprint areas of the final antenna designs obtained using the methods considered in this work. Results concerning adaptive the acceptance threshold method and the feasible region boundary search have been extracted from respective research papers prepared as a result of the conducted research. Consequently, not all of the methods were applied to all antenna structures of the benchmark set. Detailed discussion of these results have been provided earlier in this chapter.

Table 5.1: Final footprint area size of antenna designs, using approaches presented in this thesis, all measurements are in mm$^2$

<table>
<thead>
<tr>
<th>Design objective and optimization approach</th>
<th>Footprint area [mm$^2$]</th>
<th>Antenna I</th>
<th>Antenna II</th>
<th>Antenna III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflection Threshold Value ($S_{\text{max}}$)</td>
<td>-10 dB</td>
<td>885</td>
<td>852</td>
<td>336</td>
</tr>
<tr>
<td>Minimization of maximum in-band reflection $</td>
<td>S_{11}</td>
<td>$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final antenna size using fixed acceptance thresholds (cf. Section 4.1)</td>
<td>580</td>
<td>772</td>
<td>287</td>
<td></td>
</tr>
<tr>
<td>Final antenna size using quadratic approximation model (cf. Section 4.2)</td>
<td>-*</td>
<td>760</td>
<td>275</td>
<td></td>
</tr>
<tr>
<td>Final antenna size using adaptive acceptance threshold (cf. Section 4.3)</td>
<td>507</td>
<td>764</td>
<td>-†</td>
<td></td>
</tr>
<tr>
<td>Final antenna size using adaptive acceptance threshold (cf. Section 4.4)</td>
<td>520</td>
<td>754</td>
<td>255</td>
<td></td>
</tr>
</tbody>
</table>

*Approach did not improve from starting position
†Not optimized using this approach
Chapter 6

Discussions

In this section the results are discuss and interpret. Future work, based on the results, is introduced as are relevant papers both submitted and to be submitted.

6.1 Research Conclusion

There are several conclusions that can be drawn from this work. Among the presented methods, the technique involving quadratic models was able to predict the EM simulation more precisely, resulting in better control of the reflection characteristics. However, no noticeable benefits concerning antenna miniaturization have been observed. Also, given the increased (compared to the reference method) computational complexity of the algorithm, the approach was deemed unsatisfactory.

The second approach, Adaptive Acceptance Threshold, exhibits visible improvement over the benchmark procedure. In particular, it resulted in smaller footprint areas over the considered benchmark set. The results have been described in an accepted paper An Improved Procedure for Simulation-Driven Miniaturization of Antenna Structures to be published in the proceedings of IEEE Antenna & Propagation Symposium (San Diego, July 2017).

The last approach, Feasible Region Border Search, also showed improvement over the reference procedure. In this case, three antenna structures were examined and the results have been described in a paper Reliable EM-Driven Size Reduction of Antennas Using Feasible Region Boundary Search submitted to LAPC 2017 conference.

6.2 Future Work

Two papers have been submitted as a result of this work, see Table 6.1. Two additional papers, currently awaiting fabricated antennas for measurements, will be submitted at the earliest convenient as journal papers to ISI-ranked journals and will contain experimental validation of the miniaturized antenna prototypes.

The work done here is the first step in creating novel approaches, however given the sample size of only a few antennas no general results can be drawn. The next step is to ensure that measurements of fabricated antennas agree with simulations. Following that further antenna simulations, using different antennas and antenna designs. Assuming these approaches are capable a rigorous mathematical analysis can be applied to try and draw general conclusions.
### Table 6.1: Publications concerning this work

<table>
<thead>
<tr>
<th>Paper name</th>
<th>Authors</th>
<th>Publication status</th>
<th>Where published</th>
</tr>
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<tr>
<td>Feasible Space Boundary Search for Improved Optimization-Based Miniaturization of Antenna Structures</td>
<td>David O. Johannesson; Slawomir Koziel; Adrian Bekasiewicz</td>
<td>To be submitted</td>
<td>Int. J. RF and Microwave CAE, 2017.</td>
</tr>
</tbody>
</table>
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