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Quantitative assessment of wideband antenna geometry modifications for size-reduction-oriented design

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A R T I C L E I N F O

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A B S T R A C T

Incorporation of various topological modifications to basic antenna structures is a common strategy in the context of size-reduction-oriented design. Modifications can be applied to the ground plane, the feed line, and/or antenna radiator, and may lead to achieving smaller physical dimensions of the antenna at hand. Unfortunately, various topology alteration options are normally reported on a case-to-case basis; systematic comparisons of different modification types are lacking in the literature. In this paper, thorough investigations of selected topological changes in terms of their effect on antenna size reduction are carried out. Numerical experiments are performed using two ultra-wideband monopoles. In order to ensure a fair comparison, for each antenna topology, all geometry parameters are rigorously optimized to obtain the minimum footprint while maintaining acceptable electrical performance. The results clearly indicate the advantage of feed line modifications (56% average physical size reduction) over a ground plane and radiator ones (43% and 2.15% respectively). Experimental validations confirming the numerical findings are also provided.

1. Introduction

In modern communication systems, miniaturization of wideband antennas is an important design criterion, originating from the necessity of mounting them within compact devices such as wearable ones [1] or related to the Internet of Things (IoT) [2], cognitive radio [3], microwave imaging [4], Wi-Fi, Wi-MAX, and UWB applications [5]. At the same time, reduction of the physical dimensions of the antenna affects its electrical properties due to disturbance of the current path and may result in performance degradation, among others, difficulties in ensuring required impedance bandwidth. Moreover, size reduction may also affect field properties such as radiation pattern stability, gain, and efficiency [6]. Consequently, the design of miniaturized wideband antennas with acceptable performance is not a trivial task.

Perhaps the most widely used approach to antenna size reduction is incorporation of various geometry modifications into the basic antenna structures. There are plenty of examples available in the literature, e.g., an exponential slot edge applied in a Vivaldi antenna [7], a C-shape radiator [8], a bending microstrip feed line [9], rectangular slots edge on a radiator [10], or a differential stepped slot [11]. These and other examples represent case studies, and hardly any systematic investigations have reported in the literature regarding the comparison of different topology modification techniques and their effects on antenna miniaturization rate and electrical performance.

Another critical issue—apart from setting up the antenna topology—is a proper adjustment of geometry parameters of the structure so that an accurate optimum design can be obtained. Majority of researchers utilize experience-driven parameter sweeping [12], which typically yields designs that are acceptable, but definitely not optimal. Especially in case of complex antenna topologies, simultaneous adjustment of all geometry parameters through numerical optimization is a necessity due to various and sometimes subtle interactions between parameters that cannot be detected by handling one or two parameters at a time [13]. There is a large variety of optimization algorithms available, including local search methods (gradient-based [14] and derivative-free [15,16]), as well as global search algorithms such as genetic algorithms [17], particle swarm optimizers [18], and differential evolution [19]. Many of these algorithms have been applied for antenna design [20–22].

In this work, a comprehensive study has been carried out in relation to wideband antenna geometry modifications (concerning a ground plane, a feed line, and a radiator) having in mind their effect on antenna miniaturization rate. The study is performed using a benchmark set of two wideband monopole antennas. The feed line and a ground plane modifications considered here are multi-section stepped-impedance lines and slits below the feed line, respectively. For a radiator, rectangular, circular and elliptical slits are investigated. EM-driven optimization is performed to obtain minimum-size designs with acceptable

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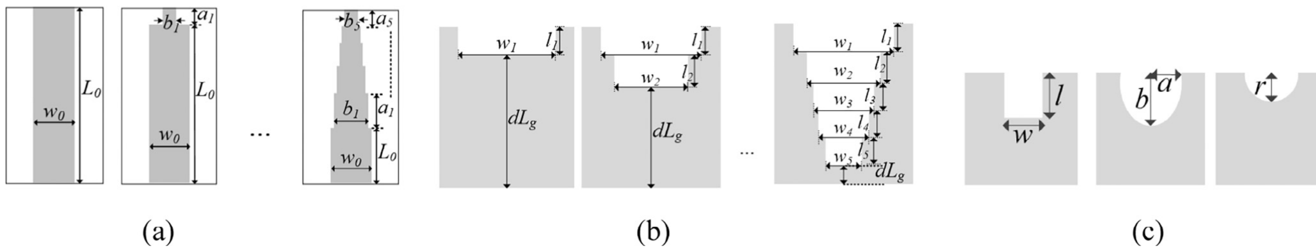

Fig. 1. Selected topological modifications for benchmark UWB monopole antennas. (a) Stepped-impedance feed line complexity, (b) ground plane modifications up-to five-section slit, and (c) radiator modifications: rectangular, elliptical and circular, respectively.

electrical performance. The results indicate superiority of feed line modification (average miniaturization rate of 56%) over a ground plane and radiator modifications (miniaturization rates of 43% and 2.15%, respectively). Experimental results are also provided for selected antenna prototypes for the sake of auxiliary verification.

2. Antenna modifications and case studies

In this work, a detailed study related to the topological modifications of conventional wideband antenna structures is carried out. Specific selected modifications are applied to antenna ground plane, feed line and radiator as shown in Fig. 1. The purpose of this study is to determine the overall effect of the considered modifications on physical size of the antenna, in particular, on its achievable miniaturization rate. Two monopole wideband antennas shown in Fig. 2 are used as a benchmark set. Both antennas are implemented on 0.762 mm thick RF-35 substrate with ($\varepsilon_r = 3.5$). CST Microwave Studio [23] is used to simulate the computational models of the structures. Antenna models are also integrated with SMA connectors to ensure better agreement between simulated and measured results. The design variable vectors for Antenna I and II are $\boldsymbol{x}_1 = [L_g\ L_0\ L_p\ W_p\ a\ b]^T$ and $\boldsymbol{x}_2 = [L_g\ L_0\ r\ a\ b\ d_W]^T$. All dimensions are in mm. The initial numerical values for both antenna design structures are $\boldsymbol{x}_1^{(0)} = [8.9\ 10.2\ 14.8\ 21.8\ 0.43\ 0.38]^T$ and $\boldsymbol{x}_2^{(0)} = [9.28\ 9.48\ 10.3\ 0.40\ 5.17\ 4.0]^T$. Both vectors are extended upon applying particular modifications to antenna components as shown in Fig. 1. The antennas are to operate in the standard UWB frequency range (3.1–10.6 GHz).

3. Design optimization approach

The objective is to determine the minimum antenna footprint while satisfying the condition $S(\boldsymbol{x}) \le -10$ dB. Here, $S(\boldsymbol{x})$ is the maximum reflection level for the entire UWB frequency range (from 3.1 GHz to 10.6 GHz) and $\boldsymbol{x}$ denotes the adjustable geometry parameters of the structure to be optimized (cf. Section 2). $A(\boldsymbol{x})$ denotes the antenna size.

The design problem is therefore formulated as

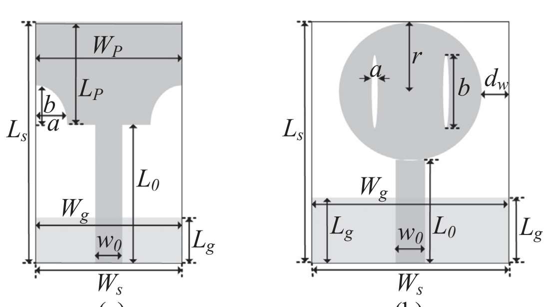

Fig. 2. Benchmark set of two UWB monopole antennas: (a) Antenna I, (b) Antenna II.

$$\boldsymbol{x}^* = \underset{\boldsymbol{x}}{\operatorname{argmin}}\{A(\boldsymbol{x})\}, \quad S(\boldsymbol{x}) \leqslant -10\ \text{dB} \tag{1}$$

The problem (1) is solved using a pattern search algorithm [17]. The starting point is a design obtained by minimizing $S(\boldsymbol{x})$. The reason for such a procedure is twofold: (i) the pattern search routine requires a feasible starting point, (ii) optimization-wise, the problem (1) is easier to solve when starting from the best possible $S(\boldsymbol{x})$, i.e., the interior of the feasible region rather than by traversing the feasible region boundary.

A pattern search implementation utilized here [18] is a derivative-free stencil-based search routine that consists of several steps executed sequentially:

- Estimation of the objective function gradients based on on-grid design perturbations.
- Grid-restricted line search.
- Poll search (i.e., nearest neighbor search) in case of a failure of the line search, further extended in the direction of the best design found.
- Grid refinement in case of a failure of the poll search.

Termination condition for the pattern search is grid refinement beyond a user-defined minimum size (here, 10^{-3}).

Optimization for minimum reflection is arranged differently,

Table 1
Antenna dimensions with feed line modifications.

Antenna #	Optimized antenna footprint area [mm^2]					
	Ref. antenna	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$
Antenna I	539	472	374	344	282	233
Antenna II	780	544	463	406	372	356

*n denotes number of feed-line sections.

Table 2
Antenna dimensions with ground plane modifications.

Antenna #	Optimized antenna footprint area [mm^2]					
	Ref. antenna	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$
Antenna I	539	491	431	326	270	238
Antenna II	780	635	557	496	458	435

*n denotes number of ground plane sections.

Table 3
Antenna dimensions with radiator modifications.

Antenna #	Optimized antenna footprint area [mm^2]			
	Ref. antenna	Rect. slit	Ellipt. slit	Circ. slit
Antenna I	539	538	533	528
Antenna II	780	751	768	746

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