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Design and Optimization of a Compact Planar Radiator for UWB Applications and Beyond

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***Abstract*—A compact monopole antenna for ultra-wideband (UWB) and beyond applications has been proposed. The radiator is based on the monopole topology. The super-wideband behavior has been achieved using a combination of spline-based modifications applied to the driven element, as well as utilization of a tapered feed and a slot-modified ground plane. The electrical performance of the structure has been tuned using a numerical optimization algorithm. The proposed design features reflection below the level of –10 dB within 2.8 GHz to 30 GHz range, as well as a footprint of only 404 mm^2. The proposed structure has been compared in terms of bandwidth and size with the state-of-the-art antennas from the literature. The numerical results are supported by measurements of the fabricated antenna prototype.**

***Index Terms*—broadband antennas, multi-system radiators, numerical optimization, spline-based geometry.**

I. Introduction

Integration of various connectivity technologies within mobile devices is often achieved using multiple dedicated radiators. Regardless of diverse operational frequencies, many systems impose similar sets of specifications on antennas, including small size, suitable electrical performance, circularized radiation patterns, etc. For structures with convergent requirements, replacing multiple radiators with a single, broadband component seems to be an interesting solution with a potential to reduce power consumption, and/or complexity of the transceiver.

Popular realizations of broadband (or ultra-wideband – UWB) antennas include planar monopole, slot, and dipole configurations [1], [2]. Miniaturization-oriented design of mentioned structures has also been considered in the literature [2], [3]. Apart from implementing radiator on high-permittivity substrates, size reduction is often achieved through modification of conventional geometries using non-standard features dedicated to enhance impedance matching and/or reduce electrical size of the structures [3]. Volume constrained antennas can also be implemented using self-complementary, asymmetrical, and protruded topologies [3], [4]. Although frequency independent antennas seem to be useful for enhancing bandwidth beyond UWB, they often suffer from relatively large dimensions [3]. Alternative, more compact (and planar) realizations are often based on circular-disc topologies [2]. The latter support generation of overlapping resonant modes, and hence provide a decent matching over super wide frequency ranges [3].

The main challenge pertinent to design of the super broadband structures involves controlling performance- and size-related figures concurrently. Conventional design approaches based on manual or semi-manual adjustment of input parameters intertwined with visual inspection of characteristics are unsuitable for reliable adjustment of both mentioned factors. Consequently, for many structures, small size is often obtained as a by-product of performance-oriented tuning [3], [4]. Numerical optimization methods can address difficulties related to maintaining simultaneous control over the electrical/field properties and the size of radiators. Furthermore, optimization algorithms can reliably handle multi-parameter designs featuring complex mutual-relations between individual variables. Owing to the mentioned features, numerical methods are capable of producing superior solutions compared to manual design approaches.

In this work, a compact, super-wideband spline-enhanced antenna has been proposed. Small dimensions and broadband operation of the radiator have been obtained by means of a rigorous optimization using a two-stage trust region (TR) framework. The final design is characterized by a size of only 404 mm^2. It features reflection below the –10 dB within 2.8 GHz to 30 GHz frequency range. The presented antenna has been benchmarked against the state-of-the-art geometries from the literature. Measurements of the fabricated antenna prototype have also been provided.

II. Antenna Structure

Figure 1 shows the proposed structure. The antenna is implemented on a Rogers RO4003C dielectric substrate (ε_r = 3.55, tanδ = 0.0027, h = 0.81 mm). Its topology is derived from a rectangular monopole and heavily modified in order to enhance attainable bandwidth while maintaining compact dimensions. The geometry changes include the use of a rectangular slot in the ground plane located under the microstrip feed, implementation of the spline-based cutouts located in the bottom corners of the radiator, as well as replacement of conventional microstrip feed with a tapered transformer. The spline shape is controlled using two independent parameters that permit smooth changing of the cutouts shape in the course of the optimization process (cf. Fig. 1). The antenna design parameters are $\boldsymbol{x} = [a\ b\ d_1\ d_2\ f\ k_1\ k_2\ l\ r\ v\ w\ z]^T$, whereas f_w = 1.79 to maintain 50 Ω input impedance. All dimensions are in mm. Relatively large number of variables ensures flexibility of the presented geometry in terms of adjusting the performance and footprint. It is worth noting that, due to fundamental limitations on antenna size [3], reduction of the lower corner frequency while maintaining small dimensions is challenging. In practice, the problem involves the use of design methods that are tailored to handle steep response changes around the lower edge of the frequency spectrum.

The antenna footprint $A(\boldsymbol{x})$ is defined as an $X \cdot Y$ rectangle where $X = (2a + w)$ and $Y = (d_1 + d_2 + l + b)$. The lower and upper bounds for the structure design are: $\boldsymbol{l} = [0\ 0\ 4\ 4\ 0\ 0\ 0\ 2\ 0\ 0\ 2\ 0]^T$, $\boldsymbol{u} = [5\ 6\ 9\ 9\ 8\ 4\ 6\ 20\ 0.8\ 7\ 20\ 7]^T$.

III. DESIGN METHOD

The antenna optimization problem can be defined as:

$$\boldsymbol{x}^* = \arg\min U\left(\boldsymbol{R}(\boldsymbol{x})\right) \tag{1}$$

where $\boldsymbol{R}(\boldsymbol{x})$ is the response of the structure obtained for the given set of input variables $\boldsymbol{x}$, U is the scalar objective function and $\boldsymbol{x}^*$ represents the optimal design to be found. Direct solving of (1) is expensive as it involves numerous high-fidelity electromagnetic (EM) simulations of the structure. It can be replaced by the surrogate-assisted design procedure implemented in the form of a TR framework that iteratively ($i = 0, 1, 2, \ldots$) approximates the final design [6]:

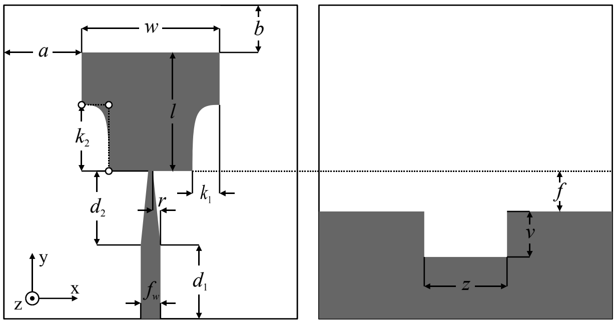
$$\boldsymbol{x}^{(i+1)} = \arg \min_{\boldsymbol{x}:\left\|\boldsymbol{x}-\boldsymbol{x}^{(i)}\right\|<\rho} U\left(\boldsymbol{G}^{(i)}(\boldsymbol{x})\right) \tag{2}$$

Here, $\boldsymbol{G}^{(i)}(\boldsymbol{x})$ is the linear model constructed based on a large-step finite differences and ρ is the TR radius updated based on a set of standard rules [6]. The computational cost of the TR-based optimization is much lower compared to direct solving of (1) as it requires only $d + 1$ EM simulations per successful iteration (d is the problem dimensionality). Additional evaluations are needed for failed steps. The optimization engine used by the TR framework is a standard gradient-based algorithm implemented in MATLAB. For more information on the optimization method see [6].

The design optimization is realized in a bi-stage setup where minimization of the antenna in-band reflection is followed by a constrained reduction of the size. The design objective for the first design step is defined as:

$$U_1(\boldsymbol{x}) = \frac{1}{N}\sum_{k=1}^{N} \max\left(\left|S_{11.f_k}\right| - S_{\max}, 0\right)^2 \tag{3}$$

Here, $|S_{11,fk}|$ is the reflection (in dB) evaluated over $k = 1, \ldots, N$ frequency points where $f_L = f_1$ and $f_H = f_N$ define the lower and upper limits on bandwidth. The parameter $S_{\max}$ represents the target value of reflection (here, $S_{\max} = -10$ dB). Consequently, only the components of the response that violate $S_{\max}$ at f_k contribute to (3). The design $\boldsymbol{x}^{\#}$, obtained by minimization of U_1, is used as a starting point for antenna miniaturization. The second design objective is:



(a) (b)

Fig. 1. Geometry of the proposed antenna with highlight on design parameters: (a) radiator and (b) ground plane. Coordinates that represent the spline control points are denoted using circles.

$$U_2(\boldsymbol{x}) = A(\boldsymbol{x}) + \beta \max\left\{\frac{\max\left(\left|S_{11.f_k}\right|\right) - S_{\max}}{S_{\max}}, 0\right\}^2 \Bigg|_{f_L \le f_k \le f_H} \tag{4}$$

The additive component of (4) is an auxiliary function which is activated only when the antenna in-band reflection (specified using min-max representation) violates the $S_{\max}$ threshold. The parameter $\beta = 10^4$ is a scaling coefficient used to control contribution of the penalty function to U_2 when the specification of in-band reflection is not fulfilled.

IV. RESULTS AND DISCUSSION

The initial design $\boldsymbol{x}^{(0)} = [2.53\ 2.54\ 9.00\ 9.00\ 1.39\ 2.30\ 1.96\ 7.81\ 0.59\ 6.01\ 8.10\ 1.41]^T$ has been obtained through parametric adjustment of the topology. The intermediate design $\boldsymbol{x}^{\#} = [2.98\ 5.87\ 9.00\ 9.00\ 1.39\ 2.29\ 4.24\ 11.05\ 0.42\ 5.25\ 8.27\ 1.52]^T$ has been found by minimization of (3). It maintains reflection below –10 dB within the frequency range from f_L = 2.8 GHz to f_H = 30 GHz. The size of the structure is 496 mm^2. The design $\boldsymbol{x}^{\#}$ has been used as a starting point for miniaturization-oriented optimization. The close-to-optimal solution is $\boldsymbol{x}^* = [2.77\ 3.22\ 8.04\ 9.00\ 1.35\ 1.86\ 4.63\ 10.76\ 0.49\ 3.67\ 7.49\ 1.35]^T$. The optimized structure features reflection below the –10 dB level in a frequency range from 2.8 GHz to 30 GHz and the footprint of around 404 mm^2 (31.2 mm × 12.9 mm). The structure's reflection at the initial, intermediate and final designs, as well as the maximum realized gain over the antenna frequency range are shown in Fig. 2. The average value of gain from 3 GHz to 30 GHz is 4.7 dB.

The proposed structure has been compared against the state-of-the-art antennas from the literature in terms of the operational bandwidth BW (expressed as a f_H to f_L ratio) and the size [31]-[35]. The dimensions of considered antennas are expressed in terms of a guided wavelength λ_g (calculated w.r.t. f_L and electrical properties of the given substrate). The results collected in Table I indicate that the proposed structure is characterized by the smallest size while maintaining competitive electrical performance. Note that the benchmark antennas featuring improved bandwidth w.r.t. the proposed design are also noticeably larger.

The presented antenna has been fabricated and measured. The photographs of the manufactured prototype are shown in Fig. 3. The measurements have been performed in a range up to 20 GHz (bounded from the above due to limitations of the available equipment). The comparisons of reflection characteristics and radiation patterns (obtained at 5 GHz, 10 GHz, and 15 GHz, frequencies) are shown in Fig. 4. It is worth noting that the radiation responses have been measured in non-anechoic environment using a time-gating method [10]. The agreement between the simulated and measured responses is acceptable. Slight discrepancies between the results are mostly due to fabrication tolerances, as well as manual assembly of the prototype. In the case of radiation patterns the measurement errors are also affected by the (non-optimal) setup, as well as inaccuracy of relative positioning between the transmitting and receiving antenna.

V. Conclusions

A planar antenna for UWB and beyond applications has been presented. The structure is based on a monopole topology with modifications that promote broadband behavior while maintaining small dimensions. The rigorous design of the radiator has been performed using a two-stage framework oriented towards minimization of in-band reflection followed by size-reduction-oriented tuning. The optimized structure is characterized by a small footprint of around 404 mm^2 and operates in a frequency range from 2.8 GHz to 30.0 GHz. The radiator has been compared against the state-of-the-art antennas from the literature. Moreover, the numerical results have been confirmed by measurements of the fabricated antenna prototype.

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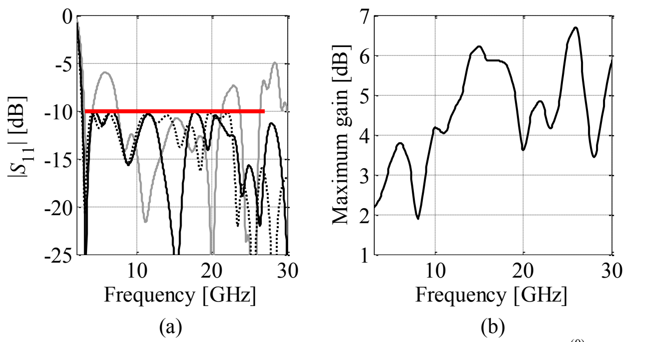

Fig. 2. Characteristics of the proposed antenna: (a) reflection at $\boldsymbol{x}^{(0)}$ (gray), $\boldsymbol{x}^{\#}$ (dotted), and $\boldsymbol{x}^{*}$ (solid black) designs, and (b) maximum gain at $\boldsymbol{x}^{*}$.

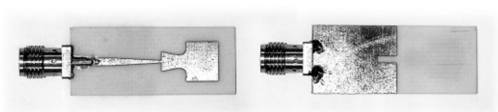

Fig. 3. Photographs of the fabricated antenna prototype.

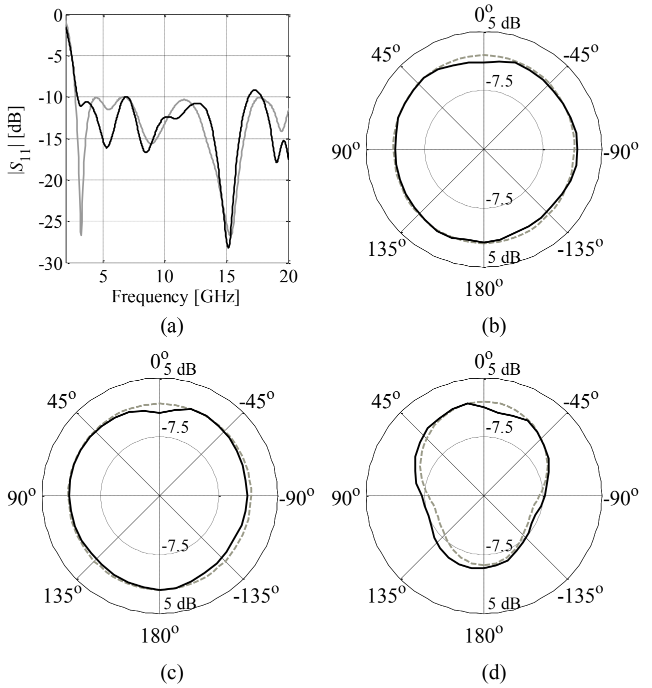

Fig. 4. Comparison of simulation (gray) and measurement (black) results: (a) reflection, and radiation patterns (xz-plane; cf. Fig. 1) at: (b) 5 GHz, (c) 10 GHz, and (d) 15 GHz, respectively.

Table I. Proposed Antenna: Comparison with Benchmark Designs

Antenna	f_L [GHz]	BW	Dimensions [mm × mm]	Footprint [mm^2]	Dimensions $\lambda_g \times \lambda_g$	Size λ_g^2
[9]	5.7	7:1	20.0 × 30.0	600	0.71 × 1.07	0.763
[8]	3.5	9.1:1	25.0 × 35.0	875	0.48 × 0.67	0.318
[6]	1.4	13.1:1	77.0 × 35.0	2695	0.67 × 0.31	0.207
[2]	1.7	91:1	40.0 × 60.0	2400	0.35 × 0.52	0.178
[7]	5	30:1	17.6 × 15.7	276	0.40 × 0.36	0.144
This work	2.8	10.7:1	31.2 × 12.9	404	0.47 × 0.20	0.092

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