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A Compact Switched-Beam Planar Antenna Array for Wireless Sensors Operating at Wi-Fi Band

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Abstract—In this work, the design of a switched beam antenna array based on an optimized Butler matrix feeding network was done with a compact microstrip structure and a microchip antennas working at 2.45 GHz. The obtained antenna feeding network was tuned and optimized by using suitable unsupervised techniques to obtain a compact and efficient structure. A microstrip antenna array prototype composed by four elements was fabricated and experimentally tested. Good impedance matching and radiation properties have been experimentally verified with reference to the main beam steering capability.

1. INTRODUCTION

In the past decades, there has been a growing demand of wireless applications for handheld devices or wireless sensor networks (WSNs). This has forced the designers to study methodologies to over exploit the available radio frequency and to strongly reduce the dimensions of devices such as smart-phones and tablets. This growing need of miniaturization requires not only simple, low-cost and small devices, but also compact radiators [1]. Different strategies to design smart antenna systems able to remove or strongly reduce interfering signals, while maintaining the integrity of the received signals have been developed.

Smart antenna systems are able to reconfigure radiation patterns, guarantee additional functionalities to wireless systems such as the detection of the direction of arrival (DOA) of incoming signals or for localization applications. Despite the advantages of smart antenna systems with fully adaptive properties such as phased arrays, their extensive use in commercial applications is strongly limited by their complexity, cost and dimensions. For low cost applications, switched beam antennas are usually adopted instead to phased arrays. In particular, the radiation properties of fully adaptive smart arrays are approximated with a discrete set of radiation pattern configurations available by means of suitable ports or electronic switches [2–4]. A number of electronically scanning antennas, which employ Butler matrix networks have been proposed to improve the signal to noise ratio of telecommunication systems. The switched beam antennas based on the Butler matrix have multiple input/output ports, each corresponding to a different beam direction. By considering the power levels of detected signals, the main beam of the radiation pattern of the antenna can be steered to the optimal direction to build or enhance the communication link. Moreover, these antennas can be used with a high degree of effectiveness in multiple-input multiple-output (MIMO) systems. This work presents the design of a Wi-Fi multi-beam antenna array based on a compact planar microstrip structure. The array structure and performances have been tuned by using suitable unsupervised techniques [3] to obtain an efficient and compact structure. The proposed antenna array is a complex system composed by different passive microstrip microwave components. Conventional microwave design techniques are

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quite effective for the development of basic microwave active and passive devices [5], but these design techniques are not able to model the interactions between different components of complex system with efficacy. Usually a final tuning phase is required to increase the system performances. This tuning phase requires a lot of computation time and resources due to the design/fabrication cycles, typical of the standard trial and measurement techniques. Recently, unsupervised CAD tools [6, 7], have been proposed for the design of complex microwave systems and solution of complex electromagnetic problems such as antenna design [8, 9], control [10] as well as other interesting applications [11]. These tools can analyse, design and modify, microwave devices in unsupervised manner. They cannot replace an expert microwave engineer, but they can offer a valuable help to designers and strongly reduce the time necessary to design a complex microwave system. In these tools, the problem is usually recast as an optimization one that can be handled by means of a suitable optimization algorithm and a cost function. This work presents the optimized synthesis of a compact switched beam planar antenna array able to operate in the whole Wi-Fi band. The design and tuning of the antenna structure is carried out considering a numerical procedure based on a particle swarm optimization (PSO) algorithm [7, 12]. The advantage of the proposed procedure is that it takes into account all the different interactions and coupling phenomena of different antenna subsystems. At the end of the design procedure this methodology provides not only the structure of the single antenna components, namely the quadrature hybrids, microwave cross-overs, coplanar to microstrip transitions, and matching transformers, but also a complete system where the requirements for all microwave components respect the initial requirements. An experimental array prototype consisting of 2.45 GHz microchip antennas was designed, fabricated and experimentally assessed. The paper is organized as follows. Section 2 reports a detailed description of the proposed antenna feeding network. Section 3 summarizes the optimization procedure based on a customized version of the PSO algorithm. In Section 4 an experimental antenna prototype, obtained with the design methodology described in the previous Section 3, will be fabricated and experimentally assessed. Finally, Section 5 reports the conclusions.

2. DESIGN OF THE ANTENNA STRUCTURE

The feeding network reported in Fig. 1 consists of passive planar microwave devices. The feeding network is designed to provide identical magnitude to the array elements. The array elements are equally spaced with distance d, and each succeeding element presents a phase progression b relative to the preceding one. The Butler matrix works as a beamforming network when different input ports are excited as shown in Fig. 1. It provides four output signals with the same power levels and with progressive phases of $+45$, -45, $+135$, and -135, respectively. The feeding network is composed of four quadrature hybrid rings, two phase shifters, and two microwave crossovers. To significantly reduce the antenna dimensions, compact quadrature hybrids based on the methodology described in [13, 14] are introduced. In particular, to significantly reduce the overall size of the conventional quadrature hybrid rings, the four quarter-wave lines which compose each hybrid ring are periodically loaded with capacitors obtained with open end stub [15]. Moreover, two horizontal quarter-wavelength lines are loaded with two open end stubs while the vertical lines are loaded only with one open end stub. The schematic reported in Fig. 2 describes details of the microwave crossover obtained with two compact quadrature hybrids and the structure of the compact hybrids itself. To optimally realize the compact hybrid rings, a numerical optimization procedure aimed at optimizing a suitable cost function is considered [2, 12, 16]. As a result, the overall reduced hybrid size is more than 80 percent smaller than that of the conventional hybrids. Concerning the design of the two microwave crossover, they are realized considering the chain of two compact quadrature hybrid rings. The structure and geometrical parameters of the microwave crossovers are detailed in Fig. 2. Array elements are commercial surface mount chip antennas (Johanson Tech. model P/N2450AT43F0100) whose dimensions are $2 \times 6\,\mathrm{mm}^2$. The frequency range and gain of the chip antennas are 2.4–2.5 GHz and 10 dBi, respectively, while the input impedance is $50\,\Omega$. The four surface mount chip antennas require a coplanar microstrip waveguide feeding line ($50\,\Omega$) and an LC matching transformer to better tune the antenna resonance frequency. The matching network is composed by two surface mount reactive elements (a capacitor of 0.8 pF and an inductor of 5.6 nH). It has to be noticed that it is mandatory to obtain a return loss below $S_{11} < -25\,\mathrm{dB}$ as indicated in the antenna data sheet. To connect the coplanar waveguide and consequently the surface mount

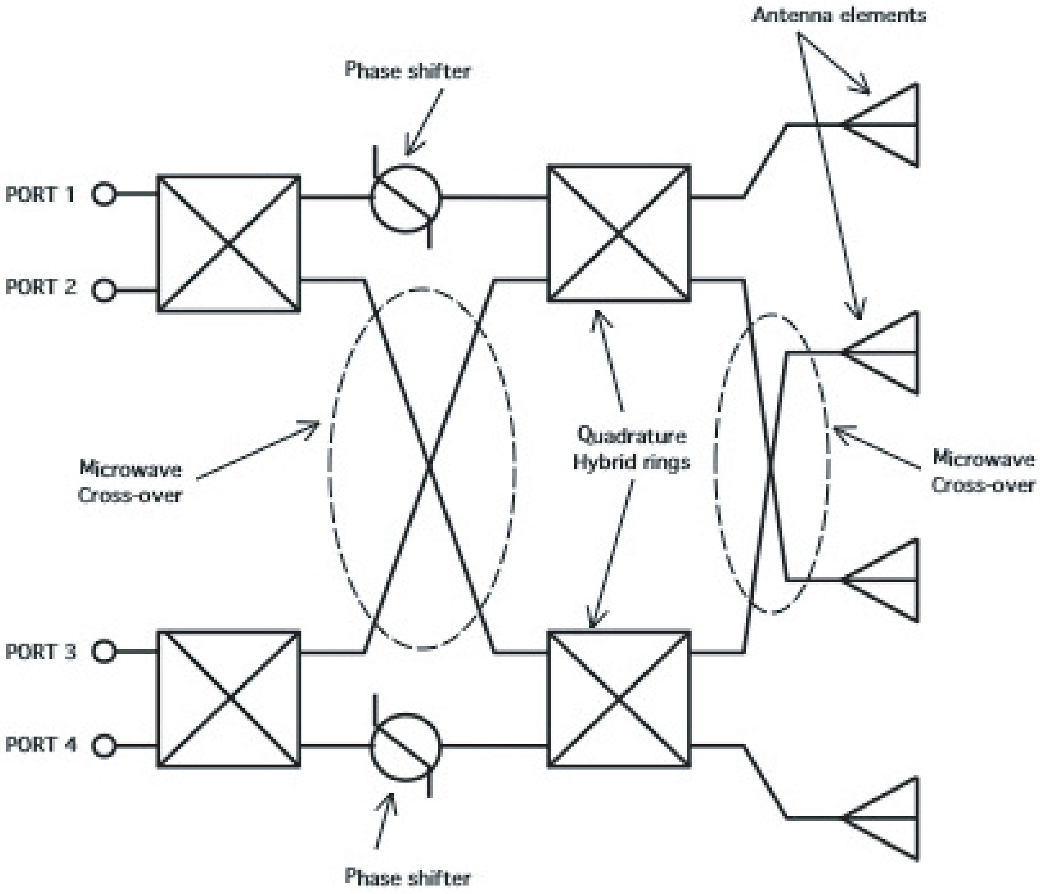


Figure 1. A schema of the proposed antenna array feeding network.

chip antennas, a coplanar to microstrip transition is mandatory. In particular, the transition proposed in [15] offers a good compromise in terms of compactness, simplicity, and performances. It can be easily optimized to guarantee a good match between the coplanar waveguide and output lines of the hybrids. At the end of the design procedure, a compact array of dimensions $35 \times 80\,\text{mm}^2$ is obtained.

3. THE PARTICLE SWARM OPTIMIZATION (PSO) BASED DESIGN METHODOLOGY

The PSO is a computational method that optimizes a problem by iteratively trying to improve the solution with regards to given quality measures. It was developed by Kennedy et al. [20] in the nineties and has been successfully used to solve complex electromagnetic problems and antenna design [16–27]. The standard PSO implementation considers a swarm of trial solutions (called particles) and explores the solution space by improving its position according to suitable updating equations. In particular, each particle moves on the basis of information collected by the particle's previous best performance (called cognitive knowledge) and the best previous performances of its neighbours (called social knowledge). With respect to other evolutionary algorithms such as genetic algorithms (GAs) and different evolution (DE), the PSO shows indisputable advantages. Specifically, the PSO is simpler, both in formulation and computer implementation, than GA, or DE which consider almost three-genetic operators (the selection, crossover, and mutation). PSO considers only one simple operator, called velocity updating equation. Moreover, PSO allows an easier calibration of its parameters since it has no critical parameters. For almost all problems and solution space sizes, a standard configuration turns out to be adequate for

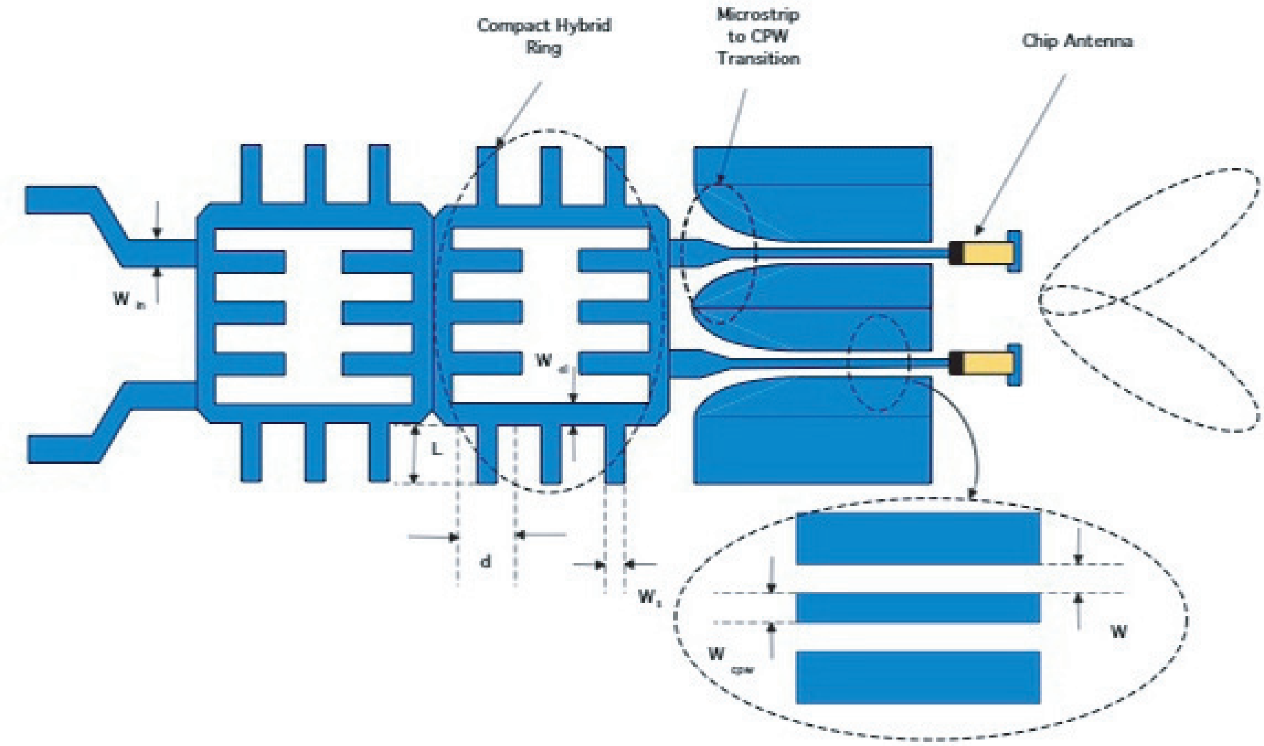


Figure 2. Details of the microstrip cross-over, coplanar to microstrip transition, and compact quadrature hybrid ring geometries.

finding a satisfactory solution with a limited number of computational resources, and thanks to this there is no need to perform a PSO calibration for every design experiment. PSO has a flexible and well-balanced mechanism to enhance the global (i.e., the exploration capability) and the local (i.e., the exploitation capability) exploration of the search space. Such a feature allows one to overcome the premature convergence (or stagnation) typical of GAs, and it enhances the search capability of the optimizer. PSO requires a very small population size, which turns out in a reduced computational cost of the overall minimization by allowing a reasonable compromise between the computational burden and the minimization reliability. The considered antenna design is formulated as an optimization problem fixing suitable constraints in terms of impedance matching at the four input ports ($|S_{11}|$ values) and on the steer direction of the main beam. The considered antenna structure is based on microstrip technology. The geometrical parameters that completely define the antenna geometry are reported in Fig. 1. The antenna structure and considered geometrical parameters are studied to simultaneously maximize the performance and minimize the size of the antenna structure. In particular, the compact quadrature hybrid rings, microwave inverters, microstrip to coplanar transition and the whole gometrical antenna structure are uniquely determined by the following vector $\underline{\psi} = \{W_{in}, L, d, W_s, W_{cpw}, W, W_{el}\}$ which represents all the antenna geometrical parameters. To meet the objectives, a suitable cost function, which represents the difference between the requirements and the performances of a trial antenna geometry, is defined by the following relation aimed at minimizing the return loss at each port and steering the direction of main beams:

$$\Phi\left\{\underline{\psi}\right\} = \sum_{n=1}^{N} \max\left\{0; \frac{\left|S_{nn}\left(\underline{\psi}\right)\right| - |S_{nn}|_{\max,n}}{|S_{nn}|_{\max,n}}\right\} + \frac{\left|\Theta_n\left(\underline{\psi}\right) - \Theta_n\right|^2}{|\Theta_n|^2} \tag{1}$$

N indicates the port number; $|S_{nn}(\underline{\psi})|$ is the return loss at nth port when the trial geometry defined by the $\underline{\psi}$ vector is considered; $|S_{nn}|_{\max,n}$ represents the return loss requirement in dB. $\Theta_n(\underline{\psi})$, $n = 1, \ldots, N$ are the direction of the main beam when the nth port is considered as input, and Θ_n is the required steering main beam direction for the nth port. To minimize Eq. (1), a suitable version of the PSO is used in combination with a geometrical generator and a commercial electromagnetic simulator (namely HFSS designer), to estimate the characteristics of the trial antenna geometries. Especially, minimization of Eq. (1) is obtained by constructing a sequence of trial solutions $\underline{\psi}_s^k$ (s being the trial solution index and k the iteration index $k = 1, \ldots, K_{\max}$) following the strategy of the PSO. The iterative optimization algorithm continues until the stopping criteria are reached, namely when $k = K_{\max}$ or $\Phi(\underline{\psi}_s^k) < \beta$, where $K_{\max}$ and β are respectively the maximum number of iterations and a user defined convergence threshold empirically chosen. At the end of the iterative procedure, the optimal solution defined as $\underline{\psi}^{opt} = \arg\{\min[\Phi(\Gamma_k)]\}$ and the obtained antenna geometrical parameters are used to fabricate the prototype.

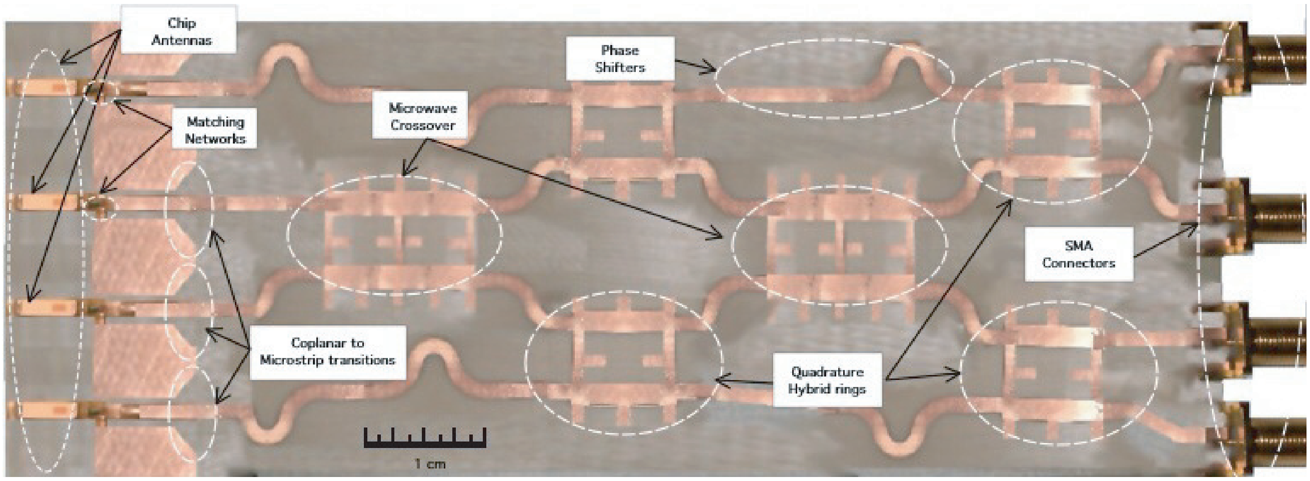


Figure 3. Photo of the antenna array prototype.

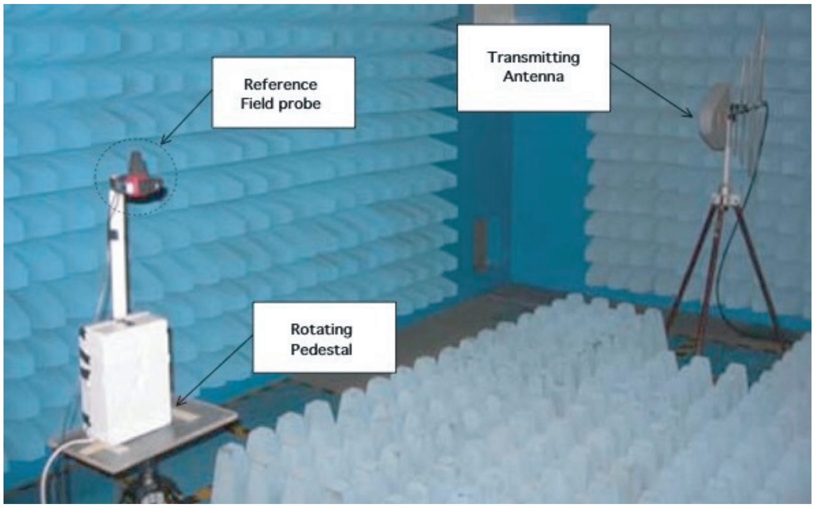
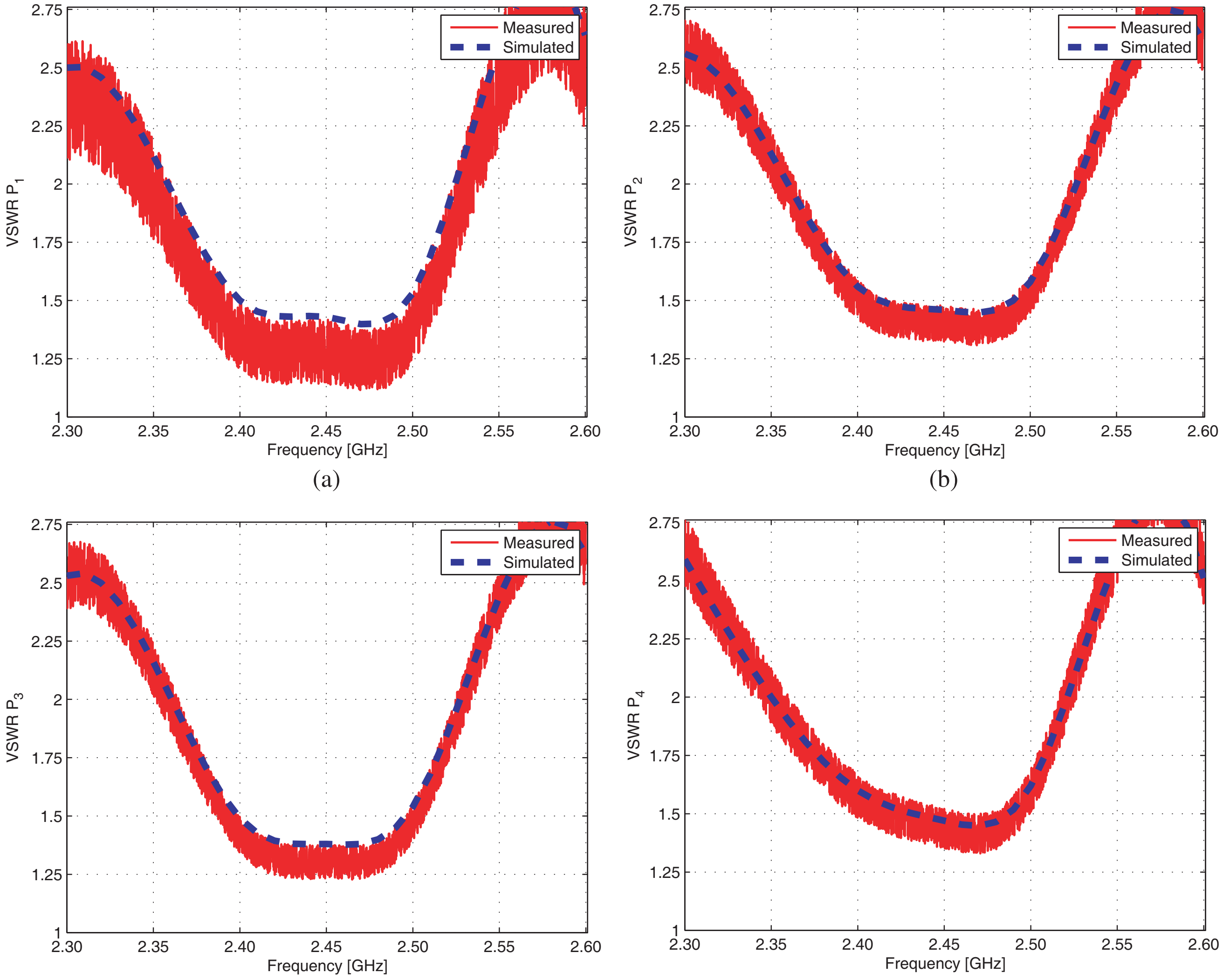


Figure 4. Photo of the experimental set-up arranged inside the anechoic chamber.

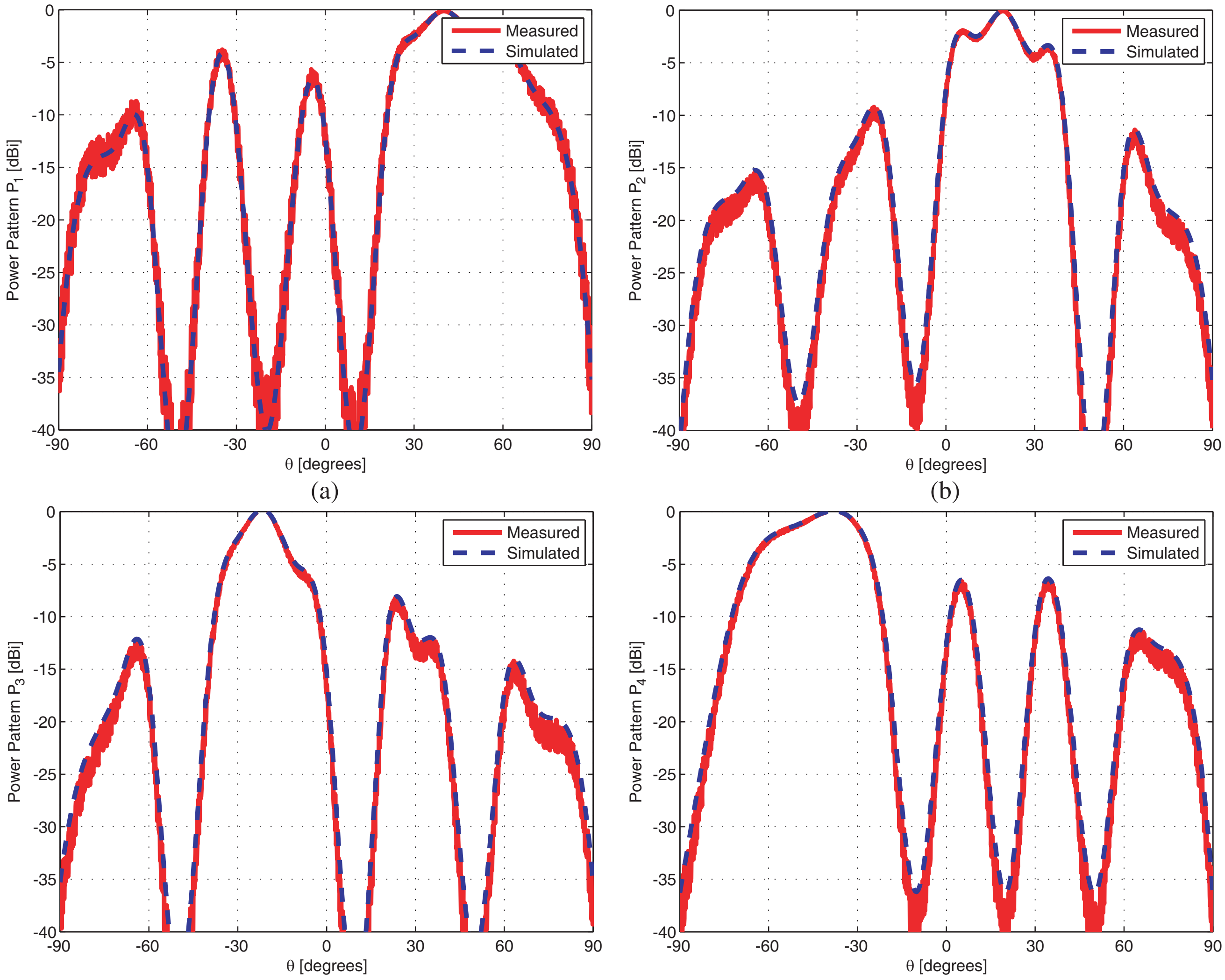
4. NUMERICAL AND EXPERIMENTAL ASSESSMENT

After the design methodology explained in the previous section and a numerical validation based on a commercial software (HFSS Designer), a prototype has been fabricated and experimentally assessed. Specifically, the antenna prototype is printed on a 0.8 mm thick dielectric substrate with $\varepsilon_r = 3.8$ (ARLON 25N), and four sub-miniature type A (SMA) coaxial connectors are connected to the input ports of the array. A photo of the prototype is reported in Fig. 3. The prototype is measured in an anechoic chamber for VSWR and radiation pattern assessment. A photo of the experimental setup is reported in Fig. 4. The VSWR measurements are performed at the four ports of the array prototype with a network analyzer. Fig. 5 shows the VSWR measured in the frequency range 2.3 GHz up to 2.6 GHz for all of the four antenna ports. Figs. 5(a)–(d) also show the comparisons between numerical and experimental data. The consistency is very good, and the capabilities of the design methodology based on evolutionary techniques are demonstrated. The VSWR values turned out to vary between 1.2 and 1.35. Fig. 6 exhibits the radiation patterns of the antenna array obtained by feeding different ports of the antenna. As can be observed, the main beam is steered in four different directions corresponding to the four input ports. Especially, the main beam shows that the measured directions of the beams are



(a) (b) (c) (d)

Figure 5. Measured VSWR values at (a) port 1, (b) port 2, (c) port 3, and (d) port 4.



(a) (b)

(c) (d)

Figure 6. Measured power patterns at (a) port 1, (b) port 2, (c) port 3, and (d) port 4.

slightly different from the theoretical ones due to using real antennas rather than isotropic elements. An error less than 10° is observed. Thus, the resulting overall beam pattern has a wide coverage angle from about 30° to 45° with relatively low side-lobe levels, as observed in Figs. 6(a)–(d). The measured data related to the return loss and the beam pattern are afflicted by noise. As can be noticed, despite the noise level, the initial antenna requirements are satisfied.

5. CONCLUSION

In this work, a method for the synthesis of a microstrip switched-beam antenna array with a compact and efficient feeding network is proposed, designed, and experimentally assessed. Each section of the feeding network is tuned by means of a minimization procedure, by defining a suitable cost function which is minimized with a customized evolutionary algorithm. The obtained antenna prototype is able to achieve good radiation and return loss characteristics. The antenna size is very small, confirming that it is a good candidate for modern wireless sensors that require cheap, efficient and compact radiating systems.

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