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COVARIANCE MATRIX ADAPTATION EVOLUTIONARY STRATEGY OPTIMIZATION OF PATCH ANTENNA FOR WIRELESS COMMUNICATION

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Covariance Matrix Adaptation Evolutionary Strategy Optimization of Patch Antenna for Wireless Communication

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Abstract—Covariance matrix adaptation evolutionary strategy algorithm is applied to optimize a dielectric loaded microstrip patch antenna. The optimization process performance is enhanced by not considering the symmetrical factor of the antenna structure. The antenna is optimized to work for IEEE 802.11a WLAN 5–6 GHz band. Experimental measurements have also been performed to validate the performance of the proposed antenna.

1. INTRODUCTION

Low cost and compact antennas are a key element of modern wireless communications. For these wireless systems, antennas need to have high gain, wide bandwidth, and also need to be a compact enough to be fabricated in portable devices.

Different wireless local area network (WLAN) communication systems are used nowadays, which can provide different operating frequencies and data rates for different applications. For a wireless transmission requiring of a higher data rate, wireless local area network (WLAN) in the 5 GHz band of IEEE 802.11a has been employed. IEEE 802.11a network is widely used in business networks and has the ability to provide high-speed connectivity (> 50 Mb/s).

Different optimization methods have been introduced in the last few years. Many of these search techniques are inspired by natural‘laws and biological swarm intelligence such as Particle Swarm Optimization (PSO) and Genetic Algorithm (GA). PSO is inspired by the ability of flocks of birds, and herds of animals to adapt to their environment, find rich sources of food, and avoid predators by implementing an "information sharing" approach, hence, developing an evolutionary advantage. On the other hand, the GA is inspired by the principles of genetics and evolution, and mimics the reproduction behavior observed in biological populations. In unconstrained non-linear problems with continuous variables, PSO tends to outperform GA in both criteria, specially in computational efficiency. If the search space is discrete and is highly constrained and discontinuous, GA would probably find higher quality solutions. The mutation and crossover operators will help GA to jump the discontinuity in the search space and lead to better exploration.

The performance of many global optimization techniques, such as genetic algorithms (GAs) and particle swarm optimization (PSO), is dependent primarily on the evolutionary settings of these algorithms. For example, by choosing different values for the mutation and crossover, the user of a GA may lead to different optimization results and convergence speed. The Covariance Matrix Adaptation Evolutionary Strategy (CMA-ES) overcomes the typical problems that are often associated with evolutionary algorithms. The CMA has the advantage of fewer human (user) settings. Based on available evolutionary information, CMA-ES automatically tunes itself during the optimization process without any human interaction. Moreover, it has the advantage of requiring fewer function evaluations

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before convergence [1]. CMA-ES shares properties of local and global optimization by avoiding early convergence to a local minimum and also by changing the internal step size to control convergence. It has been applied efficiently to different types of applications [2–5]. In order to use both local and global abilities of the CMA-ES algorithm, the value of the sigma setting parameter, which plays an important role in scaling the searching step size, should be chosen carefully. A small value (close to zero) of sigma will make the method more local and large value (close to one) will make the method more global as shown in Equation (1) where $\mathcal{N}$ is a multivariate normal distribution of the gth generation with mean m and covariance C and x is the variable vector [6]. More details for the interested reader about the complete CMA-ES procedure can be found in [7].

$$x^{(g+1)} \cong m^{(g)} + \sigma^{(g)} \mathcal{N}\left(0, C^{(g)}\right) \tag{1}$$

PSO and GA have been used widely to solve many antenna optimization problems [8–13]. In [13], Minasian and Bird used particle swarm optimization to design a microstrip antenna for WLAN application by using passive parasitically coupled sub patches. PSO is used in [14] in designing a reconfigurable planar array antenna to operate in the WiFi frequency band from 2.4 GHz up to 2.5 GHz. A binary version of the PSO algorithm has been used in [15] to design an array of plasmonic nanospheres in order to achieve broadband field enhancement. In [16], an integrated multifunction antenna has been optimized by PSO for an automotive rescue management system. PSO is used in [17] to miniaturize a pre-fractal monopole antenna for 406 MHz SARSAT radio beacons. A miniaturized fractal antenna is also reported and optimized by PSO in [18] for ISM band applications.

In this paper, CMA-ES is used to design a simple, low cost and compact dielectric loaded microstrip antenna for wireless communication systems that cover the WLAN IEEE 802.11a bandwidth. In this work, the antenna structure will not be limited by the symmetry factor in order to enhance the possibility to have the optimal solution. A simple feeding technique has been chosen in order to reduce the cost and the complexity of the final design.

The proposed design approach in this paper will solve many of fabrication difficulties that were explained in [13]. Moreover, a symmetrical broadside radiation pattern is applied as a second goal at the center frequency of operation bandwidth. The proposed antenna shows a simulated impedance BW of 19.8% (4.97–6.06 GHz), a 7.29 dBi maximum numerical gain and symmetrical broadside radiation patterns.

The 3D electromagnetic simulation software, Computer Simulation Technology (CST), is used to simulate and optimize the proposed configuration and it was followed by experimental verifications. A good agreement between the measured and simulated results are obtained.

2. OPTIMIZATION PROCEDURE

The geometry of the proposed patch antenna is shown in Figure 1. The antenna is printed on a Rogers RT5880LZ substrate with relative permittivity equal to 1.96, thickness 1.52 mm and loss tangent 0.0019. The overall size of the substrate is 40 mm × 40 mm. The structure consists of a radiating patch which

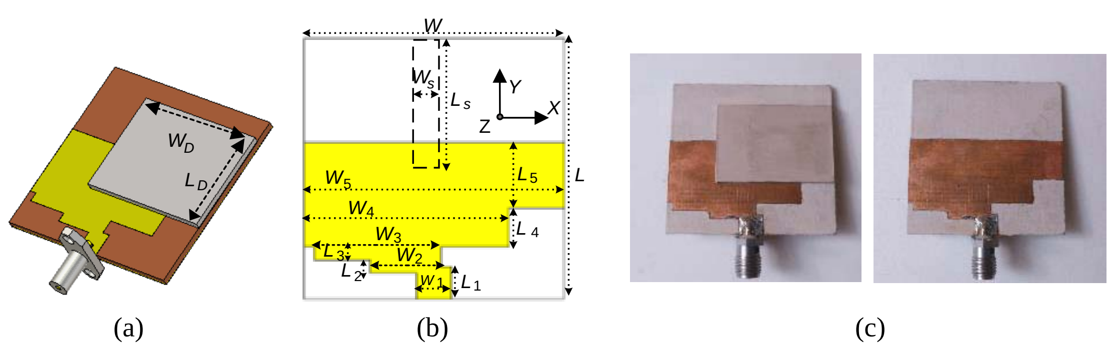

Figure 1. Proposed antenna configuration. (a) Perspective view. (b) Front view. (c) Photograph of the fabricated antenna.

is fed by a 50 Ohm transmission line. A rectangular slot has been inserted in the ground plane of the antenna. The antenna is loaded by using dielectric material RO3010 with relative permittivity equal to 10.2, thickness 1.27 and loss tangent 0.0023.

Achieving the desired bandwidth for WLAN IEEE 802.11a and a broadside radiation pattern with acceptable gain for WLAN applications are the main goals of the optimization procedure. As an initial design step, a rectangular patch antenna is printed on a RT5880LZ board. In order to get a resonance at 5.5 GHz, the width and resonant length of the patch are set as 22.42 mm of 18.49 mm, respectively. Compared to [13], the complexity of the fabrication process is taken into consideration. A 50 Ohm microstrip line which is consider a simple feeding technique will be used to excite the antenna. Moreover, the initial patch is divided into four connected strips in order to reduce the shape complexity of the final design and to solve the overlapping issue that reported in [13] which is consider a significant fabrication challenge due to the resolution limitation of the printed circuits milling machines. In order to obtain another resonant mode, a rectangular slot is inserted in the ground plane. Due to the ability of increasing the impedance bandwidth by loading the antenna with a dielectric material [19] and in order to increase the degrees of freedom for searching for the optimal candidate solution, the antenna is loaded with a dielectric rectangular brick. Table 1 lists the fixed parameters, optimization parameters and the different boundaries used in the antenna implementation. By changing the shape of the patch, slot dimension, and the dimension and location of the dielectric brick, the desired goals can be obtained.

Table 1. Summary of the antenna optimization (dimensions in millimeters).

Fixed parameters	W, L, L_1, W_1
Optimization parameters	W_2, W_3, W_4, W_5, W_S, L_s, W_D, L_D
Boundaries	$[W_2, W_3, W_4, W_5, W_S] \in (1,\ 40)$; $L_s \in (0,\ 35)$; $[W_D, L_D] \in (1, 40)$
Sigma	0.6

A weighted sum fitness function $\chi(f)$ is used to evaluate the performances of the candidate designs. This function will be used to maximize the gain (G) and front to back ratio (FB) at the center frequency of the operation bandwidth (f_c). The goal of the impedance bandwidth will be applied by using the function (δ_j).

The weighted fitness function is given as follows:

$$x(f) = A * \delta_j + B * |FB|_{fc=5.5} - FB_{des}| + C * |G|_{fc=5.5;\,\theta=0,\,\phi=0} - G_{des}| \tag{2}$$

where A, B, C are weighting factors,

$$\delta_j = \text{Minimize } \left[\max \left|S_{11_j} - S_{11_{des}}\right|\right] \quad j = 1, 2, \ldots, N_{freq} \tag{3}$$

$S_{11}|_j$ refers to the negative return loss in dB at the jth sampling frequency, and Z_{inj} and Z_o are the input impedance at the feed of the same frequency and the reference impedance, respectively. Achieving a larger bandwidth can be obtained by reducing the difference between the highest and lowest values of the negative return loss through minimizing the maximum return loss among the N_{freq} samples. Since the sum of the weighting factor should be equal to 1 [20] and to make the optimization bias more to the bandwidth goal, the weighting factors (A, B, C) are set as 0.5, 0.25, and 0.25.

3. SIMULATIONS AND MEASUREMENTS

The detailed optimized dimensions of the proposed antenna are listed in Table 2. To verify the simulation, the proposed antenna was fabricated using the milling machine LPKF ProtoMat S62, which is especially designed for RF and microwave circuit boards. Figure 2 shows the simulated reflection coefficients of the optimized designs plotted in the smith chart as the frequency change from 4 GHz to 7 GHz. The simulated and measured real and reactive part of the input impedance of the antenna are shown in Figure 3.

Table 2. Geometry details in millimeters of the optimized proposed design.

L	W	L_1	L_2	L_3	L_4	L_5	L_S
40	40	5	2	2	6	9.94	32.66
W_1	W_2	W_3	W_4	W_5	W_S	W_D	L_D
5.36	10.86	19.5	31.57	40	1.52	28.27	20.56

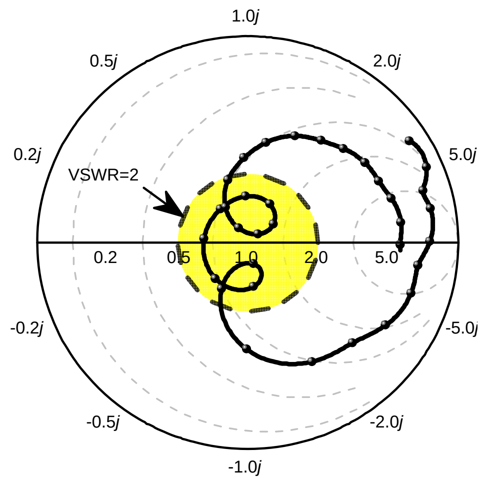

Figure 2. Simulated reflection coefficients for the optimized antennas.

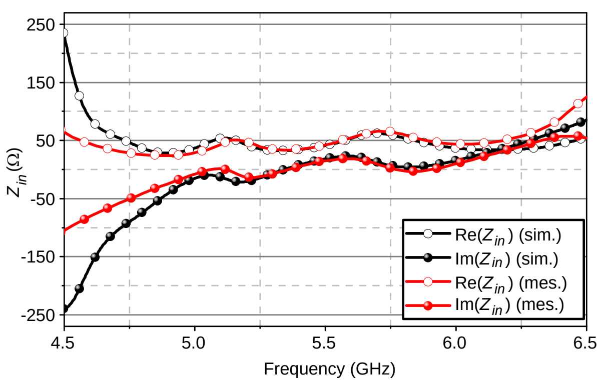

Figure 3. Simulated and measured input impedance.

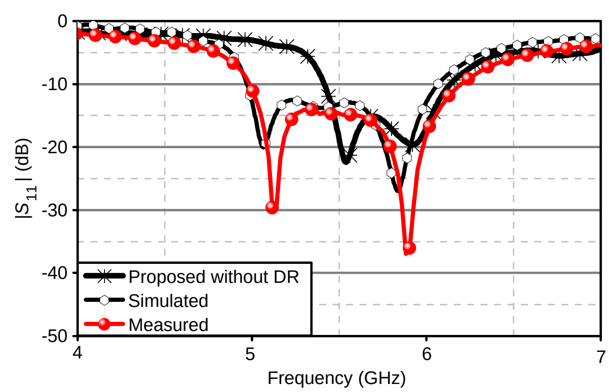

Figure 4. Return loss response of design configurations of the antenna.

The negative return loss in dB of the fabricated antenna was measured using the vector network analyzer over the frequency range 4 to 7 GHz. With reference to Figure 4, reasonable agreement between simulated and measured negative return loss is observed. With reference to the figure, the two measured resonance frequencies (min $|S_{11}|$) are 5.11 GHz and 5.88 GHz, respectively, which agree very well with the simulated resonant frequencies of 5.09 GHz (2% error) and 5.84 GHz (4% error).

As can be seen in Figure 5, the fundamental mode has come from the patch while the slot which acts as approximately a quarter wavelength at 5.88 GHz generates the second mode. Loading the overall structure with dielectric material shifted the resonance modes to lower values and also enlarge the bandwidth.

2D representation of the optimized far-field of the antenna at the center frequency is shown in Figure 6. It is evident from the figure that the maximum radiation power intensity is concentrated in the broadside direction with minimum value in the back side region.

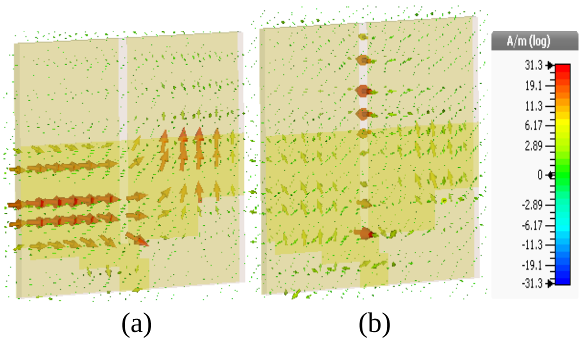

Figure 5. Magnetic field distribution at: (a) 5.5 GHz, (b) 5.88 GHz.

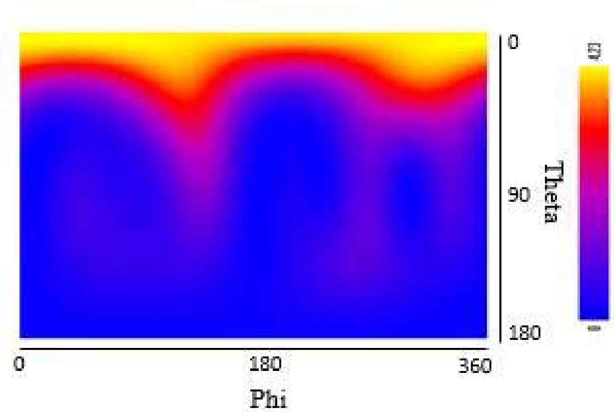

Figure 6. 2D far-field distribution at 5.5 GHz.

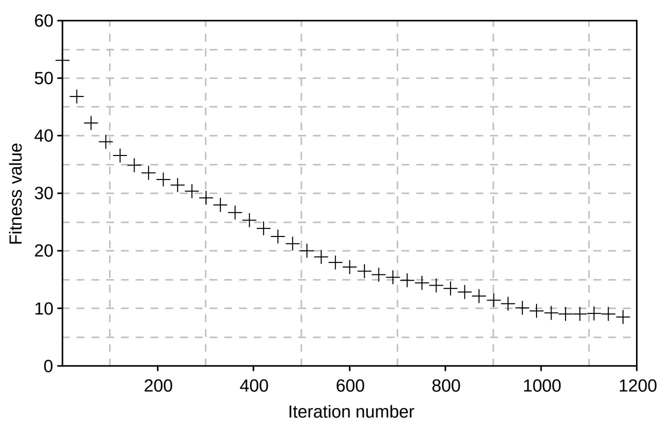

Figure 7. Convergence curve of the fitness value.

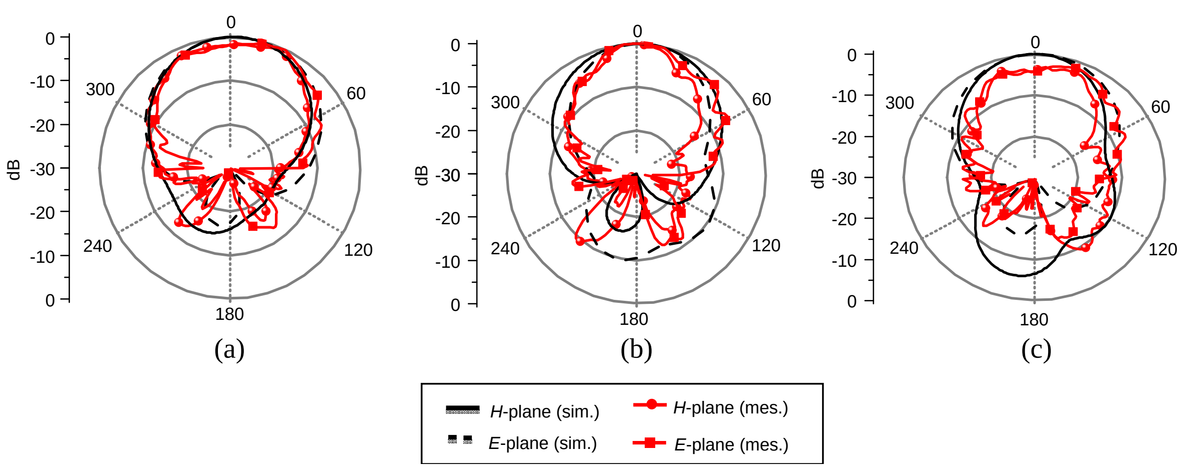

Figure 8. Measured and simulated radiation patterns: (a) 5.25 GHz, (b) 5.5 GHz, (c) 5.75 GHz.

The simulated and measured radiation patterns in the E-plane and H-plane observed at different frequency points are plotted in Figure 8. Broadside radiation could be observed in E- and H-planes in the whole frequency band points. Figure 9 shows the gain and the radiation efficiency of the antenna. The maximum measured peak gain is 6.76 dBi. The maximum antenna radiation efficiency

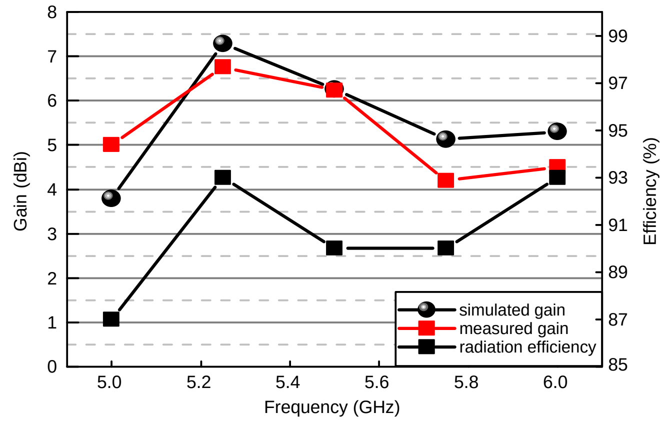

Figure 9. Measured/simulated peak gain and efficiency of proposed antenna.

Table 3. Simulated and measured results of the optimized antenna at 5.5 GHz.

	$\|S_{11}\|$ (dB)	G (dBi)	FB (dB)
Simulated	−13.2	6.26	15.5
Measured	−14.7	6.23	15.3

was computed as 93% at 5.25 GHz. Table 3 shows the simulation and measured results of the return loss, gain, and front to back ratio at frequency 5.5 GHz.

The convergence curve of fitness value is presented in Figure 7. After 1171 iterations, an optimum design is obtained compare to 1500 iterations by using PSO method to achieve the same goals which shows that CMA-ES method is quicker than PSO.

The packaging of the proposed antenna is found to be a limitation due to the presence of the slot in the ground plane. If a conducting plate is positioned parallel to the ground plane at a distance 8 mm apart or less than that, the −10 dB impedance bandwidth will drift from the 5 to 6 GHz frequency range. Such a case is considered better than the one reported in [21] where the conducting plane should be placed at a distance more than 76.5 mm in order to avoid the antenna-performance degradation.

4. CONCLUSION

In this paper, a microstrip antenna loaded with dielectric material suitable for WLAN IEEE 802.11a applications has been designed, optimized, and fabricated. The antenna has been successfully optimized by CMA-ES technique to achieve a good impedance matching and radiation characteristics in the entire band of WLAN IEEE 802.11a. The numerical simulations and experimental measurements of both electrical and radiation parameters have been used to assess the effectiveness and reliability of the antenna model as well as the corresponding prototype.

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