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Evolutionary Design of a Dual Band E-shaped Patch Antenna for 5G Mobile Communications

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***Abstract*— Fifth generation (5G) wireless technology is a promising solution for multi-Gbps data rates in future mobile communications. The new devices are expected to operate at millimeter wave frequencies. To address the 5G requirements novel antennas have to be developed. In this paper the Teaching-Learning-Optimization (TLBO) algorithm is applied in order to design a dual-band E-shaped patch antenna. The geometrical parameters of the aperture-coupled antenna are the inputs of the optimization algorithm. The method gives acceptable design solutions achieving simultaneously S_{11} minimization and low VSWR at the frequencies of interest (25GHz and 37GHz).**

***Keywords*—mmWave; 5G; mobile commnications; patch antennas; TLBO algorithm; dual-band operation.**

I. Introduction

Future fifth generation (5G) framework of cellular systems will use millimeter wave frequencies and is expected to offer extremely wide spectrum and multi-Gigabit-per-second (Gbps) data rates to mobile communications. Antenna design for the new mobile devices seems to be a challenging task.

A possible solution for this case is expected to be the use of microstrip patch antennas. Such antennas have several advantages like low profile, low cost and ease of fabrication. Several design efforts have been already carried out on this field achieving good performance in mm-wave frequency band. Shaped apertures have been also proposed to feed the antenna elements, providing dual band operation, high gain, wide bandwidth and dual polarization characteristics to the antenna [1]–[4].

E-shaped patch antennas [5], [6] extend the rectangular patch functionality and bandwidth by incorporating slots in the patch to introduce multiple resonances. They are suitable for dual-band or wide-band designs. The design in mm-wave frequencies could be employed using aperture coupled feeding [7]. However, such feeding technique requires the modification of the aperture shape to enable dual band operation. In this paper, this is accomplished using a H-shaped aperture that resonates in two operating frequencies. The geometrical parameters of both the patch and the aperture need to be determined in order to satisfy the performance requirements at the desired frequencies.

Evolutionary algorithms like Particle Swarm Optimization (PSO) and Differential Evolution (DE) have been in several occasions [5], [6] applied to E-shaped patch antenna design. Teaching-Learning-Optimization (TLBO) algorithm [8] is a recently introduced stochastic optimization algorithm. It is a parameter-less algorithm and has been used for solving engineering problems [9]. In this paper, we will use the TLBO algorithm for antenna parameters optimization.

The rest of this paper is organized as follows: In Section II the TLBO algorithm details are described. The E-shaped patch optimization details are given in Section III. Section IV includes the numerical results. Finally the conclusion is given in Section V.

II. Algorithm Description

Teaching-Learning-Based Optimization is a heuristic swarm-based algorithm also proposed by R. Venkata Rao [8]. The algorithm is also parameter-less and is inspired by the effect of a teacher's capabilities on the growth of knowledge of students. Here the population of possible solutions is a class of N students/learners, and the best student (best solution) is considered as the teacher at each iteration. TLBO is divided into two parts, the "teacher phase" and the "learner phase".

In a class of students, the teacher's scope is to increase the mean grades of the class up to some extent, based in his/her knowledge capabilities. Inspired by this process, at iteration j, the teacher T_j tries to move the mean M of the population towards to its own level. So in the teacher phase, each existing solution $\mathbf{x_i}$ is updated through:

$$\mathbf{x_i^{new}} = \mathbf{x_i^{old}} + r_i \cdot \left(\mathbf{x_{best}} - T_F \cdot \mathbf{M}\right) \qquad (1)$$

where T_F is the teaching factor, r_i is a random number within the range [0,1] and $\mathbf{M}$ is the mean solution vector of the population. The value of T_F can be either 1 or 2 with equal probability.

In the learner phase of the algorithm, two randomly chosen learners interact with each other, and a learner increases his knowledge (fitness value) if the other learner has more knowledge (thus a solution with better fitness value). So for two randomly chosen solutions $\mathbf{x_i}$ and $\mathbf{x_j}$, the above modification of the existing solution $\mathbf{x_i}$ can be expressed as:

$$\begin{aligned} \mathbf{x_i^{new}} &= \mathbf{x_i^{old}} + r_i\left(\mathbf{x_i} - \mathbf{x_j}\right), \quad \textit{if } F\left(\mathbf{x_i}\right) < F\left(\mathbf{x_j}\right) \\ \mathbf{x_i^{new}} &= \mathbf{x_i^{old}} + r_i\left(\mathbf{x_j} - \mathbf{x_i}\right), \quad \textit{otherwise} \end{aligned} \qquad (2)$$

where r_i is random number within the range [0,1]. The new solution is accepted if it provides better function value than the old one.

III. Problem Formulation

The geometry of an aperture coupled E-shaped patch antenna is given in Fig. 1. Two parallel slots are incorporated into the rectangular patch. The aperture is modified to an H-shaped, which introduces two possible lengths to generate different resonant frequencies. The antenna geometry complexity makes it difficult or even impossible to estimate the effect of each design parameter in order to achieve the desired antenna performance. Therefore an optimization technique is suitable to address this design problem. The design parameters are 15 and they are shown in Figs 2a-2c.

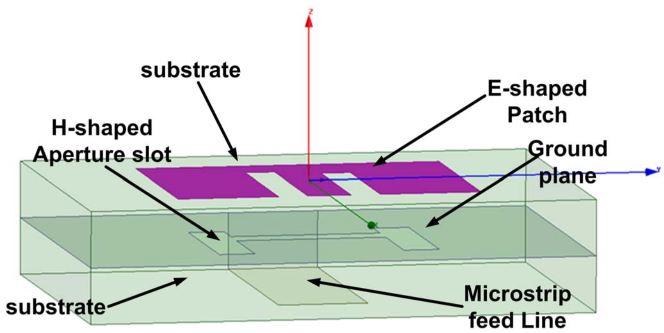


Fig. 1. Geometry of an aperture coupled E-shaped patch antenna

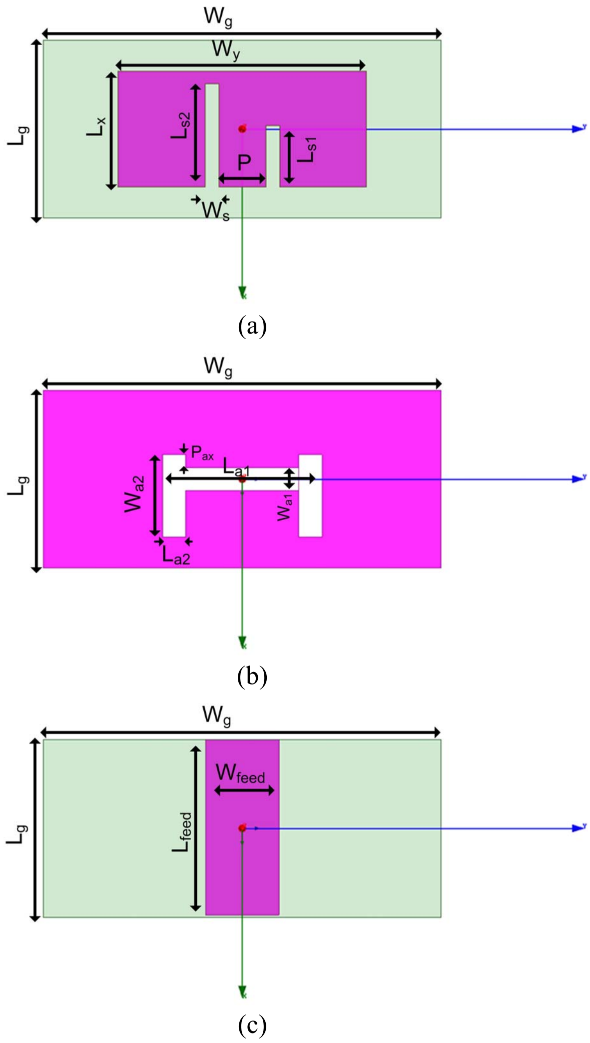


Fig. 2. Geometry of an aperture coupled E-shaped patch antenna a) Patch plane, b) ground plane with aperture and c) feed line plane.

Both antenna and feed substrates consist of the same Arlon dielectric substrate of $\varepsilon_r = 3.38$ and 30mils thick. The design goal is to minimize the S_{11} magnitude in two frequencies, 25GHz and 37GHz and to reduce Voltage Standing Wave Ratio (VSWR) below 2 in both frequencies. This design problem is therefore defined by the minimization of the objective function:

$$\begin{aligned} F(\overline{x}) &= \max(S_{11,25GHz}(\overline{x}), S_{11,37GHz}(\overline{x})) + \mathrm{VSWR}(\overline{x}) \\ y &= \max\left(\mathrm{VSWR}_{25GHz}(\overline{x}), \mathrm{VSWR}_{37GHz}(\overline{x})\right) \\ \mathrm{VSWR}(\overline{x}) &= \begin{cases} \Xi \times \left(y-2\right) & \textit{if } y > 2 \\ 0 & \textit{otherwise} \end{cases} \end{aligned} \qquad (3)$$

where $\overline{x}$ is the vector of the antenna geometry design variables, $S_{11,25GHz}(\overline{x}), S_{11,37GHz}(\overline{x})$ is the S11 magnitude, and

$\left(VSWR_{25GHz}(\bar{x}), VSWR_{37GHz}(\bar{x})\right)$ is the Voltage Standing Wave Ratio (VSWR) in 25GHz and 37 GHz, respectively, and Ξ is a penalty factor.

This optimization problem requires the use of a numerical method. Therefore all the algorithms have to be combined with an EM solver software. The E-shaped patch antenna was modeled in ANSYS HFSS [10]. In order to integrate the in-house source code of the evolutionary algorithms with HFSS, a wrapper program using HFFS Matlab API [11] was created.

IV. NUMERICAL RESULTS

We applied the TLBO algorithm for the E-shaped patch design using the objective function of eq. (3). We set the population size to 20 and the maximum number of iterations to 100. The algorithm ran for five times and the best result found is the one with the geometrical parameter values shown in Table I.

TABLE I. DESIGN PARAMETERS FOR THE BEST ANTENNA FOUND BY TLBO

Decision Variable	Value (mm)	Decision Variable	Value (mm)
W_y	4.12	W_{feed}	1.21
L_x	2.97	L_{feed}	3.53
W_g	6.86	L_{a1}	2.02
L_g	4.96	W_{a1}	0.4
W_s	0.4	W_{a2}	2.16
L_{s1}	2.11	L_{a2}	0.48
L_{s2}	2.33	P_{ax}	0.48
P	0.59		

A general view of the frequency response of the best design found is depicted in Fig. 3. It is evident that the antenna appears three modes of operation, the two of which are around 25GHz and 37GHz and the third one at 29.2GHz. Thus, the goal of the design process was obviously achieved.

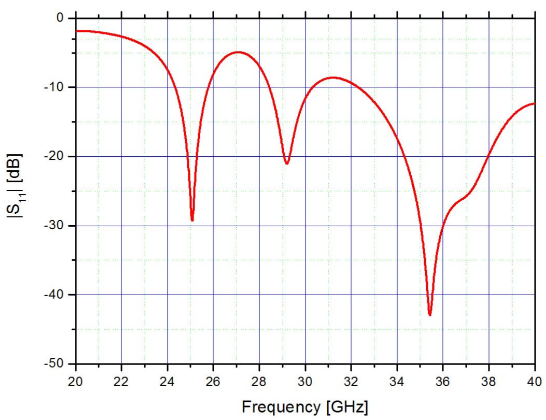


Fig. 3. S11 plot for the best design found by TLBO

The plot of the VSWR versus frequency over a 50Ohm resistance, is depicted in Fig. 4 and is in accordance to the variation of S_{11} versus frequency as well as to the constraint of the design process, namely the VSWR to be lower than 2 around both frequencies of interest.

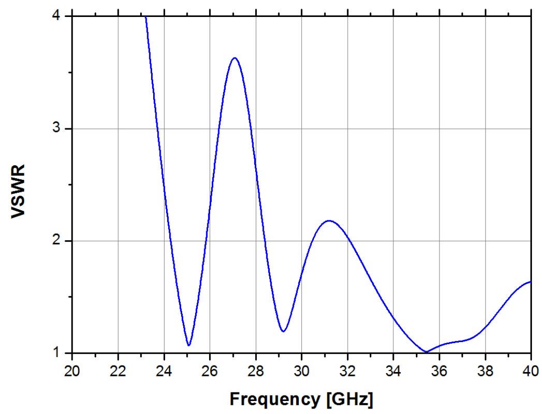
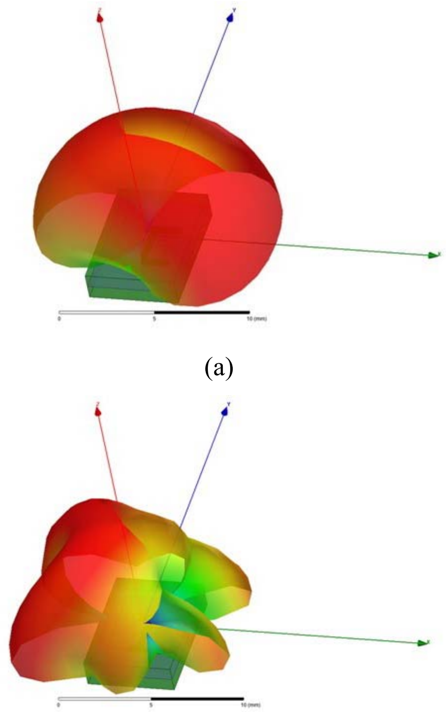


Fig. 4. VSWR plot for the best design found by TLBO

The antenna records are globally reported in Table II. At the required frequencies of operation, they show satisfactory low values both of S11 and the bandwidth, especially at the upper frequency band. The Gain values are sufficiently high at the two first modes however degradation is observed at 37GHz. The 3D radiation patterns at the frequencies of interest and the corresponding surface current distributions are depicted in Figs 5 and 6. At 25GHz an almost uniform, in space, distribution of the radiated power is obtained as the maximum values of the surface current are substantially limited to a small area of the patch. However, at 37GHz, the current spreads over larger areas appearing two separate regions of maximum and thus the distribution of the radiated power is not uniform any more. This performance at 37GHz is due to the increase of electrical size of the patch.

TABLE II. OPERATION INDICES VALUES OF THE BEST ANTENNA FOUND BY TLBO

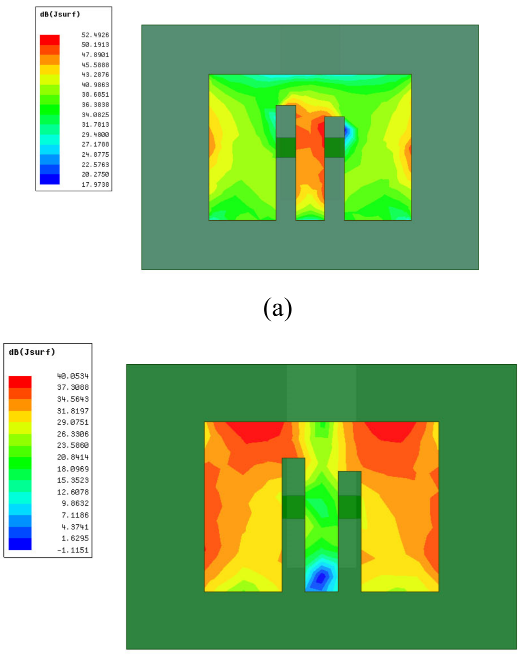
Freq (GHz)	Gain (dBi)	S11 (dB)	VSWR	Bandwidth(%)
25	6.71	-25.73	1.09	5.8
29.2	4.55	-21	1.19	6.4
37	1.72	-25.77	1.09	>20.8



(a)

(b)

Fig. 5. 3D Radiation pattern of the best design (a) at 25 GHz, and (b) at 37 GHz.



(a)

(b)

Fig. 6. Simulated surface current distribution of the best design (a) at 25 GHz, and (b) at 37 GHz.

V. CONCLUSION

A design approach for a dual band E-shaped patch antenna, suitable for 5G Mobile Communications is presented. The whole design is based on the TLBO algorithm. The problem is analyzed and the corresponding parameters concerning the geometry of the patch and its feeding aperture are defined. Dual band operation at 25GHz and 37GHz is also required in the optimization procedure. The applicability of the method is verified since the achieved results fulfill the design constraints combining minimum S_{11} and low VSWR at the desired frequencies.

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