AN EXPERIENCE TO INCLUDE ADVANCED OPTIMIZATION TECHNIQUES IN MICROWAVE UNDERGRADUATE LABORATORIES

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Abstract: In this paper, a method to introduce advanced computational optimization techniques in undergraduate laboratory subjects is presented. The experience proposed consists in using evolutionary algorithms to design a microwave device (a directional coupler in this case), and then constructing a prototype following the outcome of the algorithms. The idea is to present the undergraduate student advanced techniques that it is unlikely they study in their degree, but which may be useful for them in postgraduate courses. The results of the application of the experience in the subject *Antennas and Microwave Laboratory* of Universidad de Alcalá, Spain, is presented.

1 INTRODUCTION

Advanced computational techniques are currently a fundamental part in processes of design, management and even deployment of electrical, electronic and telecommunications systems. Thus, these techniques are taught in almost every university postgraduate courses about electrical engineering. In modern postgraduate electrical engineering studies there are specific subjects which cover the majority of advanced computational techniques such as evolutionary computation, neural networks, advanced heuristics etc. However, in spite of their importance in engineering, these techniques are not usually included in undergraduate courses. Due to the extensive curriculum to be taught in electrical engineering degrees, it is very difficult to plan specific subjects in undergraduate curses which cover these techniques. However, it is possible to introduce them as part of laboratories or practices, in which the students can have a first contact with these techniques.

This paper presents an experience to include advanced computational techniques (evolutionary computation-based techniques in this case) in a laboratory subject of the electrical engineering degree at Universidad de Alcalá, Madrid, Spain. Specifically, a microwave laboratory subject has been chosen to carry out a first implementation of the proposed experience. High-frequency circuit design is

an important part of the majority of microwave engineering courses. Among others, microwave amplifiers, analog filters and directional couplers are some of the most studied devices, due to their importance in a large amount of electronic systems and circuits (Pozar, 1998). Specifically, the ideal directional coupler is a passive, reciprocal, completely matched and lossless four port network studied in the majority of undergraduate courses related to microwave systems design.

The implementation of the experience at Universidad de Alcalá has been carried out in the subject *Antennas and Microwave Laboratory*. In a laboratory practice of this subject, advanced optimization algorithms based on evolutionary computation (Yao et al., 1999), (Eberhart et al., 2001) have been introduced in the design of a directional coupler. The idea is that the students are introduced in the use of intelligent soft-computing algorithms, to optimize any type of microwave device in this case (a directional coupler). The fact that the evolutionary-based algorithms are based on concepts easy to understand (the evolution of species and survival of the fittest solution), makes easier the inclusion of these techniques in the laboratory. In addition, the fact that usually people who do not know anything about these kind of algorithms find them very interesting, is an important part of the experience, because it introduces a novelty in the class that motivates students to work harder in the labora-

tory. The specific experience carried out includes the design of a directional coupler, the construction of a prototype following the outcome of the algorithms for optimization, and the comparison with the simulation of the device using a commercial software package. This experience can be extended to any other type of subject, but it is specially well-suited for laboratories, where practices can be focus on different advanced techniques to be presented to the students.

2 ANALYSIS OF THE DIRECTIONAL COUPLER PROPOSED IN THE EXPERIENCE

As it has been mentioned before, several design topologies for directional couplers can be found in the literature. The proposed experience could be carried out using any topology difficult enough to involve the optimization of several parameters. In any other case, the optimization can be carried out by simple inspection, and it is not necessary to use advanced optimization techniques, such as evolutionary computation. Following this premise, a directional coupler as the one shown in Figure 1, has been chosen to be designed. This topology is based on the well-known branch-line coupler, but diagonal strips are added in order to include constructive constraints which make harder the optimization of the device. The proposed coupler has has double symmetry in x and y axis.
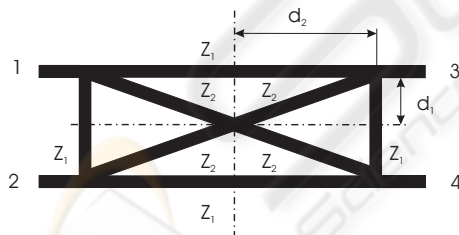

Figure 1: Example of the directional coupler used in the application of the method in Universidad de Alcalá.

Thus, four different S parameters are enough to describe it. Using these symmetry properties, the coupler can be analyzed by using even and odd modes recursively. The following equations show the normalized input admittances in the even and odd excitations:

$$Y_{ee} = j\frac{1}{Z_1}\tan(\beta_1 \cdot d_1) + j\frac{1}{Z_1}\tan(\beta_1 \cdot d_2) + j\frac{1}{Z_2}\tan(\beta_2 \cdot d_3)$$
(1)

$$Y_{eo} = -j\frac{1}{Z_1}\cot(\beta_1 \cdot d_1) + j\frac{1}{Z_1}\tan(\beta_1 \cdot d_2) - j\frac{1}{Z_2}\cot(\beta_2 \cdot d_3)$$
(2)

$$Y_{oe} = j\frac{1}{Z_1}\tan(\beta_1 \cdot d_1) - j\frac{1}{Z_1}\cot(\beta_1 \cdot d_2) - j\frac{1}{Z_2}\cot(\beta_2 \cdot d_3)$$
(3)

$$Y_{oo} = -j\frac{1}{Z_1}\cot(\beta_1 \cdot d_1) - j\frac{1}{Z_1}\cot(\beta_1 \cdot d_2) - j\frac{1}{Z_2}\cot(\beta_2 \cdot d_3)$$
(4)

Note that $d_3 = \sqrt{(d_1)^2 + (d_2)^2}$, so its admittance depends on four parameters. The even and odd reflection coefficients can be calculated from the previous admittances as follows:

$$\Gamma_{ij} = \frac{Y_0 - Y_{ij}}{Y_0 + Y_{ij}}$$
(5)

where i and j take the values e or o depending on the case, Y_0 stands for the reference admittance value, $Y_0 = \frac{1}{50}$ Ω^{-1} in this case. Finally, the S parameters are calculated as follows:

$$S_{11} = \frac{1}{4} \cdot (\Gamma_{ee} + \Gamma_{eo} + \Gamma_{oe} + \Gamma_{oo})$$
(6)

$$S_{21} = \frac{1}{4} \cdot (\Gamma_{ee} - \Gamma_{eo} + \Gamma_{oe} - \Gamma_{oo})$$
(7)

$$S_{31} = \frac{1}{4} \cdot (\Gamma_{ee} + \Gamma_{eo} - \Gamma_{oe} - \Gamma_{oo})$$
(8)

$$S_{41} = \frac{1}{4} \cdot (\Gamma_{ee} - \Gamma_{eo} - \Gamma_{oe} + \Gamma_{oo})$$
(9)

3 DESIGN METHODOLOGY: EVOLUTIONARY OPTIMIZATION ALGORITHMS

The four parameters' optimization of the proposed coupler must be optimized for different values of the coupling P, at a given design frequency. The design frequency affects the values of the different design parameters, whereas the coupling must be specified in the objective function of the optimization algorithm. In this experience two well-known evolutionary computation techniques have been used: An Evolutionary Programming algorithm (EP) (Yao et al., 1999) and a Particle Swarm Optimization (PSO) (Eberhart et al. 2001) approach.

The EP and the PSO implementations considered (the basic ones given in (Yao et al., 1999) and (Eberhart et al. 2001)) can be directly applied to solve the optimization of the directional coupler proposed,

with very few changes: In the case of the EP, the individual $\mathbf{x}$ is $\mathbf{x} = \{d_1, d_2, Z_1, Z_2, \sigma_{d_1}, \sigma_{d_2}, \sigma_{Z_1}, \sigma_{Z_2}\}$. If the PSO algorithm is used, each particle $\mathbf{x}$ is $\mathbf{x} = \{d_1, d_2, Z_1, Z_2\}$. The objective function for the optimization process is given, in both cases, by the following expression:

$$g(\mathbf{x}) = |S_{11}|^2 + (|S_{41}|^2 - P)^2, \qquad (10)$$

where P stands for the desired coupling and S_{11}, S_{41} are given by Equations (6) and (9), respectively.

4 ORGANIZATION AND EDUCATIONAL ASPECTS OF THE PROPOSED EXPERIENCE

The structure of the presented method, as it has been implemented in Universidad de Alcalá, is the following: First, the students are given a brief summarize of what they have to do (including the analysis given in Section 2), an outline of the directional coupler they have to design (similar to the Figure 1), a small tutorial on evolutionary computation and finally the source code (in Matlab) of the EP and PSO algorithms. In this experience it is not intended that the students learn to program the EP and PSO algorithms, but they must understand their principles, and how to apply them to design a given circuit. The students are requested to theoretically design the coupler by optimizing the objective function given by Equation (10) using the EP or the PSO, and then to construct a prototype to be analyzed, using the values given by the EP or PSO. This is the most interesting part of the experience, where the students must analyze the results obtained.

4.1 Prototype Construction and its Analysis

After obtaining the best set of values for the couples, the students must construct a prototype, according to the values obtained by optimization algorithm. The students can choose the value of the design frequency and the coupling ratio. Figure 2 shows a picture of the coupler that was constructed in the preparation of the experience. In this case the design frequency has been set up to 1 GHz, and the coupling ratio P has been fixed to 0.75. The prototype was made using a low-cost FR-4 substrate, the same available for the students. With this P, the EP obtained the following values of $\mathbf{x} = \{d_1, d_2, Z_1, Z_2\}$: $d_1 = 69.41$, $d_1 = 26.78$, $Z_1 = Z_2 = 51.43$ Ω. Using these values a simulation of the circuit with lossy transmission

lines, but without considering interconnection effects can be carried out using the Monolithic Microwave Integrated-Circuit Analysis and Design (MMICAD) simulator (Safwat et al., 1997). The analysis of the differences between the constructed and the simulated coupler is very interesting, and may help the students to understand the behavior of the circuit.

Figure 2: Picture of the constructed coupler.

Different analysis can be done at this point. For example it is possible to compare the measured and simulated responses of the coupler (Figure 3). Figure 3 (a) displays $|S_{11}|$ and $|S_{31}|$, and Figure 3 (b) $|S_{21}|$ and $|S_{41}|$. At $f_0 = 1$ GHz, the simulated $|S_{11}|$, $|S_{21}|$, $|S_{31}|$ and $|S_{41}|$ values are 0.05, 0.476, 0.039, 0.79, and the measured $|S_{11}|$, $|S_{21}|$, $|S_{31}|$ and $|S_{41}|$ are 0.11, 0.14, 0.13, 0.84, respectively. As shown in Figure 3 (b) there is a good agreement between the ideal and measured coupling value (S_{41}). Its behavior is not so good at high frequencies however, where there are significant differences between the expected (simulated) and measured behavior. This is due to the extremely simple transmission line model used for the simulations, which do not take into account the effects of discontinuities and joints. The students must extract their own conclusions out of this analysis, and it is an important part of the mark of the laboratory.

4.2 Educational Aspects of the Experience

The proposed experience has several educational aspects which makes it appealing to be implemented in University courses. First, the main characteristic of the experience is that it allows the students to have a first contact with advanced computational techniques (evolutionary-based), applied to an interesting problem of circuit design in this case. Second, these algorithms introduce a point of novelty to the classical practices of laboratories. This usually encourages the students to work harder in the practice, which is also useful from the lecturer's point of view. The possibility of extending this experience to other subjects,
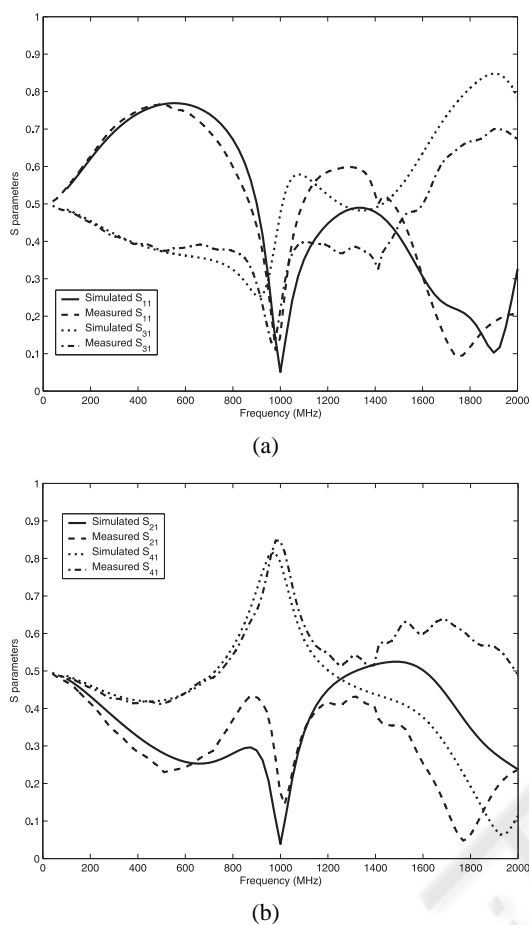
(a)

(b)

Figure 3: Performance of the designed directional coupler; (a) $|S_{11}|$ and $|S_{31}|$; (b) $|S_{21}|$ and $|S_{41}|$.

and including different advanced algorithms, is another interesting point to take into account.

The experience presented in this communication has been carried out in Universidad de Alcalá, Madrid, Spain, in an undergraduate subject called *Antennas and Microwave Laboratory*, belonging to the Bachelors Degree in Telecommunications. In this course, 79 students students learned about microwave circuits design in the first part of the semester, whereas the second part is devoted to antennas. It is important to note that this laboratory subject has a previous theoretical counterpart, where the main concepts of microwave circuits systems are studied. In order to assess the impact of the proposed experience, feedback was collected by asking the students to anonymously complete a questionnaire. Students' opinion about the difficulty of the work carried out, the difficulty of using the evolutionary computation algorithms and to understand how they work, and their opinion on the level of learning obtained, were collected. As a summary, about about 80% of the stu-

dents considered the experience carried out as "good" or "very good", about 15% considered it "fair" and 5% of students marked it as "bad" or "very bad". The majority of students considered the comparison of the simulated and measured coupler as the most interesting part of the experience, where they have learned the most.

5 CONCLUSIONS

This paper presents an experience carried out in Universidad de Alcalá, consisting in introducing evolutionary computation techniques in an undergraduate microwave laboratory, as part of the design of directional couplers. The idea is that this experience can be generalized to any laboratory subject and different computational techniques. This allows to introduce concepts which usually are not taught in undergraduate courses, as part of practices in laboratories. Another interesting point of the experience is that it introduces certain novelty in the laboratory practices, which encourage the students to work harder. The results of the application of the experience in the microwave circuits laboratory mentioned before are analyzed and discussed, offering a first result of the proposed experience in a real environment.

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