Evolutionary Design of a Wide Band Flat Wire Antenna for WLAN and Wi-Fi Applications

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Abstract **─** This paper presents a wire antenna for multi-band WLAN application, having a very simple geometry, designed using the Structure-Based Evolutionary Programming; an innovative antenna design technique, based on evolutionary programming. The chosen fitness function includes far-field requirements, as well as wideband input matching specifications. The latter requirements, which must be present in every useful antenna design, allow to stabilize the algorithm and to design both optimal and robust antennas. The antenna has been analysed with NEC-2 during the evolutionary process and the outcome of the procedure shows a very good performance; with a -10dB bandwidth that covers the required frequencies for multi-band WLAN applications (2.4/5.2/5.8 GHz) and beyond, and an end-fire gain greater than 10 dB. The NEC-2 results have been also compared to the ones obtained by a well-assessed, general purpose, 3D electromagnetic software, HFSS by Ansys, showing a very good agreement.

Index Terms **─** Evolutionary programming, wide band antennas and wire antennas.

I. INTRODUCTION

The rapid development of short-range radio links in the mobile communications industry, such as Bluetooth (BT), Wi-Fi and Wireless Local Area Network (WLAN), calls for antennas offering wideband operations covering the whole WLAN services. The desirable frequency bands required to a single antenna are: 2.4-2.484 GHz for BT applications, 2.4 GHz and 5 GHz for Wi-Fi applications (following HiperLan protocol) and 2.4 GHz, 5.2 GHz and 5.8 GHz for WLAN applications (following WLAN IEEE 802.11 standards).

Different WLAN antennas in planar technology have been recently proposed, based on known antenna concepts, but showing either a multiband [1] or a tuneable behavior [2]. So, significant improvements are yet to be reached, though a few wideband wire antennas have been proposed [3]. In the past literature, antenna design has been performed at different levels, from simple formulas [4] to sophisticated synthesis techniques [5]-[13], heuristic models [14] and random optimization procedures [15]. All of them, however, require a quite detailed specification of the antenna structure from the beginning, so that they can be more or less considered as dimensioning approaches.

A significant breakthrough can be achieved only by exploring new design concepts, allowing more general solution spaces to be searched in an effective way. Among them, Structure-Based Evolutionary Design (SED) has recently emerged as a new design paradigm [16-18]. SED provides a method for automatically creating a high-level working structure description, delivering elegant human-like solutions not anticipated by the programmer, requiring only a minimum amount of pre-supplied human knowledge, analysis and information. With SED, if we have to design a wire antenna following predetermined requirements, the procedure is able to look for the final design among all possible wire antennas. Therefore, SED can be used to automatically

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search, in this very huge solution space, for novel antenna configurations, which can be significantly more performant than antennas developed using standard techniques.

In this work, a very simple wire antenna is proposed covering the full WLAN range. The proposed antenna has been designed exploiting the power of the Structure-Based Evolutionary Design (SED).

II. STRUCTURE-BASED EVOLUTIONARY DESIGN

The traditional approach to the design of wire antennas starts by choosing a well-defined antenna structure, able to comply with the design specifications and whose parameters need to be suitably optimized. Besides, a good design requires also a continuous human monitoring, especially to trim the initial structure to better fit the antenna specifications, together with a deep knowledge and experience in order to effectively change the structure under design. This traditional approach is quite expensive and therefore, design techniques without human interaction are of increasing interest, as long as they are able to provide equal or better results. This can be achieved only when no initial structure is assumed, since this choice (by necessity fixed in a fully automated procedure) can constrain too strongly the final solution.

An effective way to pursuit this approach is SED. SED is a new global random search method derived by the strategy first proposed by Koza [19]. The SED approach mimics the behavior of the natural evolution for the search of the individual showing the best adaptation to the local environment (in our case, to the requirement we set). As a matter of fact, Darwin stated that “the natural system is founded on the descent with modification” [20], since what is commonly named natural selection, is a process leading to biological units better matched to local changing environments. Therefore, from a conceptual point of view, design approaches based on natural selection should be formulated as a search for antennas fulfilling a set of antenna specifications (the local changing environment), rather than as optimization of a given performance index. SED allows following this paradigm and in a way closer to how natural selection works. Natural selection has, in fact, a number of peculiar characteristics. First, if we look at it in a functional, or effective way, it works at the organ level. Moreover, it allows an enormous variability, which is limited only by some broad-sense constraints.

Each individual in SED is a “computer program;” i.e., a sequential set of unambiguous instructions completely (and uniquely) describing the physical structure of an admissible antenna and its realization. In the practical implementation of SED, populations of antennas (descriptions traditionally stored as tree structures) are genetically bred; this breeding is made using the Darwinian principle of survival and reproduction of the fittest, along with recombination operations appropriate for mating computer programs. Tree structures can be easily evaluated in a recursive manner; every tree node has an operator function and every terminal node has an operand, making mathematical expressions easy to evolve and to be evaluated. At each iterative step, the fitness of those individuals is evaluated, in order to select the ones best adapted to the design specifications. Then, a new population is obtained, by a suitable implementation of standard “evolutionary” operators like cross-over and mutation.

As a matter of fact, the SED does not require any antenna model, neither asks for a structure locked from the beginning, but it considers a virtually infinite solution space, defined only by very loose constraints. SED allows to automate the whole project (and not only its repetitive parts) and provides original solutions, not achievable using standard design techniques. This is obtained since the whole antenna is described in terms of elementary parts (wire segments, junctions, and so on) and of their spatial relations (distance, orientation). In this way, the final antenna is sought for in an enormous search space, with a very large number of degrees of freedom, which leads to better solutions both in terms of performance and overall dimensions.

SED optimization process starts with a random initial population and it may move in different directions, converging to different results for the final designed antenna. SED start point is totally random; it is a global optimization method, particularly suitable for solving problems with several parameters and no clear starting location in the solution space. The solution space; i.e., the set of admissible solutions in which the procedure looks for the optimum, has the power of the continuum. This is the main advantage of SED, since it allows exploring and evaluating, general structure configurations, but on the other hand, it can lead to a severely ill-conditioned synthesis problem. As a consequence, a naive implementation usually does not work, since different starting populations lead to completely different final populations, possibly containing only individuals poorly matched to the requirements (a phenomenon similar to the occurrence of traps in optimization procedures).

A suitable stabilization is therefore needed. This role can be accomplished by suitable structure requirements, or forced by imposing further constraints, not included in the structure requirements. Whenever possible, the former ones are the better choice and should be investigated first. Typically, a high number N of individuals for a certain number of generations must be evaluated in order to obtain a good result from the design process. Since each individual can be evaluated independently from each other, the design process is strongly parallelizable and this can significantly reduce the computation time.

The main operators used in SED to build up the new generations are:

1. Cross-over: switching one sub-tree of an individual with a randomly selected sub-tree from another individual in the population. The expressions resulting from a single cross-over can be either quite close or very different from their initial parents. This sudden jump from an individual to a very different one is a powerful trap-escaping mechanism.
2. Mutation: modifies a whole node in the selected individual. In order to maintain integrity, operations must be fail-safe; therefore, the type of information the node holds must be taken into account.

The performance of each individual in the population is measured by a suitable fitness function, tailored to the problem at hand. Different fitness functions, built from different requirements, can lead to completely different results; each one best fitted to the corresponding original requirements.

SED has been used here to design a wideband wire antenna with an end-fire radiation pattern and a very simple geometry, operating in a range from L to C frequency bands, namely from 1 GHz to 6 GHz and with a very good input matching. Apart from these simple "constraints." SED does not assume any other a priori information on the antenna structure, building up the structure of the individuals-antennas as the procedure evolves.

In the design process, each individual in the population represents an admissible antenna. The performances of each antenna are evaluated by NEC-2 [21], a well assessed Method of Moments code, successfully used to model a wide range of wire antennas and considered as one of the reference electromagnetic software. The best individual obtained by the SED has been analysed also using a well-assessed, general purpose, 3D electromagnetic software, HFSS by Ansys. The results obtained by HFSS have been compared with NEC-2 simulations, showing a very good agreement.

III. ANTENNA STRUCTURE AND DESIGN

SED is a global random search procedure, looking for individuals best fitting a given set of specifications. These individuals are described as instruction sets and internally represented as trees. The main steps of the whole evolutionary design can be summarized in the flowchart of Fig. 1.

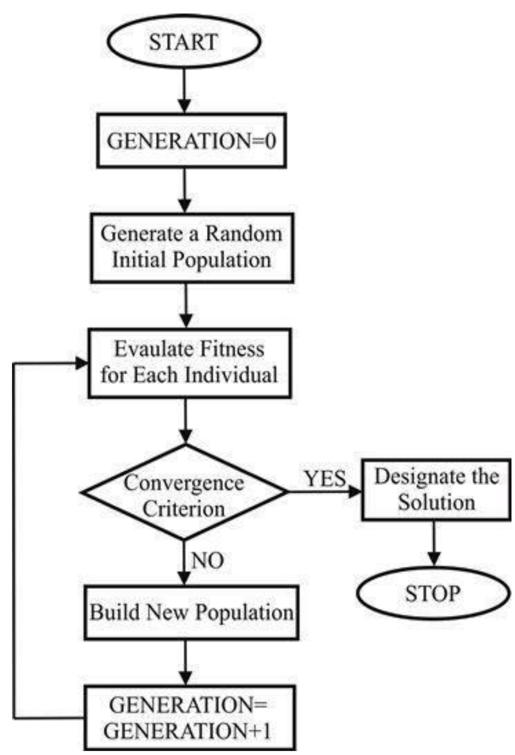


Fig. 1. Flowchart of the evolutionary design.

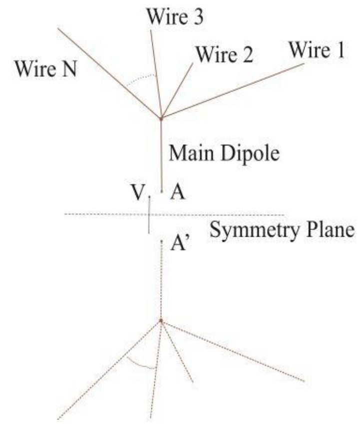
The initial structure of each individual of the population (antenna) generated by SED, is depicted in Fig. 2 (a) and is composed by a principal vertical wire (the main dipole in Fig. 2 (a)), connected to the feeding port on its bottom side and by a number N (chosen by SED) of wires connected to the upper side of the Main Dipole with an arbitrary length and orientation in space. At the remote end of each of the N wires, the SED procedure can connect zero, one or more further wires; still with arbitrary length and orientation, and so on, in an iterative manner. The structure is finally mirrored with respect to the horizontal plane, as indicated in Fig. 2 (a).

The proposed antenna is a broadband antenna, whose principle is not based on the principle of self-similarity like the bi-conical, spiral or log-periodic antennas. As shown in Fig. 2, where both the antenna geometry (Fig. 2 (a)) and the final designed antenna after the optimization process (Fig. 2 (b)) are depicted, the designed antenna is simply a branched dipole antenna suitably arranged in space. This choice strongly simplifies the antenna feeding network (which is simply a dipole feeding node) with respect to other broadband antennas, such as log-periodic dipole antennas (which need a twisted cable feeding network).

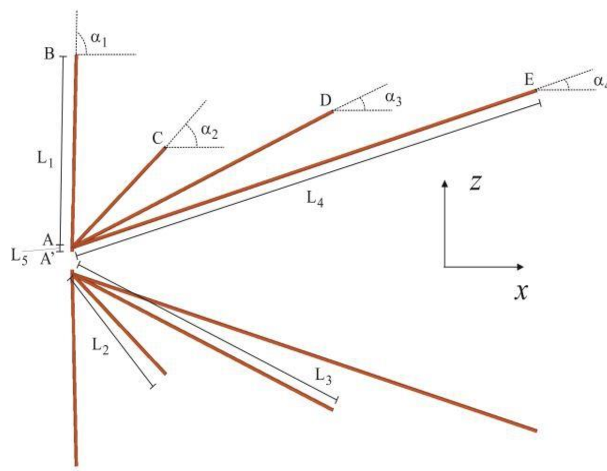
Each individual is built up using one of the following operations:

1. Add a wire according to the present directions and length.
2. Transform the end of the last added wire in a branching point.
3. Modify the present directions and length.
4. Stretch (or shrink) the last added wire.

This mixed representation largely increases the power of the standard genetic operations (mutation and cross-over), since each element can evolve independently from the others. Of course, after each complete antenna is generated, its geometrical coherency is verified, and incoherent antennas (e.g., an antenna with two elements too close, or even intersecting) are discarded.



(a)



(b)

Fig. 2. (a) Wire antenna geometry and (b) geometry of the final designed wire antenna after optimization: L_1=195.1 mm, L_2=144.6 mm, L_3=311.8 mm, L_4=522 mm, α_1=88.6° mm, α_2=44.7°, α_3=25.6° and α_4=17.4°.

The SED approach has been implemented in Java, while the analysis of each individual has been implemented in C++ (using the freeware source code Nec2cpp) and checked using the freeware tool 4nec2. The integration with NEC-2 has mainly been achieved through three classes:

1. A parser for the conversion of the s-expressions, represented as n-ary trees, in the equivalent NEC input files.
2. A NecWrapper, which writes the NEC listing to a file, launches a NEC2 instance in a separate process and parses the output generated by NEC.
3. An Evaluator, which calculates the fitness using the output data generated by NEC.

The evaluation procedure for each individual (i.e., for each antenna) can be described by the flowchart in Fig. 3.

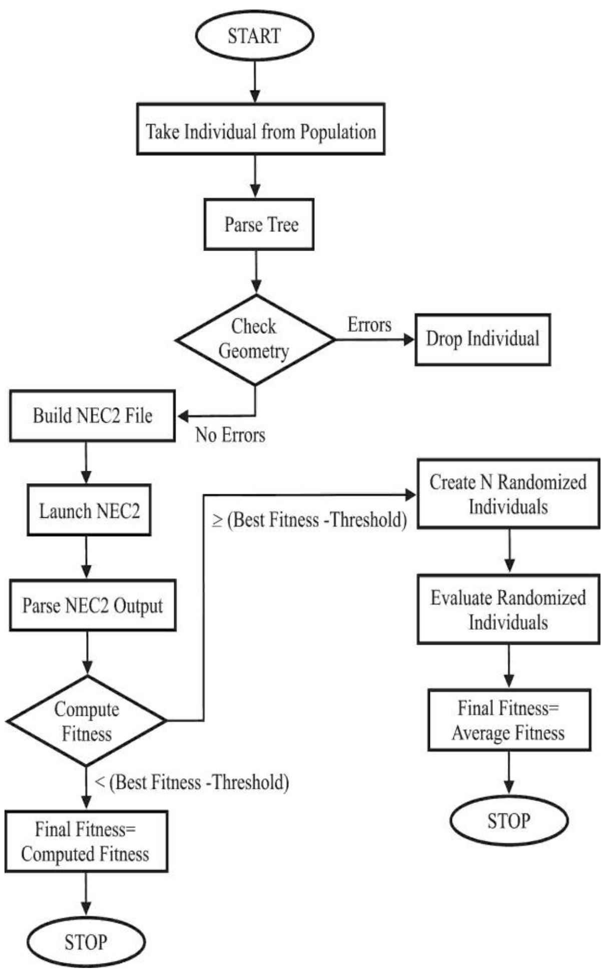


Fig. 3. Flowchart of the evaluation procedure for each individual of the population.

In the first step of the evolutionary design, N individuals are randomly built. Then, an iterative procedure starts, where the fitness of each individual is evaluated and the next generation of the population is built assigning a larger probability of breeding to the individuals with the highest fitness. The iterative procedure ends when suitable stopping rules are met (i.e., when the individual-antenna fulfills, within a predetermined tolerance, the specified requirements).

After each antenna has been generated, its geometrical coherency is verified, and incoherent antennas (e.g., an antenna with two elements too close, or even intersecting) are discarded. Then it is analysed by NEC-2 [21] and its fitness is computed.

The performance of each individual (antenna) of the population is evaluated by a proper fitness function, which is strongly dependent by the problem at hand, namely by the electromagnetic behavior of the designed antenna and must measure how closely the actual antenna meets the design specifications.

In the specific case of the broadband wire antenna of this paper, the fitness function has been selected in order to lead the evolution process toward a structure with a good input match in a frequency range as wide as possible (within L, S and C Bands), while keeping the highest end-fire gain and a reduced size. In order to obtain a very simple and compact antenna, we impose the following constraints to the evolution process:

1. Individuals must lie over a plane, namely the *xz* plane.
2. No further wire can be connected at the remote end of each of the N wires shown in Fig. 2 (a).
3. A larger weight is assigned to the fitness of the individuals with a size lower than 0.1 square meters.

Since the increase in a parameter (i.e., the gain) usually results in a reduction in the other ones (i.e., frequency bandwidth and input matching), the design procedure must manage an elaborate trade-off between these conflicting goals. Therefore, the form of the fitness function can be a critical point, since only a suitable fitness can lead the design process to significant results. Moreover, depending on the used fitness, the computation time can be largely reduced (i.e., a good result can be obtained with less generations).

The chosen fitness has been built from the desired antenna performances [16-18] as:

$$Fitness = \left(\left| 1 - \overline{SWR} \right| \cdot \alpha_{SWR} + \left| \frac{G_{MAX}}{\overline{G}} \right| \cdot \alpha_{GAIN} \right) \cdot \left(1 + \frac{D_{MAX}}{D_{ANT}} \cdot K_{SIZE} \right), \quad (1)$$

wherein α_{SWR} and α_{GAIN} are suitable weights (whose values depend also on the input impedance of the actual antenna), $\overline{SWR}$ and $\overline{G}$ are, respectively, the mean values of the antenna Standing Wave Ratio (SWR) and of the antenna gain G over the bandwidth of interest, D_{ANT} represents the actual antenna size and D_{MAX} is the maximum allowed size for the antenna; which is equal to 0.2 m^2 in this case. Finally, K_{SIZE} is an appropriate weight, which takes into account the requirement of a small size of the antenna and is equal to 0.65 in this case. The values for the fitness weights have been obtained after a suitable local tuning, following an approach similar to the one described in detail in [16-18] voltage.

The weight α_{GAIN} in the fitness function (1) has the following expression:

$$\alpha_{\text{GAIN}} = \left(1+\alpha_{\text{Back}} * G_{\text{Back}}\right)\cdot\left(1+\alpha_{\text{Rear}} * G_{\text{Rear}}\right) \cdot\left(1+\alpha_{\text{Front}} * G_{\text{Front}}\right) \quad , (2)$$

where G_{Back} is the gain computed in the back direction (θ=90°; φ=180°), G_{Front} is the average gain computed in the front region ($|\theta|>90°+2\Delta\vartheta$; $0°+2\Delta\varphi<\varphi<90°$, where $\Delta\vartheta$ and $\Delta\varphi$ indicate the main lobe amplitude) and G_{Rear} is the average gain computed in the rear region ($0°\le|\vartheta|\le180°$; $90°\le|\varphi|\le180°$). The weigths α_{Back}, α_{Front} and α_{Rear} are chosen through a local tuning, in order to get the maximum gain in the end-fire direction and an acceptable radiation pattern in the rest of the space. After the evolutionary process, these parameters assume the following values: α_{Back}=0.12, α_{Front}=0.17 and α_{Rear}=0.06.

The weight α_{SWR} in the fitness function (1) is expressed using suitable parameters strictly related to the antenna input impedance, which are individually tuned. The resulting expression for α_{SWR} is:

$$\alpha_{\text{SWR}} = \left(1+\alpha_{\text{IN}}\right)\cdot\left(1+\alpha_{\text{X}}\left|X_{IN}^{A}\right|\right)\cdot\left(1+\alpha_{\text{Q}}\frac{R_{IN}^{A}-\left|X_{IN}^{A}\right|}{R_{IN}^{A}}\right) \cdot\left(1+\alpha_{\text{VarR}}\cdot\sigma_{\text{R}}^{2}\right)\cdot\left(1+\alpha_{\text{VarX}}\cdot\sigma_{\text{X}}^{2}\right) \quad , (3)$$

where:

- α_{IN}=50 if $|X_{IN}^A|> R_{IN}^A$ and α^{IN}=0 otherwise (weight introduced in order to boost up structures with $R_{IN}^A> |X_{IN}^A|$);
- α_X=0.12 (weight related to $|X_{IN}^A|$, introduced in order to force the evolution process to structures with an $|X_{IN}^A|$ as small as possible);
- α_Q=0.2 (weight related to R_{IN}^A-$|X_{IN}^A|$, introduced to advantage structures with a low Q factor);
- α_{VarR}=α_{VarX}=0.03 (weight related to the normalized mean square variation of R_{IN}^A and X_{IN}^A in the antenna required bandwidth, introduced to advantage structures with a regular impedance behaviour);

R_{IN}^A and X_{IN}^A are, respectively, the real part and the imaginary part of the antenna input impedance, while σ_{R2} and σ_{X2} are the normalized mean square variation of R_{IN}^A and of X_{IN}^A in the antenna required bandwidth. The two weights α_{IN} and α_Q are both connected to the Q factor of the antenna. However, α_{IN} gives a significant penalization to antennas with a large imaginary part of the input impedance, but it has a step-like behavior. Therefore, in order to get a further, smooth penalization to antennas with a large Q, we have added also the term with α_Q. We have observed that a combination of the two terms is more effective than either one separately.

The requirement of a given and low VSWR all over the design bandwidth, is obviously needed to effectively feed the designed antenna. Moreover, the VSWR requirement (which is a near-field requirement) allows to stabilize the severely ill-conditioned synthesis problem (due to the extremely large SED solution space), at virtually no additional cost.

IV. RESULTS

The best individual of the evolution is shown in Fig. 2 (b), and the Cartesian coordinates of each wire are reported in Table 1; each wire has a diameter of 1.77 mm and is made by copper with a conductivity of σ=5.8*10^7 S/m. The designed antenna lies on the *xz* plane and occupies an area of only 0.498x0.195 square meters. This antenna is extremely easy to realize, especially due to its planar configuration and can be produced with a very low cost by the same technology used for Yagi and LPDA arrays.

Table 1: Cartesian coordinates of the ends of the wires for the antenna in Fig. 2 (b)

	X [mm]	Z [mm]
A	0	5.327
B	4.511	195.025
C	102.815	101.698
D	280.852	135.408
E	498.249	155.577

The antenna has been designed using a population size of 1000 individuals, with a crossover rate set to 60% and a mutation rate set to 40%. Its convergence plot is shown in Fig. 4, and it appears that 150 generations are enough to reach convergence.

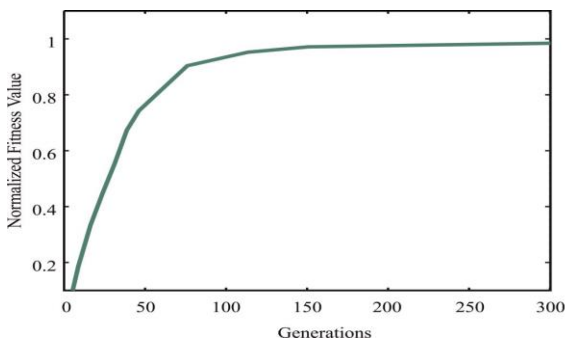


Fig. 4. Plot of convergence of the designed antenna shown in Fig. 2 (b).

The frequency response of the designed antenna, simulated using NEC-2, is reported in Fig. 5. The S11 module is below -10 dB in a frequency band, which extends from 1 GHz up to well beyond 6 GHz, showing a very good input matching within the whole operating bandwidth. In order to validate these results, since sometimes the S11 data of NEC-2 could have a reduced accuracy, the designed antenna has been simulated also with HFSS, a commercial FEM code which has been demonstrated to be in very good agreement with experimental data and the results are reported in Fig. 5. This comparison shows that NEC-2 and HFSS results are in very good agreement.

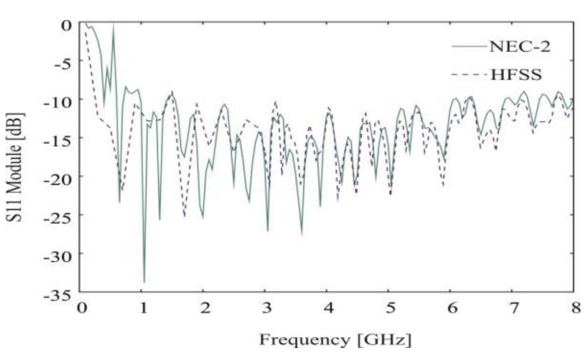


Fig. 5. Reflection coefficient of the designed antenna.

The end-fire Gain of the designed antenna, plotted in Fig. 6, remains higher than 10 dB both in the Bluetooth, Wi-FI and WLAN operating bandwidths. Also, the front-to-back ratio, plotted in Fig. 7, is higher than 10 dB in the frequency bandwidth 2-6 GHz. In the bandwidth 1-6 GHz, the mean Gain of the antenna is equal to 10.5 dB and the mean F/B ratio is about 14 dB.

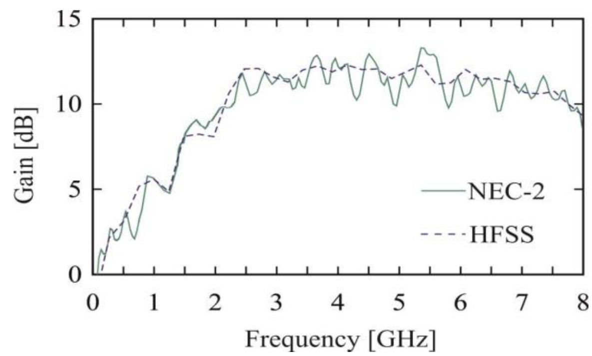


Fig. 6. Gain of the designed antenna.

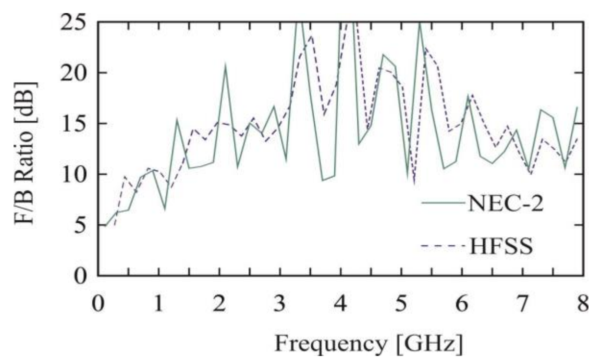


Fig. 7. Front-to-back ratio of the designed antenna.

Figure 8 shows the antenna efficiency, which is above 99% in the bandwidth of interest (2-6 GHz). The inclusion of ohmic losses into the gain computation is very important, since this prevents from selecting super-directive antennas during the evolution, as we thoroughly explained in [22].

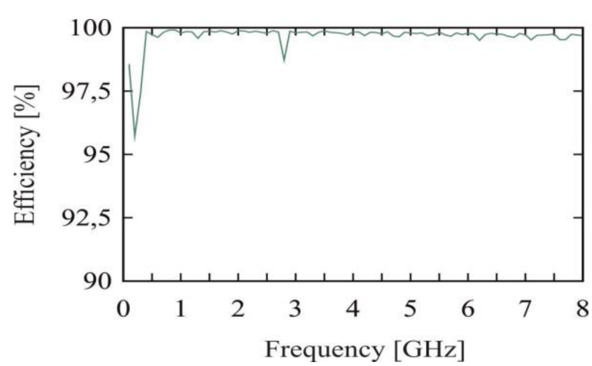


Fig. 8. Efficiency of the designed antenna.

Finally, the NEC-2 Far Field Pattern in the operating frequency bandwidth is plotted in Fig. 9. For each frequency, the E-plane and the H-plane are shown. The reported radiation patterns confirm that the useful bandwidth of the designed antenna is 1-6 GHz, where the input matching is very good and the far field is essentially end-fire, with a good Gain and F/B ratio.

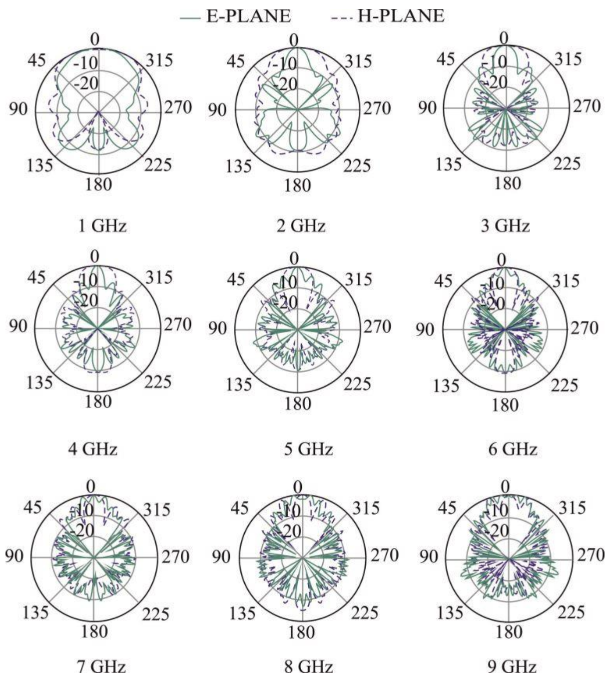


Fig. 9. Simulated (NEC-2) normalized Far-Field pattern of the designed antenna. Continued green line: E-plane and dashed blue line: H-plane.

It is well known as optimization techniques can often lead to solutions very sensitive to little variations both in manufacturing, deployment and/or hosting environments. Therefore, in order to test the robustness of the proposed antenna, we studied several random perturbations related both to manufacturing errors (random rotations and random lengths of the branches) and to the environment (random deformations due, for example, to the effect of the wind). In Fig. 10, three perturbed elements are shown: the first one is obtained by randomly modifying the wire length by adding or subtracting a quantity equal to 10% of the design value (Fig. 10 (a)); the second one is obtained by randomly modifying the wire orientation in the xz plane by clockwise or counterclockwise rotating the wire of an angle equal to 10% of the design value (Fig. 10 (b)); the last one is obtained by randomly modifying the wire orientation in the xy plane by clockwise or counterclockwise rotating the wire of an angle such that the y coordinate of the wire is equal to 10% of the total design length of the wire itself: i.e., $\phi_i = arctan(y_i = L_{i,})$, (Fig. 10 (c)). The first two perturbations are related to manufacturing errors and/or to deployment, while the last perturbation can model the effect of the wind. All the considered perturbations are very huge ones, since the design values have been varied of a significant quantity (10%). Nevertheless, both the simulated reflection coefficient and the simulated gain of all the perturbed configurations, shown in Figs. 11 and 12, respectively, confirm that the antenna is very robust to these huge perturbations (±10% with respect to the design value).

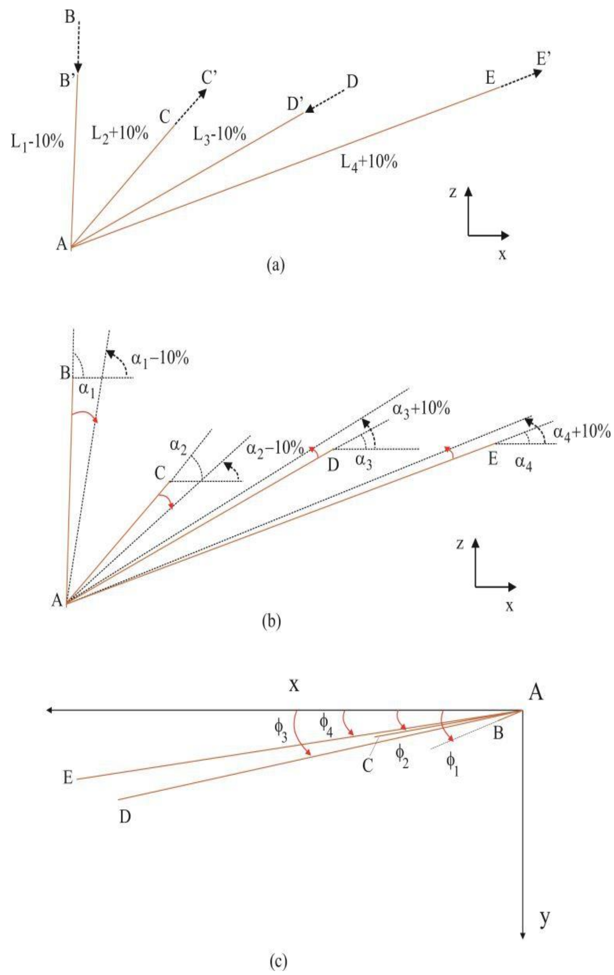


Fig. 10. Perturbed configurations of the designed antenna: (a) random length variations, (b) random rotations in the xz plane and (c) random rotations in the xy plane (ϕ_1=25°, ϕ_2=16°, ϕ_3=20°, ϕ_4=14°).

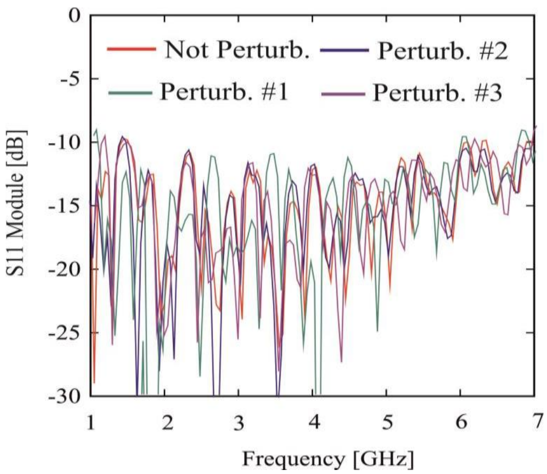


Fig. 11. Reflection coefficient of the perturbed configurations compared with the unperturbed antenna. Perturb #1: random length variations; perturb #2: random rotations in the xz plane; perturb #3: random rotations in the xy plane.

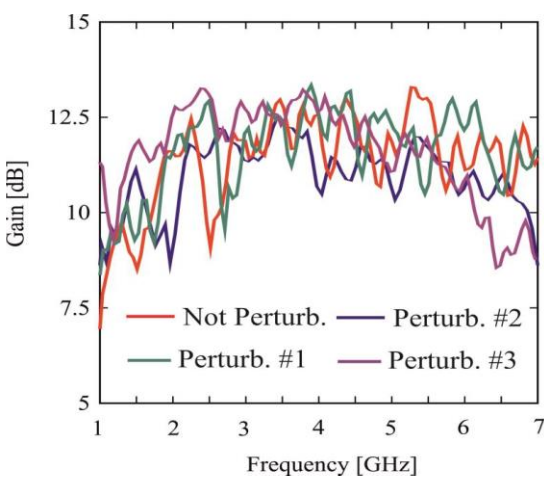


Fig. 12. Gain of the perturbed configurations compared with the unperturbed antenna. Perturb #1: random length variations; perturb #2: random rotations in the xz plane; perturb #3: random rotations in the xy plane.

V. CONCLUSION

In this work, the Structure-Based Evolutionary Design, an innovative antenna design technique based on evolutionary programming, has been used to design a wideband wire antenna for multi-band WLAN application, with an end-fire radiation pattern and a very simple geometry. The chosen fitness function includes far-field requirements, as well as wideband input matching specifications, which allow to stabilize the algorithm and to design both optimal and robust antennas. The designed antenna operates in a range from L to C frequency bands; therefore, covering the required frequencies for multi-band WLAN applications (2.4/5.2/5.8 GHz), showing a very good input matching and keeping an end-fire gain greater than 10 dB.

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