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Structure-Based Evolutionary Design Applied to Wire Antennas

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1. Introduction

Antennas are 3D structures, so, at variance of other MW subsystems like filters and couplers, their design has been a matter of intuition and brute-force computations from the beginning (Silver, 1949; Elliott, 1981 just to remember a few). Therefore, an antenna design has been faced at different levels, from simple formulas (Collin, 1985) to sophisticated synthesis techniques (Orchard et al., 1985; Bucci et al., 1994), and from simple heuristic models (Carrel, 1961) to modern global random optimizations, such as GA (Linden & Altshuler, 1996, 1997; Jones & Joines, 1997) and PSO (Baskar et al., 2005), with their heavy computational loads.

Moreover, an antenna design problem is typically divided into two phases, namely an external problem (the evaluation of the antenna currents from the field requirements) and an internal problem (the design of the feed structure needed to achieve those currents, and the input match) (Bucci et al., 1994). In many cases these two phases are almost independent, but for some mutual constraints, as in reflector (Collin, 1985) and slot (Costanzo et al., 2009; Montisci, 2006) or patch (Montisci et al., 2003) array synthesis, since in these cases there is a clear boundary separating the feeding and radiating part of the antenna. In other problems, as in wire antennas design (Johnson & Jasik, 1984), such phases are strictly interconnected, since no clear-cut divides the two parts. For parasitic wire antennas, the interconnection is even stronger, since every element acts as feeding and radiating part at the same time.

The traditional approach to the design of wire antennas starts by choosing a well-defined structure, whose parameters are then optimized. However, a good design requires also a continuous human monitoring, mainly to trim the initial structure to better fit the antenna specifications. A trimming which requires both a deep knowledge and experience in order to effectively change the structure under design. As a matter of fact, such traditional approach is quite expensive, and therefore design techniques without human interaction are

of interest, as long as they 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.

The present work proposes such an alternative technique which allows to automate the whole project (and not only its repetitive parts), and provide original solutions, not achievable using standard design techniques. This is obtained by describing the whole antenna in terms of elementary parts (wire segments, junctions, and so on), and of their spatial relations (distance, orientation), and searching for high-performance structures by distributing, in the space, groups of these elementary objects. 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. On the other hand, such solution space must be searched for in an effective, and automatic, way in order to get the required antenna. Aim of this work is to describe how to effectively perform an automatic design of wire antennas without an initial choice of the structure, in order to achieve higher performances than those obtainable by using classical design techniques (eg Yagi antennas and log-periodic antennas (Johnson & Jasik, 1984)).

This can be achieved using a new design technique, namely the Structure-based Evolutionary Design (SED), a new global random search method derived by the strategy first proposed by Koza (Koza, 1992). Many optimization techniques recently proposed, such as GA, share the same inspiration, though natural selection is definitely not an optimization process. As a matter of fact, Darwin stated that "the natural system is founded on the descent with modification" (Darwin, 1859), 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. As we will show later, 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 the SED approach is a "computer program", i.e., a sequential set of unambiguous instructions completely (and uniquely) describing the realization (almost in engineering terms) of the physical structure of an admissible individual. This is a marked difference with GA, where an individual is only a set of physical dimensions and other parameters. In the practical implementation of SED, populations of thousands of individuals, which are traditionally stored as tree structures, are genetically bred 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.

The performance, in the particular problem environment, of each individual computer program in the population is measured by its "fitness". The nature of the fitness measure depends on 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.

The only information which the design process requires to advance in its search within the space of possible solutions are the current population and the fitness of all its individuals. A new population is then generated, by applying simple rules inspired by natural evolution.

The main (meta)-operators used in SED are reproduction, crossover and mutation.

- The reproduction simply reproduces in the new population, without any change, a predetermined number of individuals among those who obtained the best fitness.
- Crossover is applied on an individual by simply switching one of its nodes with another node from another individual in the population. With a tree-based representation, replacing a node means the replacement of the whole branch. This adds greater effectiveness to the crossover operation, since it exchanges two actual sub-individuals with different dimensions. The expressions resulting from a single crossover can be either quite close or very different from their initial parents. The sudden jump from an individual to a very different one is a powerful trap-escaping mechanism.
- Mutation affects an individual in the population, replacing a whole node in the selected individual, or just the node's information. To maintain integrity, operations must be fail-safe, i.e. the type of information the node holds must be taken into account.

Since each individual in the SED approach is a set of unambiguous instructions describing the realization of a generic physical structure, the presented procedure can be extended, in principle, to any 3D structure.

Before entering into the SED description, some considerations on the name chosen (Casula et al., 2011a) are in order. Koza, in his 1992 paper, coined the name "genetic programming" for his approach. Actually, this name resembles too closely another optimization approach, but with marked differences with the Koza approach, namely the genetic algorithms (GA). We decided to use a different name, better linked to the approach we use, to avoid any ambiguity between very different approaches. In order to better grasp the differences between SED and GA, we can say that GA works on the "nucleotide" (i.e. bit) level, in the sense that the structure is completely defined from the beginning, and only a handful of parameters remain to be optimized. On the other hand, the approach used in SED assumes no "a priori" structure, and it builds up the structure of the individuals as the procedure evolves. Therefore it operates at the "organ" (i.e. physical structure) level, a far more powerful level: it acts on subparts of the whole structure, thus allowing an effective exploration of a far more vast solution space than other design techniques. SED is able to determine both the structure shape and dimensions as an outcome of the procedure, and is therefore a powerful tool for the designer. As a consequence, its solution space has the power of the continuum, while the GA solution space is a discrete one, so it is a very small subspace of the former. Moreover, the

typical evolution operators work on actual physical structures, rather than on sequences of bits with no intuitive link to the structure shape. The enormous power of SED fully allows the exploration of more general shapes for the structure. The main drawback is the ill-posedness of the SED, which calls for a regularization procedure.

The rest of this chapter is organised as follows:

- Section 2 starts with a general description of the Structure-based Evolutionary Design, and of the main steps of the evolutionary process.
- SED is then specifically applied to the design of broadband parasitic wire arrays (Sections 2.1-2.3): a suitable tree representation of wire antennas is devised, appropriate antenna requirements are set, a suitable fitness is derived and the evaluation procedure for each individual is described.
- In Section 3 several examples are presented: for each set of requirements, a suitable fitness function must be derived, and some suggestions are given to choose the best fitness for the problem at hand.
- The results obtained with SED are finally compared with other algorithms like Particle Swarm Optimization and Differential Evolution, showing that the performances obtained by SED are significantly higher.

2. Description of the Structure-based Evolutionary 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:
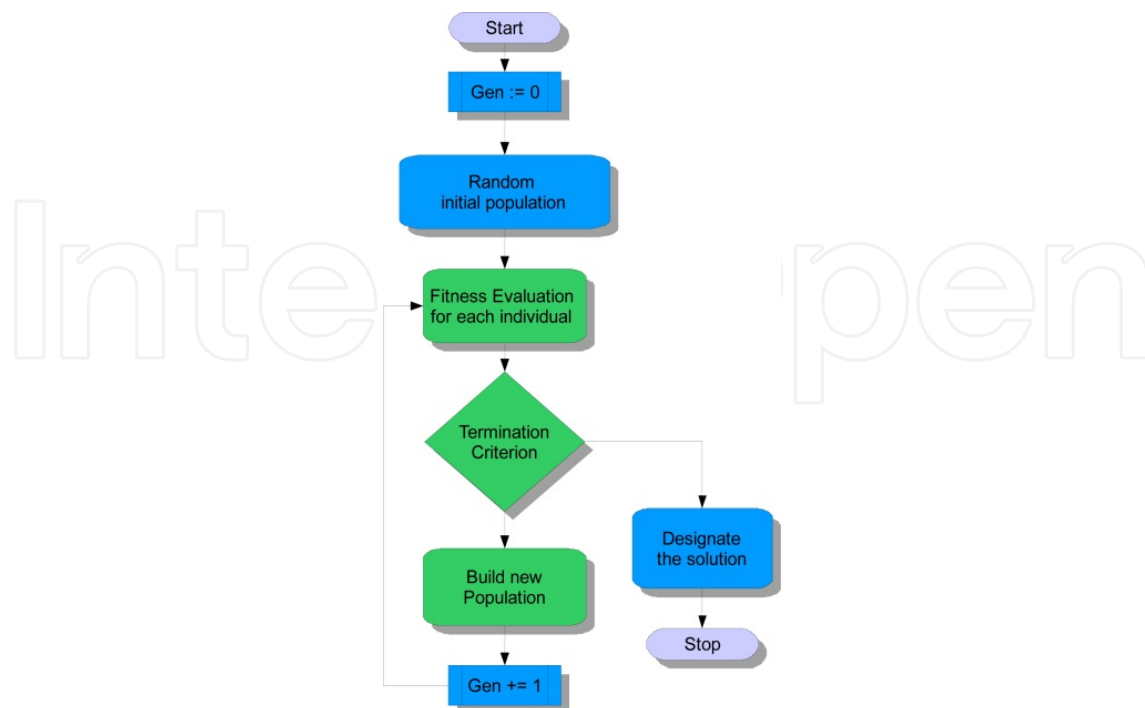

Figure 1. Flowchart of the Evolutionary Design.

After an initial step, where N individuals are picked up at random, an iterative procedure starts, which includes the evaluation of the fitness (appropriate for the problem at hand) for each individual, and the building of the next generation of the population. A larger probability of breeding is assigned to individuals with the highest fitness. The generation of new populations ends only when opportune stopping rules are met (i.e. when the individual-antenna fulfils, to a prescribed degree, the stated requirement).

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.

2.1. SED applied to the design of wire antennas

The Structure-Based Evolutionary Design, based on evolutionary programming, has been devised and applied to the design of broadband parasitic wire arrays for VHF-UHF bands. This requires first to devise a suitable tree representation of wire antennas, well tailored to the SED meta-operators, and then suitable antenna requirements. We consider only antennas with a symmetry plane, and with all element centres on a line. Therefore, each "wire" is actually a symmetric pair of metallic trees, and only one of them must be described.

In antenna design, the most intuitive fitness function can be built as the "distance" between actual and required far-field behaviour (Franceschetti et al., 1988) or, even more simply, as the antenna gain or SNR (Lo et al., 1966). However, this is not the case for SED. The solution space, i.e., the set of admissible solution in which the procedure looks for the optimum, is composed, in our case, of every Parasitic Dipole Array (PDA) antenna with no limit on the number of wire segments, nor on the size or orientation, represented as real numbers. The design problem is therefore strongly ill-conditioned and, in order to stabilize it, appropriate suitable antenna requirements must be set. Far-field requirements are unable to stabilize the problem, since the far-field degrees of freedom are orders of magnitude less than those of

the solution space (Bucci & Franceschetti, 1989), so that a huge number of different antennas gives the same far field. As a matter of fact, a wire segment whose length is a small fraction of the wavelength can be added or eliminated without affecting the far field. We must therefore revert to near-field requirements. Among them, the easiest to implement, and probably the most important, is a requirement on the input impedance over the required bandwidth. Since this constraint is a "must-be" in order to get a usable solution, we get the required stabilization at virtually no additional cost. As a further advantage, a low input reactance over the bandwidth prevents from superdirective solutions (Collin, 1985) even when a reduced size is forced as a constraint.

The performances of each individual (antenna) of the population are evaluated by its fitness function. The details of the fitness function we have chosen for PDA design are widely described in the next section. However, at this point it must be stressed that the fitness function depends in an essential way on the electromagnetic behaviour of the individual.

Since we are interested in assessing SED as a viable, and very effective, design tool, we accurately try to avoid any side-effect stemming out from the electromagnetic analysis of our individuals. Therefore we rely on known, well-established and widely used antenna analysis programs. Since our individuals are wire antennas, our choice has fallen on NEC-2 (Burke et al., 1981).

The Numerical Electromagnetics Code (NEC-2) is a MoM-based, user-oriented computer code for the analysis of the electromagnetic response of wire antennas and other metallic structures (Lohn et al., 2005). It is built around the numerical solution of the integral equations for the currents induced on the structure. This approach allows taking well into account the main second-order effects, such as conductor losses and the effect of lossy ground on the far field. Therefore we are able to evaluate the actual gain, and not the array directivity, with a two-fold advantage. First of all, the gain is the far-field parameter of interest and, second, this prevents from considering superdirective antennas, both during the evolution and as final solution, which is even worse. NEC has been successfully used to model a wide range of antennas, with high accuracy (Burke & Poggio, 1976a, 1976b, 1981; Deadrick et al., 1977) and is now considered as one of the reference electromagnetic software (Lohn et al., 2005; Linden & Altshuler, 1996, 1997). However, since SED is by no means linked, or tailored, to NEC, a different, and most effective, EM software could be used, to reduce the total computational time, further improving the accuracy of the simulation.

2.2. Construction and evaluation of each parasitic dipole array

Each PDA is composed of a driven element and a fixed number of parasitic elements. In order to get transverse dimensions close to those of Yagi and LPDA, and to ease the realization, the centers of the elements are arranged on a line, with the driven element at the second place of the row. In Yagi terminology, we use a single reflector. We actually have experimented with more reflectors but, exactly as in standard Yagi, without any advantage over the single-reflector configuration. Each element is symmetric w.r.t its center, and the upper part is represented, in the algorithm, as a tree.

Each node of the tree is an operator belonging to one of the following classes:

a. add a wire according to the present directions and length
b. transform the end of the last added wire in a branching point
c. modify the present directions and length
d. 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 PDA is generated, its geometrical coherency is verified, and incoherent antennas (e.g., an antenna with two elements too close, or even intersecting) are discarded.

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.

In order to better grasp the representation chosen, the S-expression for the simple Yagi antenna of Fig.2 follows.

Figure 2. Antenna Structure corresponding to the S-expression of the example

S-expression:

Tree 0:

(StretchAlongZ 1.3315124586134857 (Wire 0.42101090906114413 1.0

  (StretchAlongX 0.5525837649288541 (StretchAlongY 1.4819461053740617

    (RotateWithRespectTo_Y 0.3577743384222999 END)))))

Tree 1:

(Wire 0.5581593081319647 1.0 (RotateWithRespectTo_X -0.44260816356142224

  (RotateWithRespectTo_Z 0.08068272691709244 (StretchAlongZ 0.7166185389610261

    (StretchAlongX 1.42989629787443 (StretchAlongZ 1.346598788775623

      END))))))

Tree 2:

(Wire 0.3707701115469606 1.0 (RotateWithRespectTo_X 0.5262591815805174

  (RotateWithRespectTo_Z -0.7423883999218206 (RotateWithRespectTo_Z 0.07210315212202911

    END))))

The corresponding NEC-2 input file is:

GW 1 17 0.00E00 0.00E00 0.00E00 -1.34E-02 1.44E-02 1.33E-01 1.36E-03

GW 2 22 -1.38E-01 0.00E00 0.00E00 -1.25E-01 0.00E00 1.66E-01 1.36E-03

GW 3 15 1.21E-01 0.00E00 0.00E00 1.21E-01 0.00E00 1.18E-01 1.36E-03

GX 4 001

GE

2.3. Fitness function

The fitness function must measure how closely the design meets the desired requirements. To achieve our design goal, a fitness should be developed, which is to direct the evolution process on a structure with reduced size, with the highest end-fire gain, and with an input match as better as possible in the widest frequency range. Actually, 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), thus the algorithm 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).

After evaluation of different fitness structures, we have chosen a fitness function composed by three main terms suitably arranged as:

$$Fitness = \left(F_M + F_G\right) \cdot F_S \tag{1}$$

The first term (F_M) takes into account the input matching of the antenna, the second term (F_G) takes into account the antenna gain including the effect of ohmic losses, and the last term (F_S) takes into account the antenna size.

In (2.1):

$$F_M = \left|1 - \overline{SWR}\right| \cdot \alpha_M ; \qquad F_G = \left|\frac{G_{MAX}}{\overline{G}}\right| \cdot \alpha_G ; \qquad F_S = 1 + \frac{D_{REAL} - D_{MAX}}{D_{MAX}} \cdot \alpha_S \tag{2}$$

wherein α_M, α_G and α_S are suitable weights, while $\overline{SWR}$ and $\overline{G}$ are the mean values of SWR and gain over the bandwidth of interest, D_{REAL} represents the real antenna size and D_{MAX} is the maximum allowed size for the antenna.

The requirement of a given, and low, VSWR all over the design bandwidth is obviously needed to effectively feed the designed antenna. However it has an equally important role. The VSWR requirement (a near-field requirement) stabilizes the problem, at virtually no additional cost.

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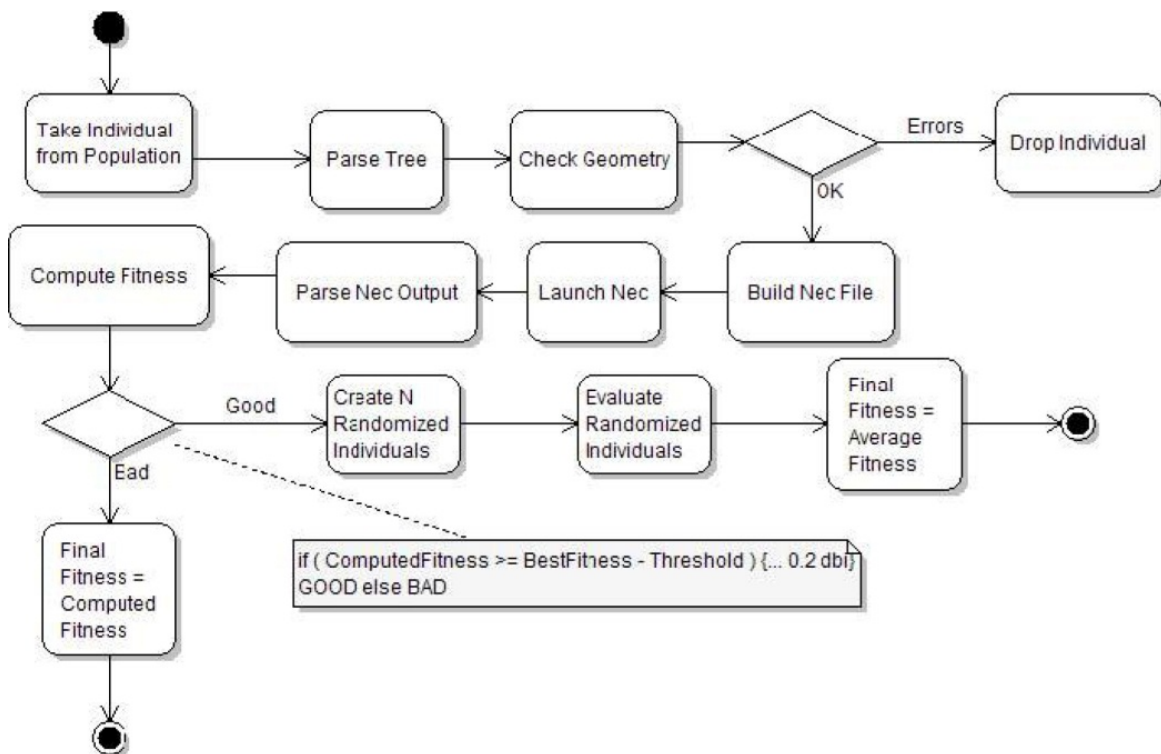

Figure 3. Flowchart of the evaluation procedure for each individual of the population.

The process requires, as inputs, the required frequency range of the antenna, the number of frequency points N_F to be evaluated, the metal conductivity and the maximum size of the antenna. Actually, the generated antenna can overcome the bounding box dimensions, but with a penalty directly proportional to the excess size.

The proposed fitness functions try to perform a trade-off between contrasting objectives, through the relative weights.

In this sense, we can say that the selected individuals are the best adapted to the (present) antenna requirements. However, a different view would be the association of each (different) requirement to a different fitness, thus leading to a multi-objective design.

In fact, generic evolutionary algorithms, like SED, PSO, DE, GA are a very powerful tool for solving difficult single objective problems, but they can also be applied to solving many multi-objective problems. Actually, real-world problems usually include several conflicting objectives, and a suitable trade-off must be found. An interesting topic is therefore the study of Multi-Objective optimization methods (Chen, 2009), and in solving such multi-objective problems the adopted optimization method must provide an approximation of the Pareto set such that the user can understand the trade-off between overlapped and conflicting objectives, in order to make the final decision. Usually, a decomposition method is implemented to convert a multi-objective problem into a set of mono-objective problems, and an optimal Pareto front is approximated by solving all the sub-problems together (Carvalho, 2012), and this requires insight not only of the algorithmic domain, but also knowledge of the application problem domain.

In design methods dealing with a set of individuals, like SED, such point of view could lead to better ways to explore the solution space, and is a promising direction for future investigations.

3. Results

The automated design of wire antennas using SED has been applied to several PDAs, with different maximum sizes, number of elements, and operation frequencies, and with different requirements both on Gain and input matching, always obtaining very good results.

We present here only a few examples, chosen also to show the flexibility of SED. All designed antennas have been compared with known antennas. However, since our antennas are wide-band 3D structures, it has been difficult to device a suitable comparison antenna. To get a meaningful comparison, we decided to compare our designed antennas with an antenna of comparable size.

The first presented antenna (Casula et al., 2009), shown in Fig.4a, has been obtained by constraining the evolution of each individual only in two directions (i.e. horizontally and vertically). This limitation is a hard limitation, and significantly affects the antenna performances. This compromise leads anyway to antennas easy to realize, and with good performances.

The designed antenna works at the operation frequency of 800 MHz, and the requested bandwidth is of 70 MHz (i.e. 9%, from 780 MHz to 850 MHz). The best designed antenna is represented in Fig.1a. The antenna size is $0.58\lambda_0$ x $0.67\lambda_0$ x $1.2\lambda_0$, λ_0 being the space wavelength at the operation frequency of 800 MHz, its gain is above 11.6 dB (see Fig.5) and its SWR is less than 2 in the whole bandwidth of 70 MHz (see Fig.1b). No additional matching network is therefore required.

The chosen comparison antenna has been a 4-elements dipole array, with the same H-plane size of our antenna. This array, shown in Fig.4b, is composed of 4 vertical elements, with a length of $1.2\lambda_0$ and spacing of $0.58\lambda_0$ in the H-plane and of $0.67\lambda_0$ in the E-plane, and its gain is within +/- 1 dB with respect to our antenna. The latter, therefore, uses in an effective way its size. However, it must be stressed that our antenna has a single, and well-matched, feed point, while the array needs a BFN to produce the correct feeding currents of the array elements, which have also a quite large Q. The array realization is therefore more complex.
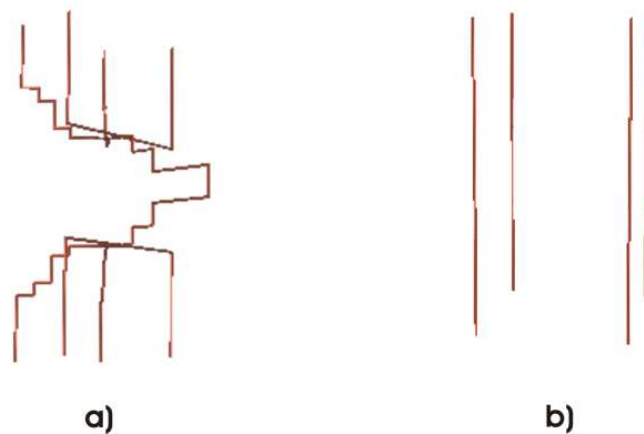

Figure 4. a) SED designed antenna; b) Reference Planar Array with 4 elements and the same size (in the H-plane).
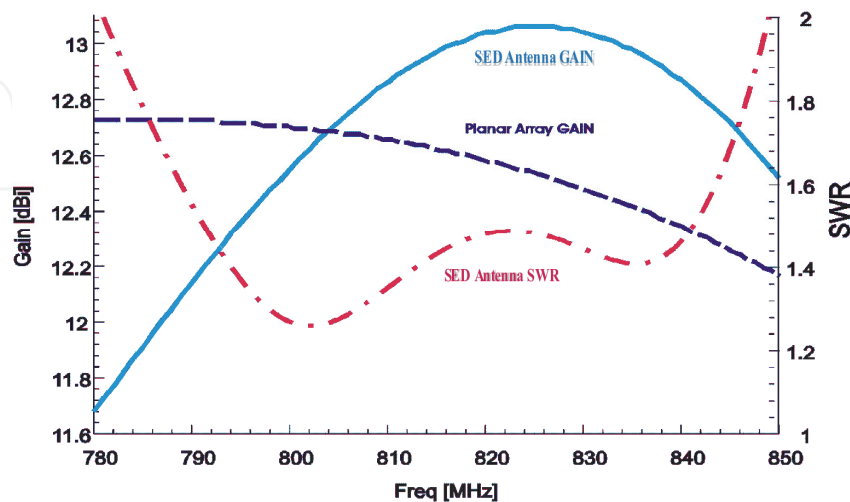

Figure 5. Gain and SWR of the GP designed antenna compared to the Gain of the reference Planar Array with 4 elements and the same size (in the H-plane).

Note that we have considered the antenna made of perfectly conducting (PEC) wires. The VSWR constraint has prevented to fall in a super-directive solution, but the robustness of a designed ideal antenna respect to conductor losses has not been checked.

The second example removes the constraints of right-angle junctions made in the first example, and will be used also to evaluate the role of the conductor losses on the SED performances. As a matter of fact, this can be easily done by designing an optimal antenna assuming PEC (Antenna 2A) and another one, assuming a finite conductivity σ (antenna 2B), in this case equal to that of pure copper ($\sigma=5.8*10^7$ S/m). Then the first antenna is analysed by including also the finite conductivity of the wires (Casula et al., 2011b).

For the 2A antenna, at the operation frequency of 500 MHz, requiring a bandwidth of 60 MHz (i.e. 12%, from 470 MHz to 530 MHz), SED designs the antenna shown in Fig.6a. The performances of the antenna 2A are shown in Table 1.

Antenna 2A has been analysed also assigning to the conductors a finite conductivity equal to the pure copper ($\sigma=5.8*10^7$ S/m). The results show a significant degradation of the antenna performances, since even using a very good conductor as material, the dissipations due to the finite conductivity are very large, making the antenna unusable (in fact NEC2 gives similar values for the SWR, but a very low efficiency). In other words, such antenna is actually close to a super-directive one.

On the other side, asking SED to design an antenna with the same specifications of antenna 2A, but assuming $\sigma=5.8*10^7$ S/m, we obtain an antenna with similar performances with respect to the 2A antenna, but with a larger size (Antenna 2B). The designed antenna is shown in Fig.6b, and, since the losses affect the antenna gain, the finite conductivity effect is already included in the fitness. The performances of the antenna 2B are shown in Table 1.

This antenna shows similar performances with respect to the antenna shown in Fig.6a, but it has a larger size ($0.1833\lambda_0^3$ with respect to $0.03\lambda_0^3$). Nevertheless, unlike the antenna shown in Fig.6a, it is feasible.

Antenna	Conductivity σ (S/m)	Design Shown	Antenna Size	Bandwidth (SWR<2)	MAX Directivity Gain (dBi)	Efficiency (%)
2A	$+\infty$ (PEC)	Fig.6a	$0.33\lambda_0$ x $0.22\lambda_0$ x $0.4\lambda_0$	70 MHz (14%)	26	100
2B	$5.8*10^7$ (pure copper)	Fig.6b	$0.47\lambda_0$ x $0.3\lambda_0$ x $1.3\lambda_0$	90 MHz (18%)	20	90.09

Table 1. Performances of the antennas 2A and 2B.

The frequency responses of both antennas are shown in Fig. 7 and 8. Also from these responses, we easily deduce that antenna 2A (designed and analysed using PEC) is almost superdirective.

The presented results show that the introduction of a finite value of metal conductivity allows to obtain antennas with similar performances with respect to the antennas designed

with perfect conductors, but with a larger size. On the other hand, antennas designed assuming perfect conductors are characterized by collected and closer branches and tend to be super-directive.
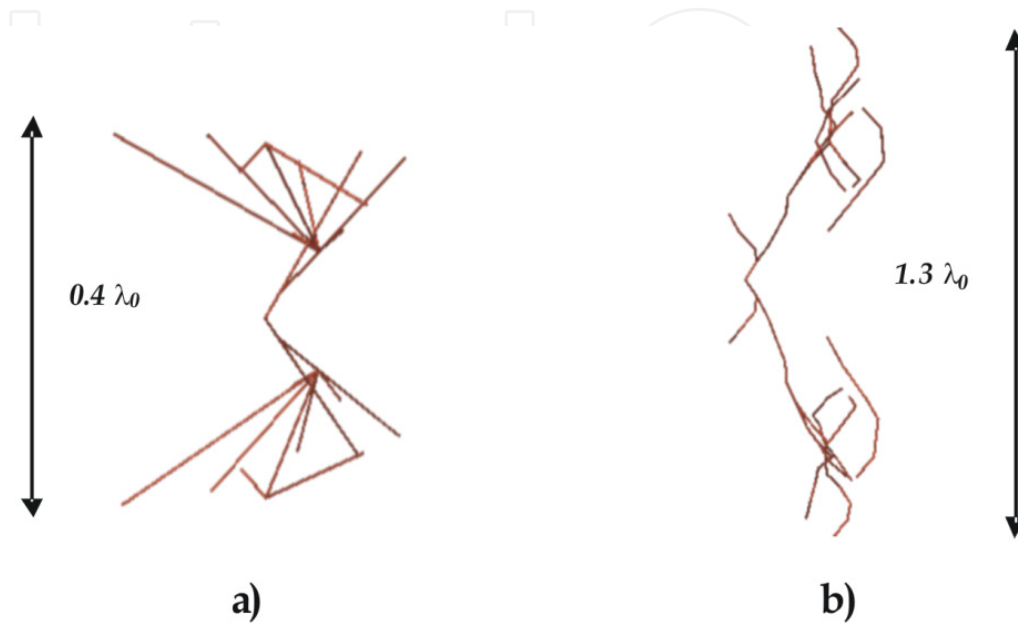

Figure 6. a) Antenna 2A, designed using perfect conductors; b) Antenna 2B, designed using finite metal conductivity.
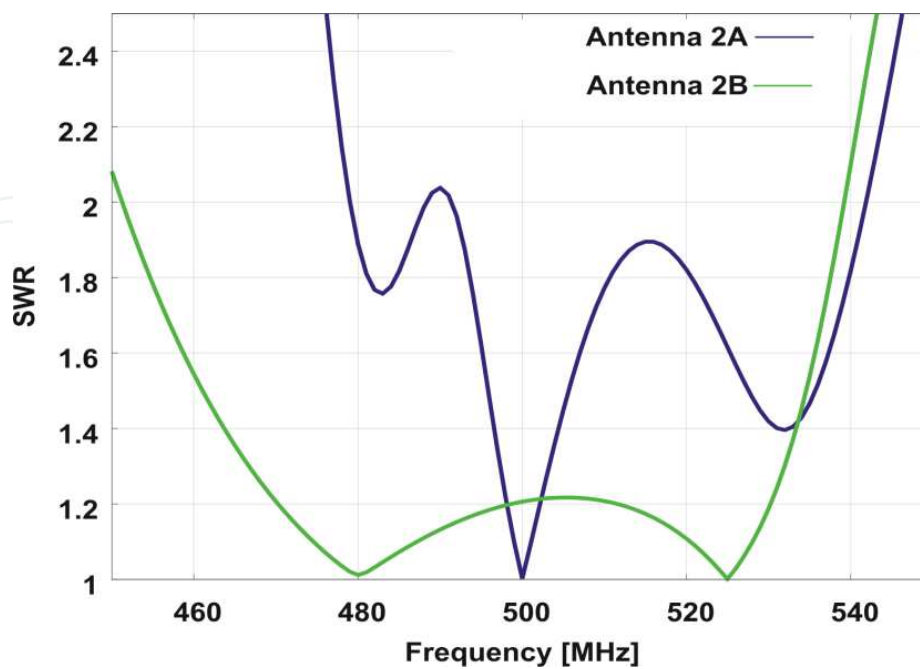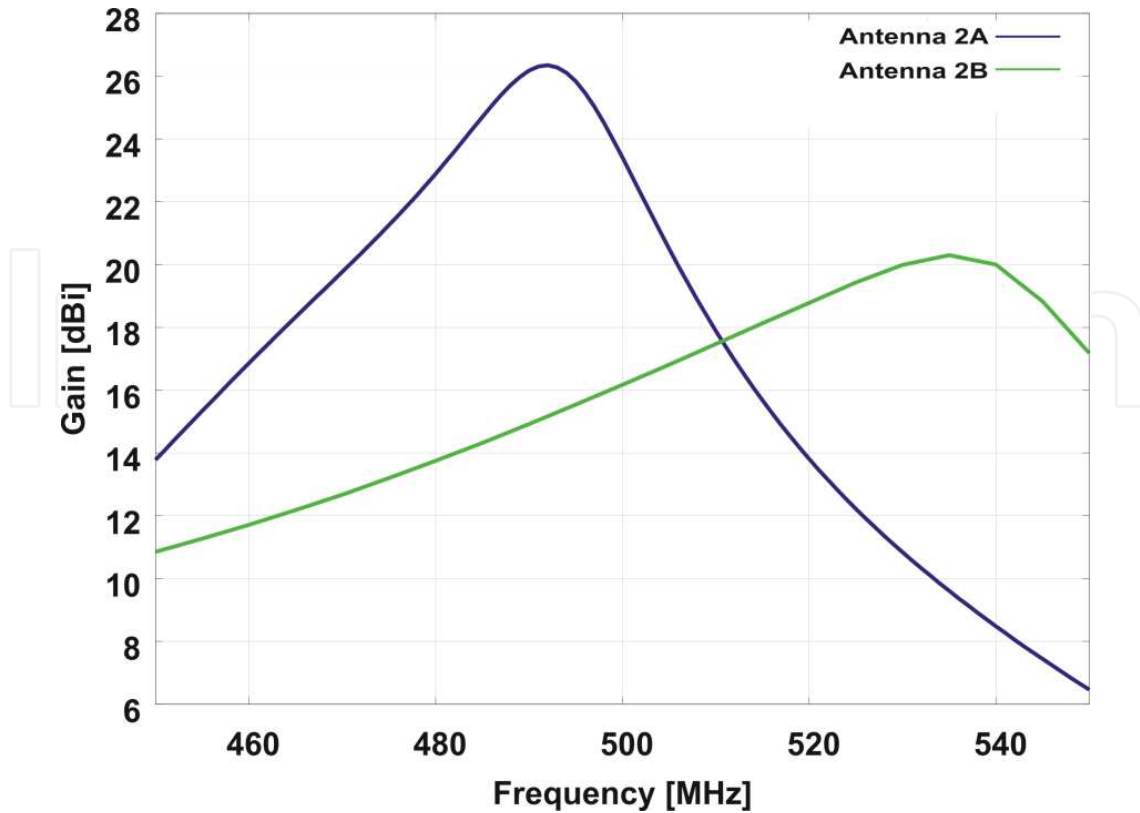

Figure 7. SWR of the antennas 2A and 2B.

Figure 8. Gain of the antennas 2A and 2B.

Material	Conductivity σ (S/m)	Efficiency (%)	Max Directivity Gain (dB)
PEC	+∞	100	20.35
Copper	$5.8*10^7$	90.09	20.3
Aluminium	$3.77*10^7$	87.71	20.29
Stainless Steel	$0.139*10^7$	34.84	20.01

Table 2. Performances of the antenna designed using pure copper (shown in Fig.6b) for different values of conductivity.

In Table 2, the antenna shown in Fig.6b, designed supposing the metal to be copper, has been analysed for different values of conductivity. While the maximum directivity is almost constant with respect to σ, the efficiency rapidly decreases. It is therefore required to take into account in SED the actual conductivity of the antenna material, but, doing so, the designed antennas will show similar performances to the antenna designed using copper, with an acceptable value for the efficiency.

The last presented antenna (Casula et al., 2011a) is a broadband parasitic wire array for VHF-UHF bands with a significant gain, showing significant improvements over existing solutions (Yagi and LPDA) for the same frequency bands. In order to fulfil these strict requirements, we had to devise a quite complicate fitness function, composed by several secondary objectives overlapped to the main goal; these objectives are expressed by appropriate weights modelling trade-offs between different goals. These relative weights have been modelled by linear relations to avoid discontinuities and thus reducing the

probability of local maxima of the fitness, which trap the evolution process. The robustness respect to realization errors is also evaluated and taken into account in the fitness.

We choose to maximize gain as the main goal of the fitness. Since we want to maximize the end-fire gain, the radiation pattern has been divided into 4 regions:

1. The endfire direction:

    $\theta = 90°;\ \varphi = 0°$

2. The back direction:

    $\theta = 90°;\ \varphi = 180°$

3. The FRONT region:

    $|\theta| > 90°+2\Delta\theta;\ 0° +2\Delta\varphi < \varphi \le 90°$

    (where $\Delta\vartheta$ and $\Delta\varphi$ take into account the desired main lobe amplitude)

4. The REAR region:

    $0° \le |\theta| \le 180°;\ 90° \le |\varphi| \le 180°;$

Our goal is the maximization of the gain in the region 1 while minimizing the gains in the other 3 regions, with all the gains expressed in dB. Since we want to optimize the antenna in a certain frequency bandwidth, we start computing a suitable weighted average gain G_{AW1} on region 1:

$$G_{AW1} = \frac{1}{N_F}\sum_{i=1}^{N_F} w_i \cdot G_{Ei} \qquad (3)$$

wherein the average is taken over the N_F frequency points, spanning the whole bandwidth of interest. In (3.1) G_{Ei} is the endfire gain and w_i depends on the input impedance of the PDA:

$$w_i = \begin{cases} 0.2 & \text{If } [(Re\,(ZIN) < 35\ \Omega)\ or\ (Re\,(ZIN) > 400\ \Omega)] \\ \alpha_i & \\ 1 & \text{If }\ \ [(35\Omega \le Re(ZIN) \le 400\ \Omega)]\ \ and\ [(Im(ZIN) > Re\,(ZIN))] \end{cases}$$

α_i is a weight proportional to the difference between the imaginary part $X_{IN}{}^A$ and the real part $R_{IN}{}^A$ of the array input impedance.

The average gains over all other regions, namely G_{BGR} in the back direction, G_{FGR} in the front region and G_{RGR} in the rear region, are then computed. An "effective" endfire gain G_{AW} is then obtained properly weighting each gain:

$$G_{AW} = G_{AW1} \cdot \frac{1}{1 + \alpha_{BGR} * G_{BGR}}$$
$$\cdot \frac{1}{1 + \alpha_{FGR} * G_{FGR}} \cdot \frac{1}{1 + \alpha_{RGR} * G_{RGR}} \tag{4}$$

The weigths α_{BGR}, α_{FGR} and α_{RGR} 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. In our case, we obtained the following values: α_{BGR}=0.08, α_{FGR}=0.14 and α_{RGR}=0.02.

In order to design a wideband antenna, we must add some parameters taking into account the antenna input matching, and therefore we introduced suitable weights connected to the antenna input impedance. Holding gain weights fixed, the other parameters concerning input matching are added one by one choosing each weight through a further local tuning.

The G_{AW} is therefore furthermore modified taking into account:

a.   The values of $R_{IN}{}^A$, $X_{IN}{}^A$ (averaged over the BW), and their normalized variance;

b.   The SWR over all the required bandwidth

according to the following guidelines:

1.   A step is introduced, with a weight α_{XR}=50 if $|X_{IN}{}^A| > R_{IN}{}^A$, and α_{XR}=0 otherwise, to boost up structures with $R_{IN}{}^A > |X_{IN}{}^A|$;
2.   A weight α_{XX}=0.03 is introduced, related to $|X_{IN}{}^A|$, forcing the evolution process to structures with an $|X_{IN}{}^A|$ as small as possible;
3.   A weight α_{RX}=0.1 is introduced, related to $R_{IN}{}^A - |X_{IN}{}^A|$, to advantage structures with a low Q factor;
4.   A weight α_{RR}=0.055 is introduced, related to $R_{IN}{}^A$, to boost up structures with a high real part of the input impedance (as long as it is lower than 300 Ω);
5.   Weights $\alpha_{VR}=\alpha_{VX}$=0.015 are introduced, inversely related to the normalized variance of $R_{IN}{}^A$ and $X_{IN}{}^A$, to advantage structures with a regular impedance behaviour;
6.   A sequence of small steps, related to the SWR (with a weight α_{SWR} between 30 for an SWR>20 and 0.005 for an SWR<4), is introduced to first boost up and then hold the evolution in areas of the evolution space with good SWR values.

At this point we have a modified average gain G_M, expressed by:

$$G_M = G_{AW} \cdot \left(\frac{1}{1 + \alpha_{XR}} \right) \cdot \left(\frac{1}{1 + \alpha_{XX} |X_{IN}^A|} \right) \tag{5}$$

$$\cdot \left(\frac{1}{1 + \alpha_{RX} \dfrac{R_{IN}^A - |X_{IN}^A|}{R_{IN}^A}} \right) \cdot \left(\frac{1}{1 + \alpha_{RR} * \dfrac{|R_{IN}^A - 300|}{R_{IN}^A}} \right) \cdot \left(\frac{1}{1 + \alpha_{VX} \cdot \sigma_R^2} \right) \cdot \left(\frac{1}{1 + \alpha_{VR} \cdot \sigma_X^2} \right) \cdot \left(\frac{1}{1 + \alpha_{SWR}} \right)$$

where σ_R^2 and σ_X^2 are the normalized variance of R_{IN}^A and of X_{IN}^A, respectively.

The difference G_R-G_M (where G_R is a suitably high gain, needed only to work with positive fitness values) is then modulated taking into account both the Q factor (obtained as the ratio between the imaginary part and the real part of the array input impedance at the central frequency) and the structure size to get a particular fitness f_1. The individual generated by the genetic process associated to a fitness f_1 higher or very close to the best fitness obtained as yet, are then perturbed (assigning random relocations to array elements) and analysed to assess their robustness respect to random modification of the structure. Two different random perturbed antennas are considered for each individual, and the final fitness f_2 is the partial fitness f_1 averaged over all the initial and perturbed configurations. This random relocation allows getting robust structures respect to both constructive errors and bad weather conditions (for example movements due to wind effect). On the other hand, this robustness test is quite time-consuming. Therefore it is performed only on antennas already showing good performances. The final population is graded according to their f_2 value.

The antenna designed using the fitness expressed by (3.3) is a PDA with 20 elements: 1 reflector, 1 driven element and 18 directors. The operation frequency is 500 MHz, and the requested bandwidth is of 70 MHz (i.e. 14%, from 475 MHz to 545 MHz). The best antenna is represented in Fig.9, and its shape is typical of all antennas designed using our SED optimization technique. The antenna size is very small, since it fits in a box large 1.72 λ_0 x 0.03 λ_0 x 0.57 λ_0, being λ_0 the space wavelength at the operation frequency of 500 MHz. Its SWR is less than 2 in the whole bandwidth of 70 MHz, and its gain is above 18 dB.
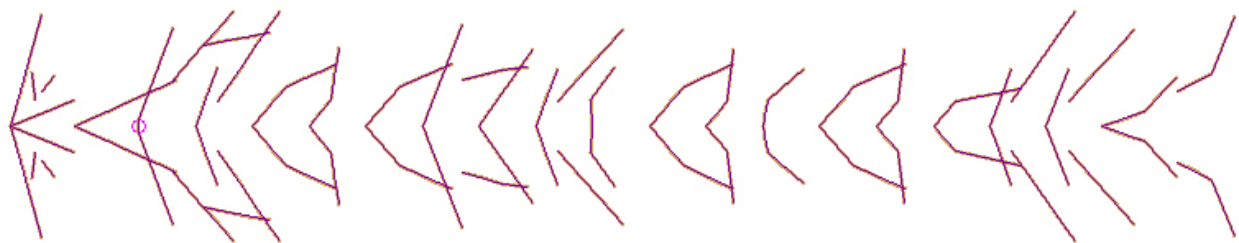

Figure 9. Designed Antenna Structure.

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.10, and it appears that 300 generations are enough to reach convergence.
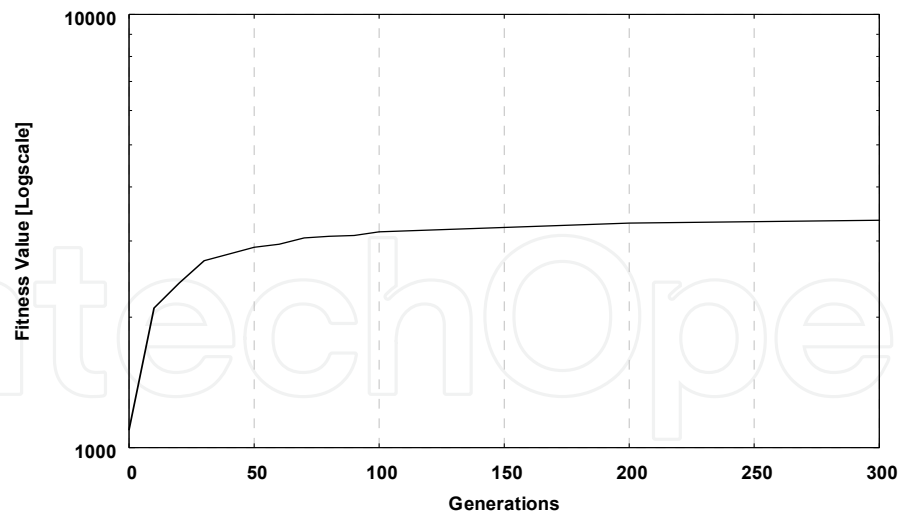
Figure 10. Plot of convergence of the designed antenna in Fig.9.

To assess the performances of our designed PDA, we need a comparison antenna. The best candidate is an existing Yagi but its choice is by no means obvious. Since, for a parasitic antenna, an increase in the number of elements adds little to the antenna complexity, we think that the most significant comparison is a gain comparison with a standard Yagi with the same size of our PDA (about $1.72\lambda_0$ in the endfire direction), and a size comparison with an Yagi with the same number of elements as our PDA. The first standard Yagi is composed of only 9 elements, and its gain and SWR, compared to our optimized PDA, are shown in Fig. 11. The standard Yagi bandwidth (SWR<2) is about 35 MHz (7% compared to 14%) with a gain between 12 and 13 dB, i.e. at least 5 dB less than ours, over the whole bandwidth.

A standard Yagi antenna with the same number of elements than our PDA, i.e., 20 has been selected for the second comparison. Though this antenna is very large (its size is about $6\lambda_0$x $0.5\lambda_0$), it has (see Fig.12) a quite narrow bandwidth (its gain is above 15 dB in a bandwidth smaller than 10%, and even its SWR is less than 2 in a bandwidth of about 9%) if compared with our PDA.

The PDA antenna of Fig. 11 and 12 has been designed choosing a fitness which pushes individuals toward higher Gain giving a smaller importance to input matching. As a further example, it is possible, by suitably choosing the fitness weights, to design a PDA antenna which favours individuals with better input matching. The performances of such an antenna are shown in Fig.13. The bandwidth (with SWR<2) has increased to 150 MHZ (30%), and its gain is only a few dB less than the first optimized PDA antenna. It is important to highlight that the size of the antenna with a larger input bandwidth is the same of the antenna with a higher gain.

In Fig. 14 we show also the F/B ratio of both the PDA designed antennas, which is very close also to standard Yagis' F/B. This comparison shows that, though the PDA we have designed appear to be more difficult to realize than a standard Yagi, they allow significantly better performances in a larger bandwidth, both on input matching, gain and F/B ratio. Furthermore, it is significantly smaller than standard Yagis.
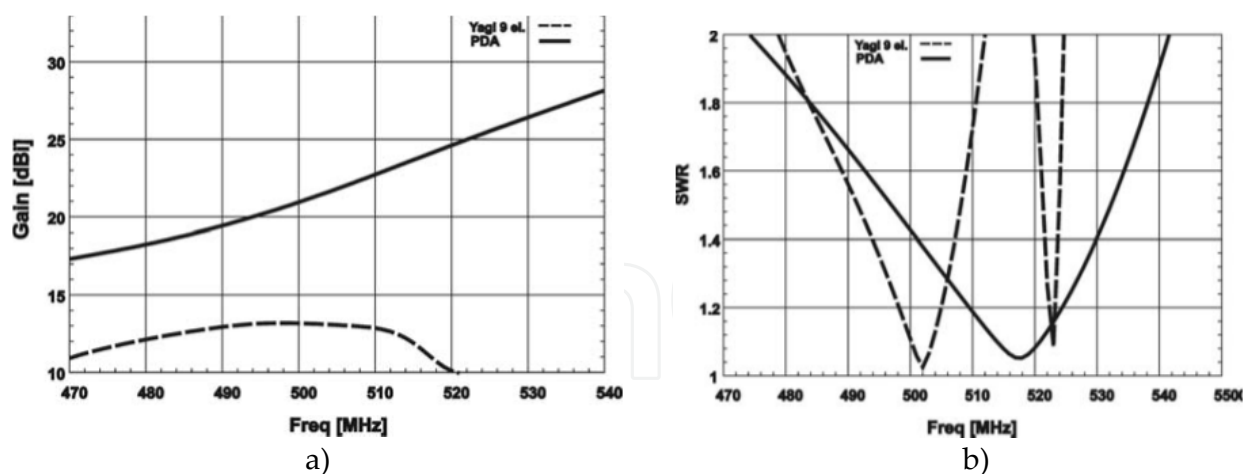
Figure 11. (a) Gain and (b) SWR comparison between the PDA Designed Antenna and a standard Yagi with the same size (and 9 elements); (b): SWR comparison between the PDA Designed Antenna and a standard Yagi with the same size (and 9 elements).
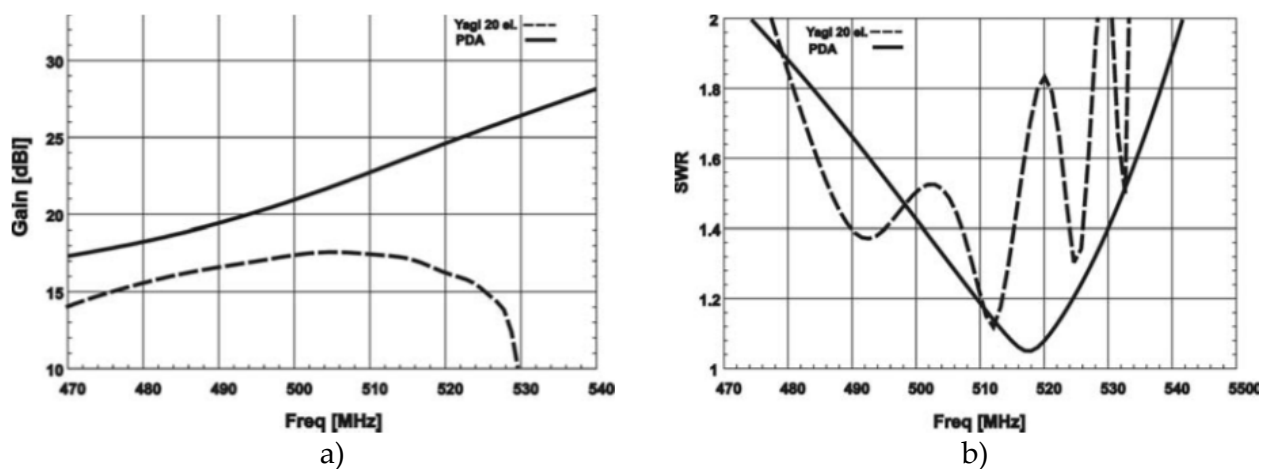

Figure 12. (a) Gain and (b) SWR comparison between the PDA Designed Antenna and a standard Yagi with the same number of elements, 20, and a far larger size (6 λ_0 vs 1.72 λ_0).
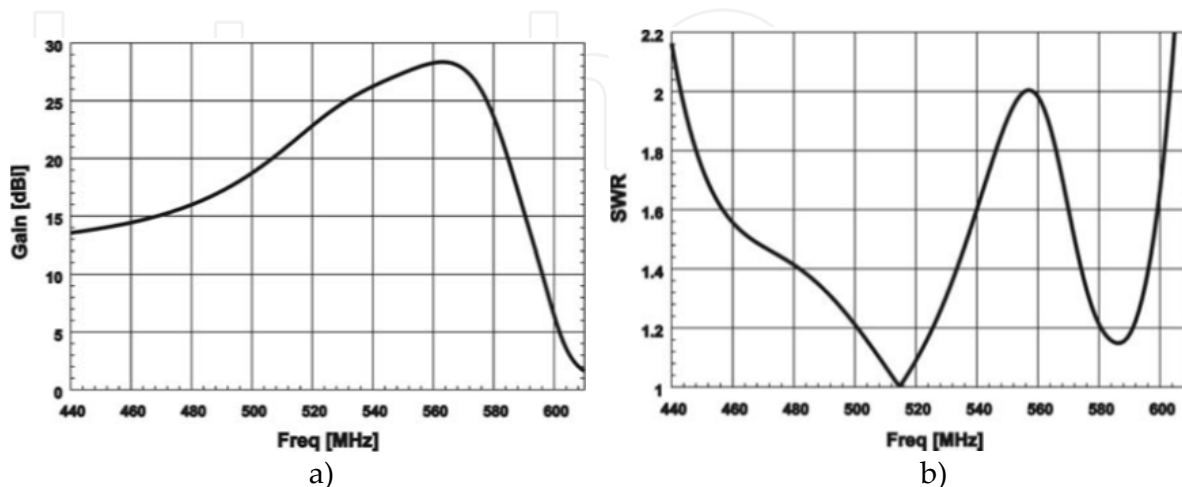

Figure 13. (a) Gain and (b) SWR of the PDA Designed Antenna with a fitness pushing towards a larger SWR bandwidth
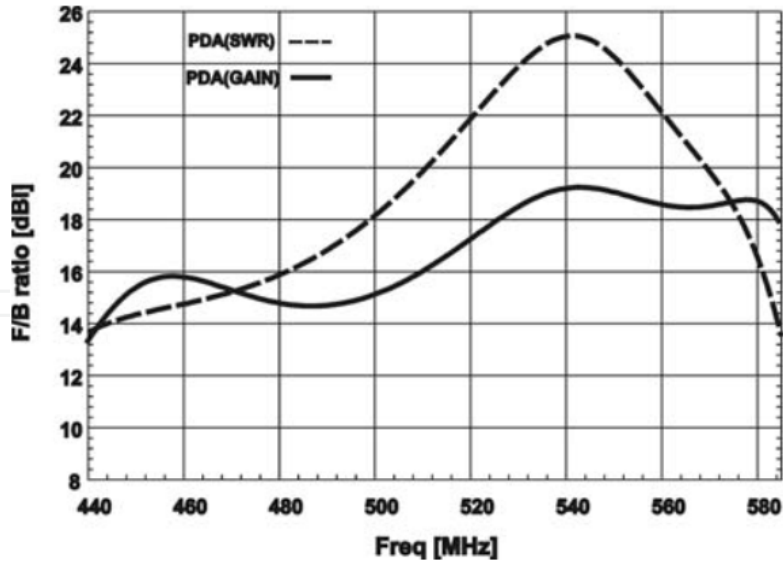
Figure 14. F/B ratio comparison between the PDA Designed Antenna with a fitness pushing towards a larger Gain bandwidth and one towards a larger SWR bandwidth.

In order to demonstrate that the inclusion of the antenna robustness into the fitness using our simple device works well, we have tested a hundred random perturbations of the reference antenna of Fig.9. These have been obtained perturbing the ends of each arm of the antenna with a random value between -2 and 2 mm. The standard deviations of the SWR and gain are shown in Fig.15 and are expressed in percentage with respect to the values of the unperturbed antenna shown in Fig.9. Despite of such huge perturbation, the designed PDA is so robust that the behaviour of all perturbed antennas is essentially the same of the unperturbed one. Therefore, despite of its (relative) low computational cost, the approach we have devised to include robustness in the fitness allows to design antennas which are very robust respect to realization errors.
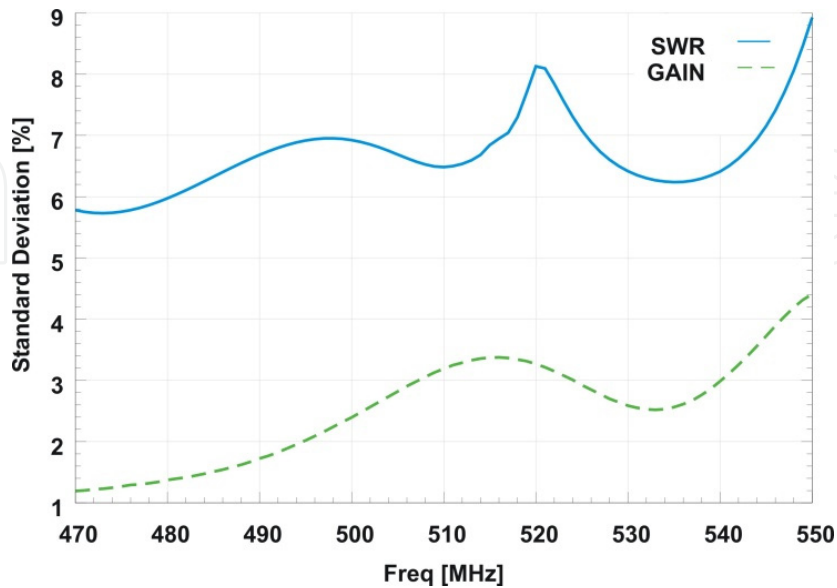

Figure 15. Standard Deviation of SWR and Gain of the PDA Designed Antenna in Fig.9, considering 100 randomly perturbed configurations.

Finally, we consider the computational issue. The computational cost of SED, like that of many other random optimization techniques, is the computational cost required to evaluate each individual. Therefore different techniques, such as SED and standard GA, can have different cost as long as they evaluate a different number of individuals, or more complex ones.

For the example presented in Fig.10, SED requires $3*10^5$ NEC evaluations of individuals. GA with comparable antenna size (such as the one described in (Jones & Joines, 1997)) requires a likely, or even larger, number of NEC evaluations. Since also the number of NEC unknown is more or less the same for both approaches, depending essentially on the antenna size, we can conclude that SED has a computational cost comparable, or slightly larger than standard GA. On the other hand, SED allows to explore a far larger solution space. If we consider as computational effectiveness of a design approach the size of the solution space explored for a given computational cost, we can conclude that SED is computationally more effective and with more performing antennas than GA.

A comparison between SED and other algorithms like Particle Swarm Optimization and Differential Evolution, shows that both the computational cost and the complexity are of the same order of magnitude, also in these cases. But, again, the performances obtained by them are not as good as the ones obtained using SED.

In Table 3, we show the results obtained by our PDA, designed using SED, compared with the results obtained by:

(Baskar et al., 2005), who used PSO to optimize the element spacing and lengths of a Yagi–Uda antenna;

(Goudos et al., 2010) who used Generalized Differential Evolution applied to Yagi-Uda antenna design;

(Li, 2007), who used Differential Evolution to optimize the geometric parameters of Yagi-Uda antennas;

(Yan et al., 2010), who designed a wide-band Yagi-Uda antenna with X-shape driven dipoles and parasitic elements using differential evolution algorithm, obtaining a bandwidth of 20%.

	N° Elements	Size	Gain at center frequency (dB)	VSWR at center frequency	Bandwidth (VSWR<2)
Baskar 2005 (PSO)	15	0.239×4.115 λ_0	16.4	1.05	-
Goudos 2010 (DE)	15	0.239×4.943 λ_0	17.58	1.1	-
Yan 2010 (DE)	11	0.527×1.391 λ_0	12.5	1.8	20%
Li 2007 (DE)	15	0.459×4.664 λ_0	16.59	1.085	-
SED	20	0.57×1.72 λ_0	21	1.4	30%

Table 3. Comparison between the performances reached by SED, PSO and DE in the design of a Parasitic Wire Dipole Array.

Both (Baskar et al., 2005), (Goudos et al., 2010) and (Li, 2007) decide to perform the optimization only at the center frequency, and this is a simpler task and can lead to better results than an optimization over the whole antenna bandwidth, which is the choice we made in our SED design. Nonetheless, the results obtained by SED are better than the ones obtained by PSO and DE even at the center frequency.

In fact we are able to get a wideband antenna with a very high gain, i.e. we both maximize antenna gain and minimize SWR and antenna size within the whole bandwidth (which is a wide bandwidth, equal to 30%).

Therefore, SED can lead to better results if compared with PSO and DE, both in terms of performances and of overall size. This is probably due to the fact that the solution space of SED is larger than the corresponding solution spaces of PSO and DE, and hence a proper choice of the fitness function can push the evolution process to more performing antennas.

4. Conclusion

In this chapter a new design technique, namely the Structure-based Evolutionary Design (SED) has been described in detail. This is a new global random search method based on the evolutionary programming concept. The proposed technique has been compared with the standard genetic algorithms (GA), a widely used design technique, showing the numerous advantages of our approach with respect to standard ones. Its main advantage is the ability to explore a far larger solution space than standard optimization algorithms. Moreover, SED assumes no "a priori" structure, but it builds up the structure of the individuals as the procedure evolves, being able to determine both the structure shape and dimensions as an outcome of the procedure. Inclusion of input matching requirements prevents from ill-posedness, a danger always present when the solution space is so large. The described procedure has been used to design wire antennas, and several examples are presented, showing very good results. The goal of the design process is to develop wire antennas fulfilling the desired requirements for both Gain and VSWR in a frequency band as wide as possible, and with the smallest size. For each set of requirements, a suitable fitness function must be derived, and some suggestions are given to choose the best fitness for the problem at hand. The results obtained with SED are finally compared with other global search algorithms showing that both the computational cost and the complexity are of the same order of magnitude, but the performances obtained by SED are significantly higher.

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