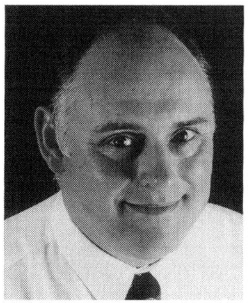

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Foreword by the Editor

Multi-band antennas using loading were widely used in the days when HF was the only long-distance radio communication option. For military use and some other specialized applications, HF remains an important band, but multi-band and broadband systems are now of great interest for general mobile communications systems. With broadband applications, the design of the loading network rapidly becomes a very complex optimization problem. This month's contribution describes a genetic-algorithm-driven optimization tool that interfaces to the classic *NEC2* code, simplifying the design of broadband loaded structures. A classroom version of the code is available from the authors, whom we thank for their submission.

Antenna optimization has been an increasingly important application of EM simulation tools, and we have featured articles on this topic before in the column (see, for instance, [1]).

1. E. A. Jones, E. A. and W. T. Joines, "Genetic Design of Linear Antenna Arrays," *IEEE Antennas and Propagation Magazine*, **42**, 3, June 2000, pp. 92-100.

BLADE: A Broadband Loaded Antenna DEsigner

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Abstract

This paper presents a software tool for designing loaded antennas equipped with matching networks for broadband or multi-band applications. The software implements a genetic algorithm to automatically optimize the large set of parameters involved in the design procedure. The graphical interface has been designed in *MATLAB*® to be used together with the popular *NEC* solver. However, the possibility of handling reduced-port models of the antenna permits the use of any kind of numerical solver for the electromagnetic analysis. Some examples of broadband and multi-band antenna designs in a complex environment demonstrate the potential of the tool.

Keywords: Antennas; multifrequency antennas; wire antennas; loaded antennas; RF traps; bandstop filters; genetic algorithms

1. Introduction

Recent advances in mobile communication systems are generating a great deal of interest in multi-band and broadband antennas. The advent of the software-defined radio (SDR) technology [1] and the modern employment of spread-spectrum techniques, such as frequency hopping, are only two examples of the growing demand for simultaneous operation over multiple channels. Electrically loaded wire antennas, widely discussed in the literature, seem to be an interesting solution for broadband transmitters and receivers. A loaded antenna can be obtained by placing lumped or distributed impedances – generally denoted as RF traps (parallel LC circuits [2], transmission-line stubs [3, 4], dielectric and magnetic beads [5]) – on simple wire radiators, in order to properly modify the current distribution along the conductors with the purpose of enhancing the desired antenna performance. Together with the antenna's loading, the broad-banding strategy can also provide an "on-body" matching network [6, 7]. Because of the multiplicity of parameters relating to the broadband antenna system, a powerful design procedure for selecting them can be based on a genetic-algorithm (GA) driven optimization [7-9]. In [10], multi-band loaded monopoles for vehicular and ground-based applications were designed with the aid of a genetic algorithm. Some examples of lumped impedances on monopoles operating in the VHF/UHF band are shown in [11].

Antenna loading is even attractive for antenna miniaturization purposes, within the theoretical limitations of small antennas [12, 13]. In [10], it was demonstrated that by using distributed impedances, more than a 30% reduction in monopole length can be achieved, preserving nearly the same radiation characteristics. The problem of antenna size is a critical issue in the HF band, particularly when the available space for an antenna installation is limited, such as in naval scenarios [14, 15]. In [16], a compact multi-function antenna for broadband HF naval communications was designed by loading the conductors of a properly chosen geometry with lumped circuits. Such a radiator could reduce the multiplicity of antennas onboard the ship, minimizing unwanted coupling and also the overall occupied space [15]. Finally, the design of loaded antennas permits flexibility when the traps are realized using tunable components. In this case, changes in the electromagnetic environment surrounding the antenna can be compensated for by a re-optimization of the electrical values of the loads, preserving acceptable performance, as discussed in the last section of [17].

In the last few years, some popular electromagnetic solvers, such as the public-domain *4NEC2* [18] or the commercial *SUPERNEC®* [19], have been equipped with genetic-algorithm-based optimizers conceived for general-purpose applications. They offer moderate customization of the whole optimization setup, including the expression of the objective function. However, they require intensive and repeated full-wave electromagnetic analysis, and therefore they are not particularly suited to broadband optimizations, due to the large running times involved.

This work presents a versatile electromagnetic tool especially dedicated to the combined design of loaded antennas equipped with a matching network. It implements a genetic-algorithm optimizer to select the great number of parameters relating to the traps and to the matching network, and uses a reduced antenna port model to quickly evaluate the system's performance. The tool allows the user to rationalize the whole antenna design, and to efficiently handle all the available degrees of freedom. Particular care has been given to setting the range of the electrical components to be optimized, so that the design is practically feasible. Moreover, the user can easily customize the objective function containing the antenna requirements, and can examine the entire optimization process by means of a monitor module. The tool, hereafter referred to as *BLADE*, can be directly linked to the *NEC2* code [20]. It can also handle a reduced-antenna-port model obtained by other means.

The paper is organized as follows. Section 2 introduces the formulation of the design problem, in which the concept of a trap, the broad-banding strategy, and the optimization procedure using a genetic algorithm are reviewed. The optimizer architecture is described in Section 3. Some application examples are given in Section 4.

2. Formulation

2.1 The Trap Concept

The trap is a circuit that anti-resonates at a given frequency, with an infinite impedance. The most common trap, the construction of which is described in [2], is represented by the parallel *LC* circuit that anti-resonates at $f = 1/2\pi\sqrt{LC}$. By properly integrating one or more of these traps into a wire antenna, it is possible to strongly modify its electromagnetic features. Figure 1 reprises the basic idea of the trap-loaded antenna. A quarter-wave monopole of length l, having the first resonance at f_0, exhibits a rather high input resistance at the second resonance, $2f_0$. If a parallel *LC* trap (designed to anti-resonate at $2f_0$) is placed in the middle of the monopole, the current distribution at f_0 is not strongly perturbed, because of the low impedance of the trap. Instead, at $2f_0$ the current in the upper part of the antenna is nullified, and it radiates as a quarter-wave monopole of length $l/2$, even at this frequency. In this case, the use of a single trap has led to a dual-band antenna that can be considered to be the combination of two quarter-wave monopoles of different sizes.

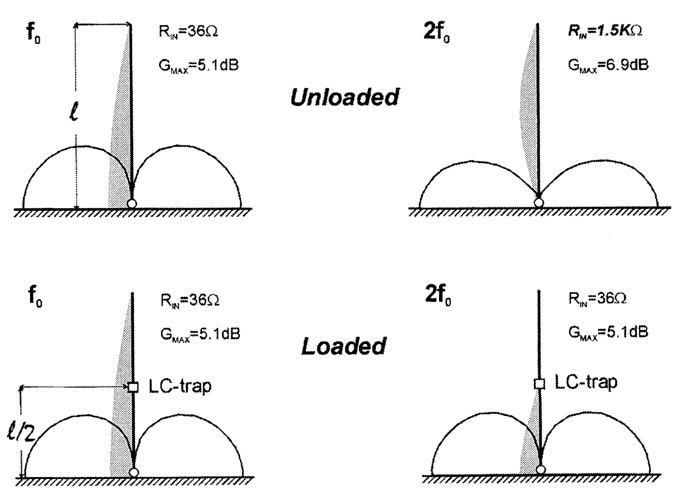

Figure 1. The concept of a trap. For the unloaded case, the current amplitude (shadowed region) and the radiation pattern of a conventional monopole at the first and second resonance are shown. For the loaded case, the features of a trap-loaded monopole that exhibits the same radiation pattern and impedance at the two frequencies are shown.

2.2 Broad-Banding Strategy

The integration of one or more loading circuits along the antenna wires permits dynamic control (with regard to frequency) of the current distribution and, consequently, of the input impedance, the radiation pattern, and the efficiency of the antenna. The traps are generally used to improve the antenna's bandwidth, or to achieve multi-band features. Although the parallel *LC* circuit is the most common kind of trap, other topologies, including lossy circuits, can be used, too. For example, parallel inductor-resistor circuits were proposed in [11]. The optimization tool proposed in this paper provides three different topologies of load: the parallel and series *LC* circuits, which respectively act as an open- and a short-circuit at their resonant frequency (Figure 2), and as reactive loads elsewhere; and isolated resistors, useful for achieving a frequency-dependent attenuator distributed along the length of antenna. By the series connection of these basic circuits, even more complex topologies can be realized. These new composite loads can exhibit multiple resonances (see Figure 2, where the series connection of a parallel and a series *LC* circuit is considered), adding further degrees of freedom in the synthesis procedure. Different kinds of traps, involving transmission-line stubs, were considered in [3, 4]. These devices require additional wire segments to be added to the original antenna and possess an infinite set of resonances, defined by a small set of degrees of freedom. The tool includes only lumped traps, since their input impedance can be better controlled over a wide band, and because the optimization of the transmission-line stubs cannot be performed by the faster antenna models that will be discussed later on. Besides the antenna loading, a matching network [6, 7] can also be introduced between the loaded antenna and the transmitter, in order to further reduce the VSWR. The general components of a matching network are a lossless ladder network, an impedance transformer, and a frequency-independent attenuator (Figure 3).

2.3 GA Design Optimization

Designing a broadband/multi-band loaded antenna system to satisfy certain requirements generally entails the solution of a non-

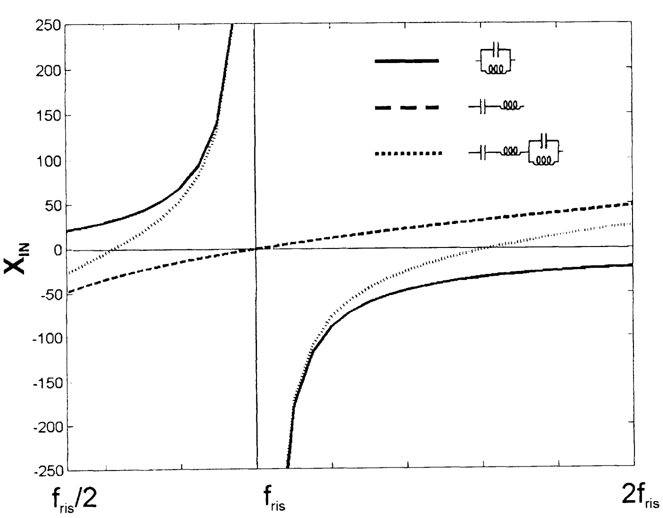

Figure 2. The input reactance of simple and combined loading circuits.

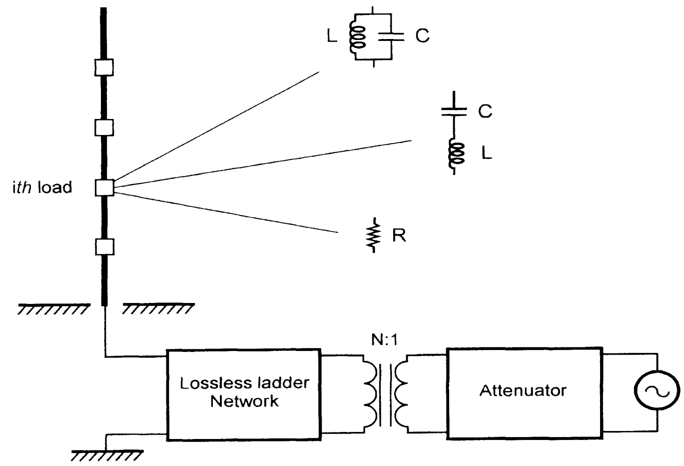

Figure 3. The general composition of a broadband antenna system.

linear optimization problem. The optimizer has to determine a large set of optimal parameters, e.g., the locations and the electrical values of the loads, and the components of the matching network. For instance, the design of an antenna loaded with four parallel *LC* traps and connected to a third-order ladder network involves the simultaneous optimization of 15 parameters. An efficient and commonly used procedure when a great number of unknowns has to be determined can be based on the genetic-algorithm concept [8]. The solution of the optimization problem involves a search for the maximum (or the minimum) of a judiciously selected objective function (or fitness function) over the space of design parameters. The objective function primarily depends on the antenna requirements, and it is typically expressed in the form of a summation:

$$F = \sum_i w_i G_i . \qquad (1)$$

Each of the G_i terms reflects a desirable antenna feature that needs to be improved, and w_i is the related weighing coefficient. The choice of the objective function reflects on the final result of the entire optimization, and therefore all the parameters included have to be carefully selected, with particular attention to the weighing coefficients. The expression of the objective function often becomes definitive only after some attempts involving adjusting the weighting coefficients at the end of each optimization, and consequently this is the most critical part of the genetic algorithm.

The tool presented in this paper directly performs the electromagnetic analysis of loaded antennas using the Method of Moments [21] by calling the *NEC2* code. The optimization procedure in principle demands thousands of antenna analyses as the circuit parameters are changed. In order to speed up the process, it is useful to define a reduced-port model of the antenna, by solving the problem for the unloaded structure at each frequency and then storing all the inverted MoM matrices. Then, for each new set of loads, the solution can be constructed from that of the unloaded antenna by using both the Sherman-Morrison-Woodbury-based scheme [7]. Alternatively, even a simpler approach can be used. This was discussed in [9] and is implemented by the tool. It requires the inversion of small matrices of a size that only depends on the number of the loads employed.

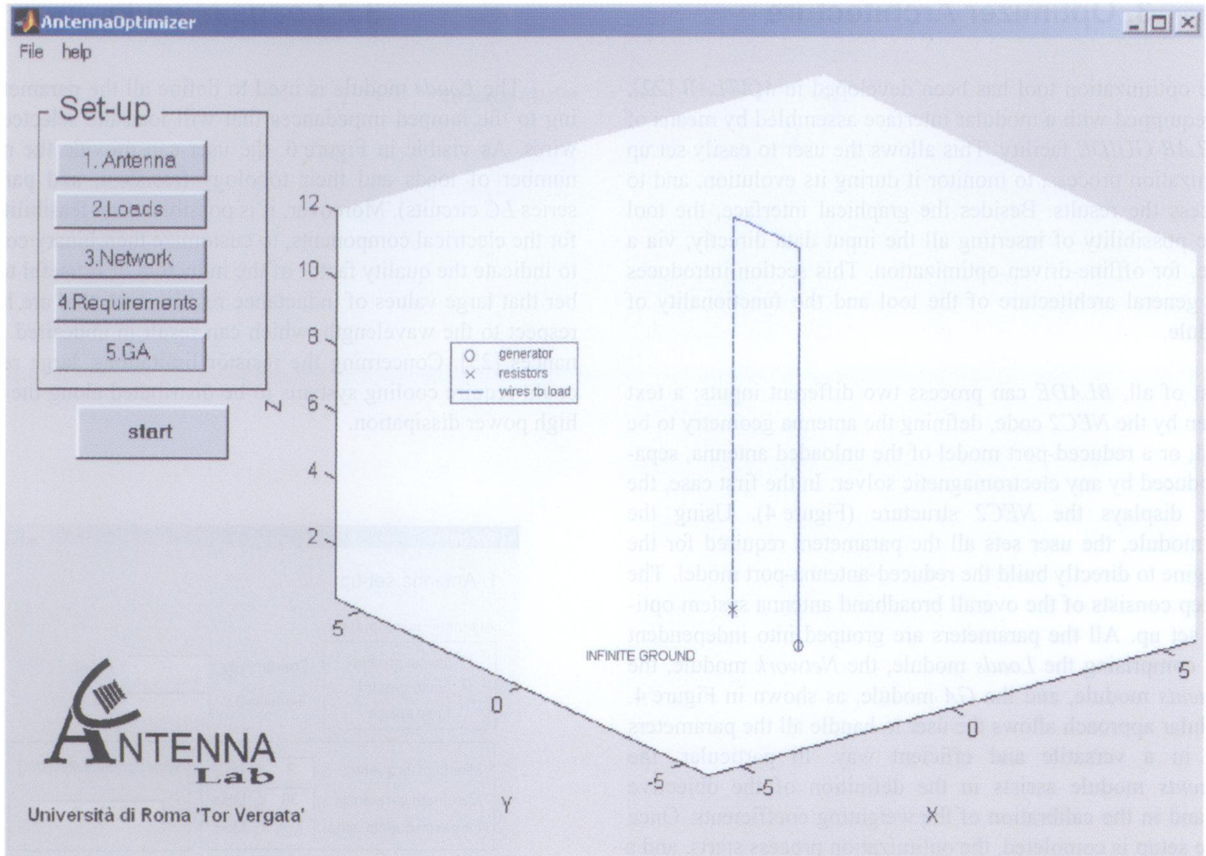

Figure 4. The optimization setup window and the geometry of an antenna to optimize. The circle is for the source position, the × indicates the constrained resistors, and the segmented wires tag the parts of the antenna that can be loaded.

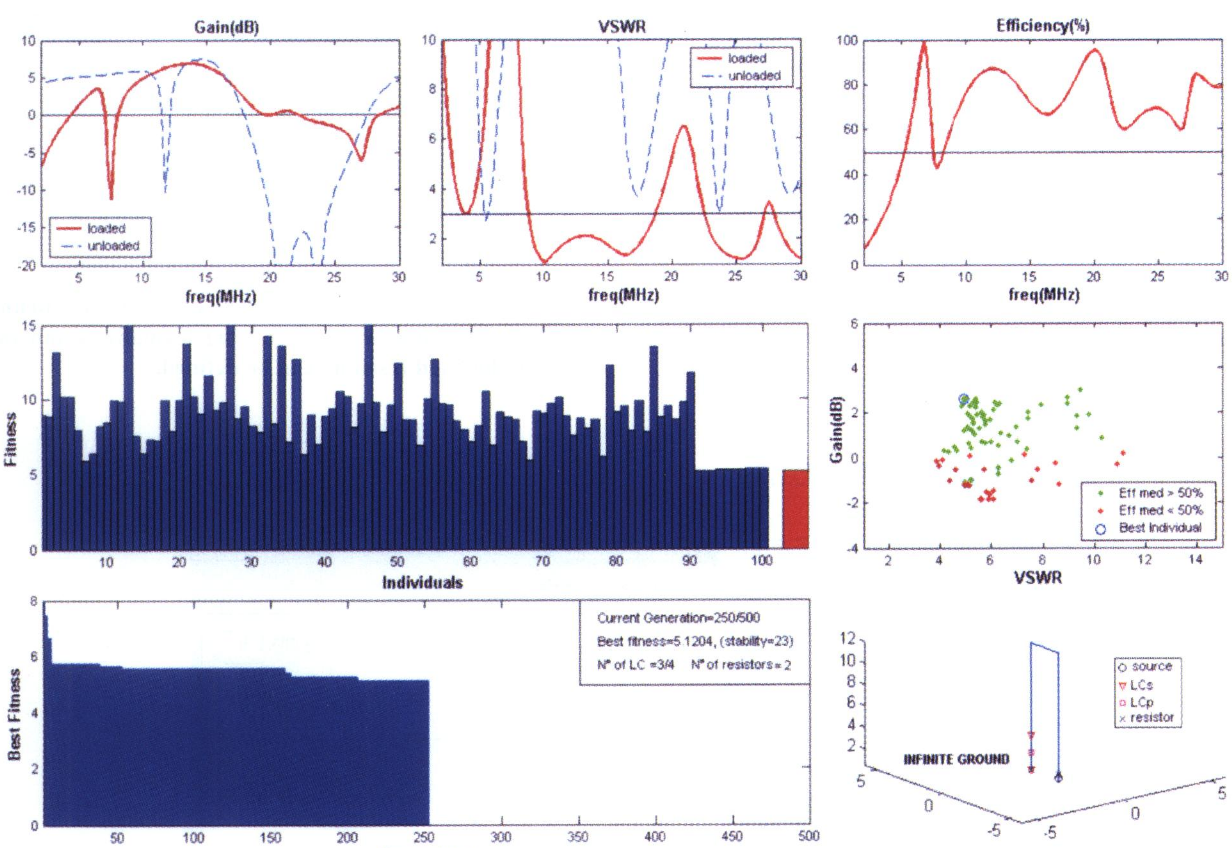

Figure 10. The *Monitor* module for controlling the evolution of the genetic algorithm.

3. Optimizer Architecture

The optimization tool has been developed in *MATLAB* [22], and it is equipped with a modular interface assembled by means of the *MATLAB GUIDE* facility. This allows the user to easily set up the optimization process, to monitor it during its evolution, and to post-process the results. Besides the graphical interface, the tool offers the possibility of inserting all the input data directly, via a script file, for offline-driven optimization. This section introduces both the general architecture of the tool and the functionality of each module.

First of all, *BLADE* can process two different inputs: a text file written by the *NEC2* code, defining the antenna geometry to be optimized; or a reduced-port model of the unloaded antenna, separately produced by any electromagnetic solver. In the first case, the optimizer displays the *NEC2* structure (Figure 4). Using the *Antenna* module, the user sets all the parameters required for the *NEC2* engine to directly build the reduced-antenna-port model. The second step consists of the overall broadband antenna system optimization set up. All the parameters are grouped into independent modules, comprising the *Loads* module, the *Network* module, the *Requirements* module, and the *GA* module, as shown in Figure 4. This modular approach allows the user to handle all the parameters involved in a versatile and efficient way. In particular, the *Requirements* module assists in the definition of the objective function and in the calibration of the weighting coefficients. Once the whole setup is completed, the optimization process starts, and a *Monitor* module permits control of the progress. The optimization results can be managed by a *Post-processing* module.

3.1 *Antenna* Module

This module is used to set all the parameters relating to the antenna (Figure 5) when the reduced-port model has to be built by *BLADE* itself. For this purpose, it is possible to explicitly indicate which parts of the antenna can potentially host the loading circuits, or it is possible to allow the whole structure to be loaded. Finally, it is possible to constrain some resistors on the antenna by specifying their locations and values. In the case of high power dissipation, e.g., in broadband HF antennas, constraining the resistors to be close to the ground plane can simplify the cooling equipment. Once all the antenna parameters have been set, Figure 4 is updated, and the generator, the resistors, the wires to load, and the antenna environment are shown.

3.2 *Loads* Module

The *Loads* module is used to define all the parameters relating to the lumped impedances that will load the selected antenna wires. As visible in Figure 6, the user can provide the maximum number of loads and their topology (resistors, and parallel and series *LC* circuits). Moreover, it is possible to set feasibility bounds for the electrical components, to customize their binary coding, and to indicate the quality factor of the inductors. It is useful to remember that large values of inductance require coils that are large with respect to the wavelength, which can result in undesired self-resonances [23]. Concerning the resistor limitations, large resistances could require cooling systems to be distributed along the wires for high power dissipation.

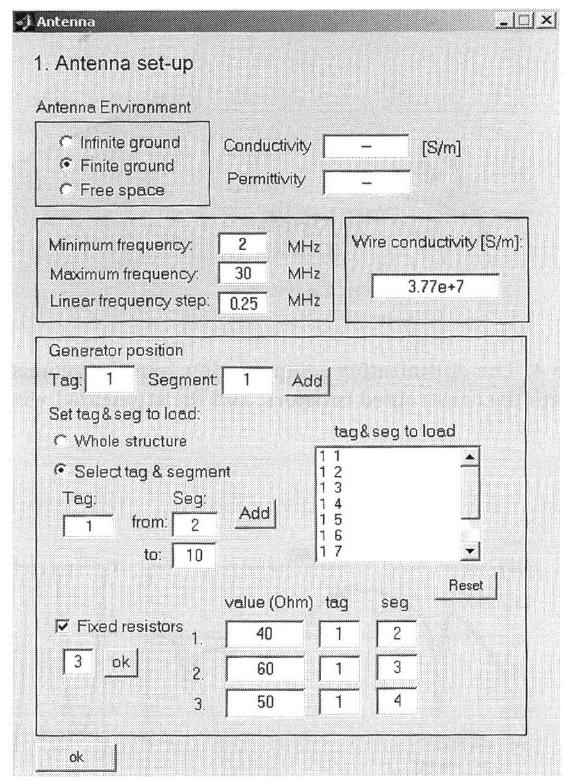

Figure 5. The *Antenna* module: the parts of the antenna to be loaded (according to the *NEC2* tag formalism) and the positions of the fixed resistors can be defined.

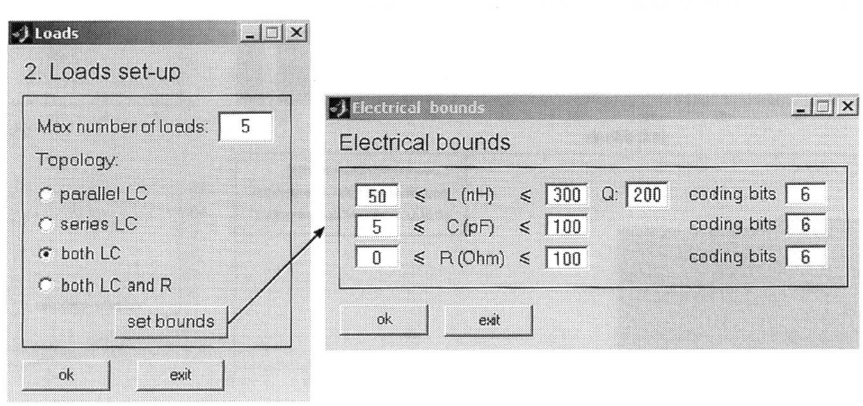

Figure 6. The *Loads* module: the set up of the topology and values of the loads.

3.3 *Network* Module

This module is used to assemble the matching network, which is generally composed of the cascade of a lossless ladder network, an impedance transformer, and an attenuator, between the transmitter and the antenna (Figure 3). As visible in Figure 7, the user can decide to optimize the electrical components of the lossless network, choosing among low-pass and high-pass filters of the third and the fifth order, the impedance transformer step-up ratio, and the attenuation constant. The bounds and the coding bits of the lossless network components are the same as for the loads.

3.4 *Requirements* Module

This module allows the user to manually assemble the objective function to be minimized, the general expression for which is shown in the upper part of Figure 8. This function evaluates the goodness of each individual with respect to the optimization problem. N_f is the total number of frequency samples in the selected range (tagged by the index n), and $F_v^{(n)}$, $F_\eta^{(n)}$, and $F_g^{(n)}$ are the functions shown in Equations (2)-(4), respectively controlling the antenna matching, the efficiency, and the gain along a given direction:

$$F_v^{(n)} = \begin{cases} 0 & \text{if } VSWR^{(n)} < s_0 \\ \dfrac{VSWR^{(n)} - s_0}{VSWR^{(n)}} & \text{otherwise} \end{cases}, \tag{2}$$

$$F_\eta^{(n)} = \begin{cases} 0 & \text{if } \eta^{(n)} > \eta_0 \\ \dfrac{\eta_0 - \eta^{(n)}}{\eta_0} & \text{otherwise} \end{cases}, \tag{3}$$

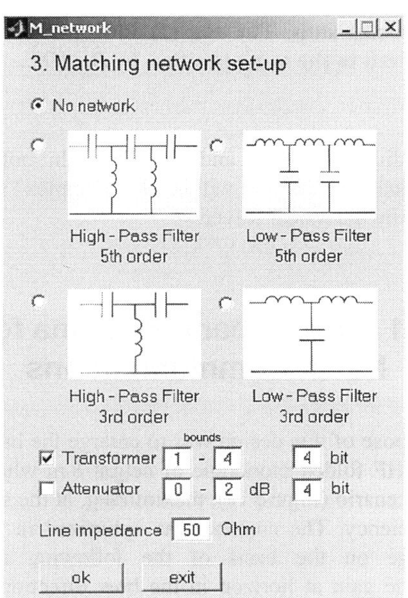

Figure 7. The *Network* module: the set up of the matching network.

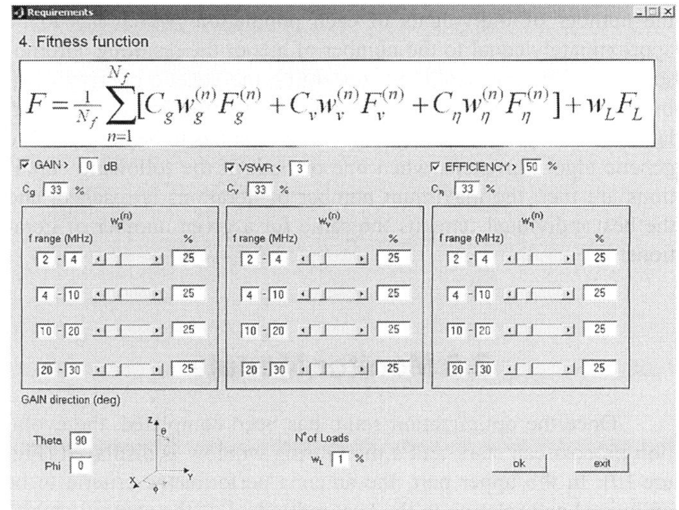

Figure 8. The *Requirements* module for the customization of the fitness function.

$$F_g^{(n)} = \begin{cases} 0 & \text{if } G^{(n)} > G_0 \\ \dfrac{G_0 - G^{(n)}}{G_0} & \text{otherwise} \end{cases}. \tag{4}$$

In these functions, s_0, η_0, and G_0 are frequency-independent thresholds, the values of which depend on the system requirements. In particular, the VSWR has to be constrained under s_0, while the efficiency and the gain have to be confined above η_0 and G_0, respectively. Functions $w_v^{(n)}$, $w_\eta^{(n)}$, and $w_g^{(n)}$ selectively weight $F_v^{(n)}$, $F_\eta^{(n)}$, and $F_g^{(n)}$ in different parts of the band, while coefficients C_v, C_η, and C_g are frequency-independent weights that add further degrees of freedom. Finally, F_L tries to minimize the number of loading impedances placed on the antenna, and w_L is the related weight. Such an objective function reaches its minimum when all the antenna's specifications are met, namely when the functions in Equations (2)-(4) are simultaneously zero.

As shown in Figure 8, the user can assemble the objective function by selecting the VSWR, the efficiency, and the direction (θ, ϕ) where the gain has to be optimized, and by defining the thresholds s_0, η_0, G_0, and all the weights mentioned above. In particular, the frequency-independent weights have to satisfy the relation $C_v + C_\eta + C_g + w_L = 100\%$, while the frequency-dependent parameters can take different values for each sub-band, the sum of which is again 100%. This arrangement of the fitness function permits broadband or also multi-band antennas (up to four bands) to be obtained. The four frequency ranges of each performance to be optimized are independent, and could be either contiguous or separated to further customize the optimization strategy. Explicit examples illustrating the role of the objective function in the optimization outcome will be shown in Section 4.

3.5 *GA* Module

The *GA* module is used to customize the parameters of the genetic algorithm. As visible in Figure 9, the user first has to set the number of individuals of each population (which has to be approximately equal to the number of bits of the resulting chromosome), and the probabilities concerning the genetic operators [8]. In particular, the generation gap indicates the fraction of the population to be reproduced. Next, an escape test has to be defined. The genetic algorithm stops when one or both of the following conditions are met: the maximum number of iterations is reached, and the best individual remains the same for a given number of iterations.

3.6 Monitor Module

Once the optimization setup has been completed, the evolution process can start, and a monitoring window is displayed (Figure 10). In the upper part, the antenna performance criteria to be optimized and relating to the best individual of the current generation are plotted and compared with those of the unloaded antenna system. In the central part, the histogram on the left represents the values of the objective function of each individual of the current generation (which has to be minimized). On the right, a visualization of the individuals in the constraint space gain-VSWR-efficiency is shown. In the lower part of the monitoring window, the actual best fitness and the best antenna loading are represented.

3.7 *Post-Processing* Module

If the antenna model is built by *NEC2*, the *post-processing* module can be useful for calculating the full performance of the optimized antenna system, both at a single frequency (Figure 11) and within a frequency range.

4. Application Examples

The potentials of *BLADE* will now be illustrated by means of two examples concerning antenna optimization over mobile platforms: a medium-size ship and a vehicle. In both cases, the reduced-antenna-port model within the complex scenario was accomplished by the *NEC2* solver.

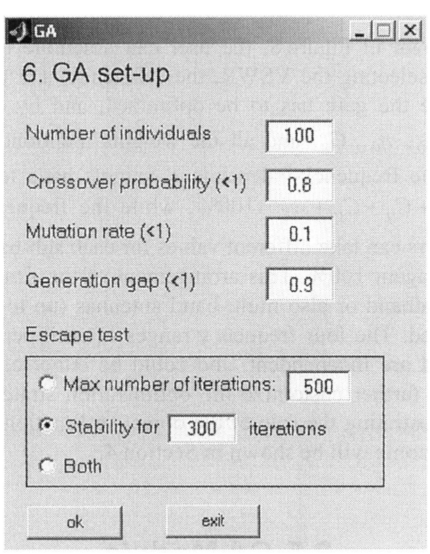

Figure 9. The *GA* module: the default number of individuals is automatically evaluated, starting from the number of bits of the resulting chromosome.

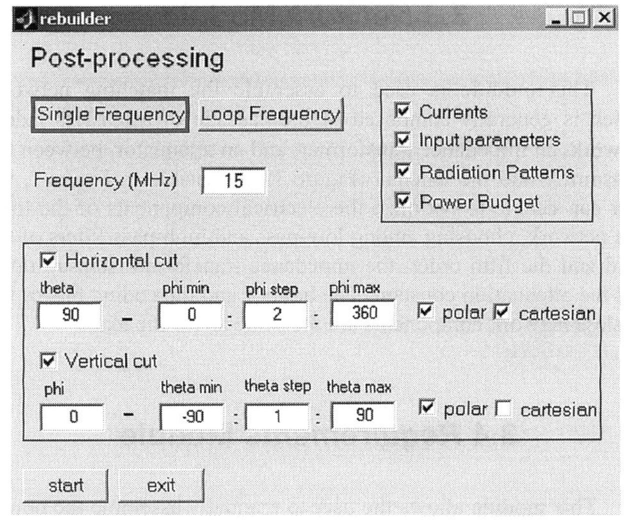

Figure 11. The *Post-processing* module: a single frequency analysis.

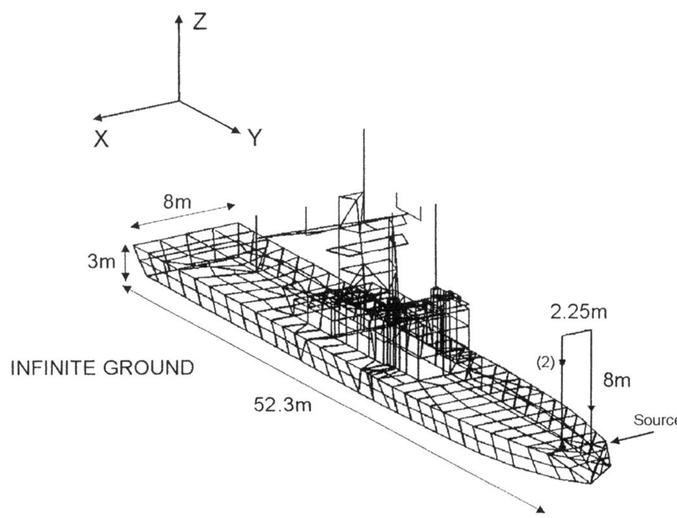

Figure 12. A folded monopole, 8 m × 2.25 m in size, mounted on a medium-size ship. The tag (2) indicates that two traps have been placed in the same position by *BLADE*.

4.1 A Broadband Antenna for Naval Communications

The purpose of this design was to enlarge the bandwidth of a conventional HF folded monopole of height 8 m when embedded into a naval scenario (Figure 12), maximizing, at the same time, its gain and efficiency. The antenna was optimized in the whole 3-30 MHz range on the basis of the following requirements: VSWR < 3, the gain at horizon in the bow direction higher than 0 dB, and the efficiency higher than 50%. The wire model of the ship was adapted, with some changes, from the *4NEC2* example catalogue. The whole structure was supposed to be made of alumi-

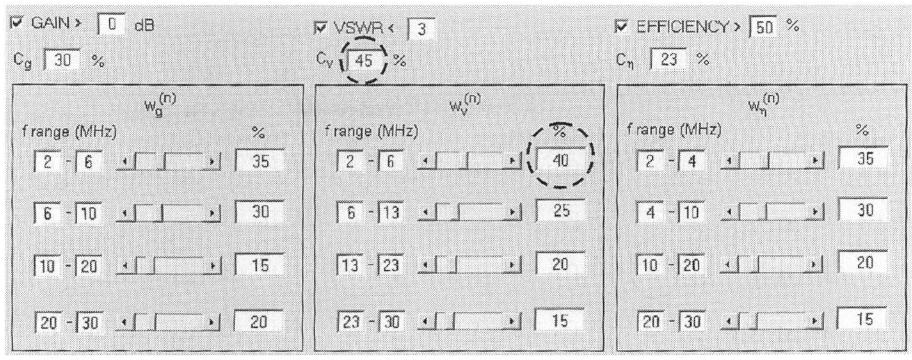

Figure 13. The naval antenna requirements and weighing coefficients. Additionally, $w_L = 2\%$ was set for the minimization of the loads number. The dashed circles highlight that the VSWR requirement has been emphasized more than the gain and the efficiency, particularly at the lower frequencies.

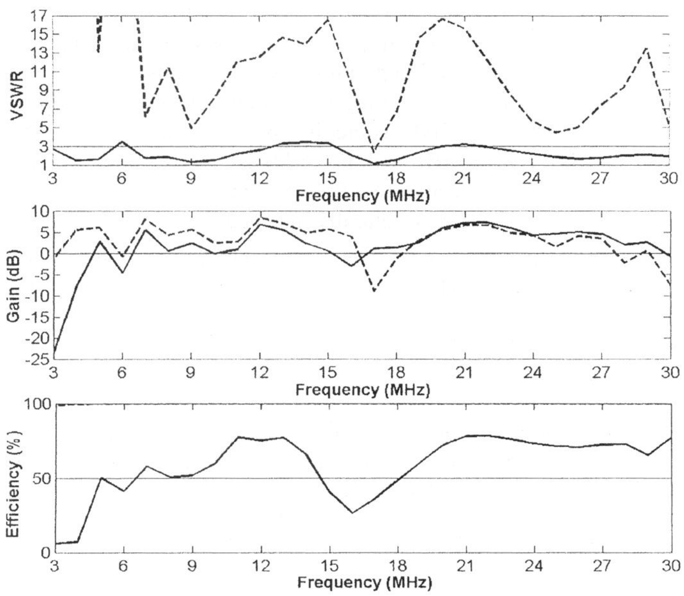

Figure 14. The performance of the naval antenna after optimization of the loads and of the impedance transformer (solid line), compared with that of the antenna without loads and impedance transformer (dashed line). The VSWR curves refer to 50 Ω.

num, and connected to a perfect ground plane, simulating the sea. The folded monopole was excited by a voltage source at the base of the left vertical conductor, and the loading circuits could be placed at any of the segments comprising the antenna wires. Two 75 Ω resistors were constrained (in the *Antenna* module of Figure 5) at the lower ends of the vertical conductors, in order to improve the antenna's bandwidth and to simplify the cooling equipment. The reduced-antenna-port model was generated by *BLADE* with a 1 MHz frequency step. The optimizer could allocate an impedance transformer and up to four loads, chosen as series and parallel *LC* circuits. Neither a ladder lossless network nor an attenuator were considered in the *Network* module of Figure 7. In the *Loads* module of Figure 6, the electrical components were subjected to the following constraints: $50\ \text{nH} < L < 300\ \text{nH}$, $5\ \text{pF} < C < 100\ \text{pF}$, and $0\ \Omega < R < 100\ \Omega$. Concerning the *Requirements* module of Figure 8, the VSWR was weighted more than the gain and efficiency (Figure 13), particularly at lower frequencies where the antenna was small with respect to the wavelength, and therefore rather difficult to match. The chromosome to be optimized was finally composed of 90 bits, and therefore a population of 100 individuals was chosen in the *GA* module of Figure 9.

After 200 iterations, *BLADE* had selected three *LC* traps. As visible in Figure 12, two of the traps, on the left vertical conductor, shared the same location as a series connection, resulting in a more complex circuit topology (as seen in Figure 2). The optimized impedance transformer value was set to 4:1. The antenna's performance, compared with that of the unloaded antenna in the same electromagnetic scenario, is shown in Figure 14. The VSWR was less than three throughout the HF band, and the antenna's gain and efficiency also satisfied the requirements over almost the whole HF range. The poor performance at the lower frequencies was due to the small size of the antenna with respect to the wavelength. It has to be noted that a further improvement of the final results could be obtained by adjusting the weighing coefficients of the objective function in further optimizations. For instance, the user could try to improve the efficiency around 16 MHz by increasing the related weighting coefficient in this sub-band.

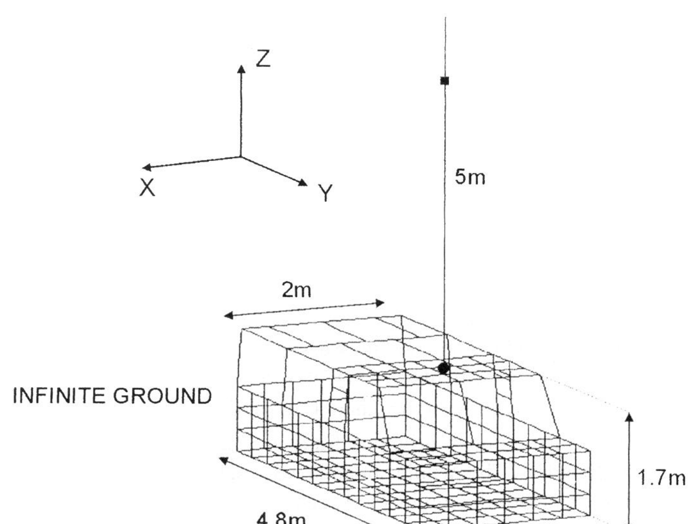

Figure 15. A 5 m monopole on a vehicle, assumed to be 0.5 m above a PEC.

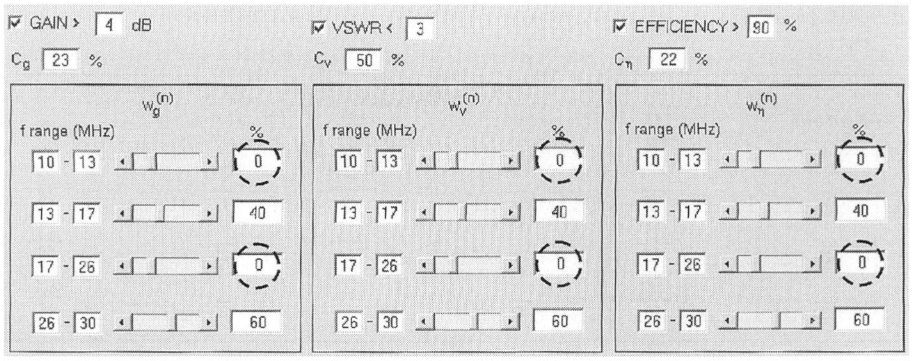

Figure 16. The requirements and weighing coefficients to obtain a dual-band radiator for the vehicular antenna. $w_L = 5\%$ was set for the minimization of the loads number. The dashed circles highlight the fact that a null weight was given to the bands that were not of interest.

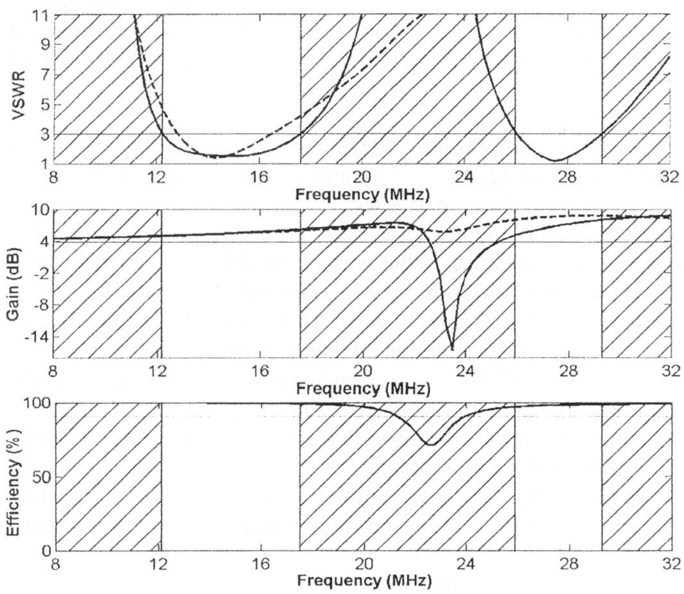

Figure 17. The performance of the vehicular antenna after the optimization of the loads and of the matching network (solid line), compared with that of the antenna without loads and matching network (dashed line). The VSWR curves refer to 50 Ω. The frequencies where the antenna was been controlled by the optimizer have been shaded.

4.2 A Dual-Band Antenna for Vehicular Communications

This example explored the potential of *BLADE* for designing dual-band antennas. In particular, an HF monopole of height 5 m, mounted on the roof of a vehicle and excited at the base, was considered (Figure 15). The antenna was optimized in order to match the following requirements: VSWR < 3, the gain at the horizon in the $\phi_0 = 270°$ direction higher than 4 dB, and the efficiency higher than 90%, in the non-contiguous frequency ranges of 13-17 MHz and 26-30 MHz. The whole antenna was selected to host up to three lossless loading circuits (series and parallel *LC* traps), and the matching network was endowed with only a high-pass filter of the third order. The ranges of the values of the electrical components were the same as in the previous example. The reduced-antenna-port model was generated by *BLADE* with a 0.4 MHz frequency step. Concerning the objective function, the dual-band requirements were obtained by weighting the VSWR more than the gain and the efficiency, and by setting to zero all the weighting coefficients in the two sub-bands where the antenna was not required to communicate (10-13 MHz and 17-26 MHz), as described in Figure 16. Moreover, because the first resonance of the monopole ($f_0 = 15$ MHz), where it is naturally matched, occurred in the first band to be optimized, a more relevant weight (60%) was associated with the other band. The resulting chromosome had 72 bits, and therefore a population of 80 individuals was chosen. After 100 iterations, only one parallel *LC* trap was selected by the optimizer, and the use of the ladder lossless network permitted enlarging the bandwidth of each sub-band. The antenna's performance compared with that of the unloaded antenna without a matching network in the same electromagnetic scenario is shown in Figure 17. The VSWR shows the dual-band operation in the required frequency ranges, where both the antenna's gain and efficiency fully matched the requirements.

5. Conclusions

This paper has presented a genetic-algorithm optimization tool for the design of broadband and multi-band loaded antennas. The tool has been designed to rationalize, and therefore simplify, the whole antenna-design procedure. Besides educational purposes, *BLADE* can be a potential aid to real projects, since it permits the optimization of antenna features in the scenario where the antenna will be installed. Moreover, the large number of controls available in the customization of the fitness function makes a fine tuning of the search procedure possible. The optimization interface is naturally suited to drive the *NEC2* engine. However, the possibility to directly input the reduced-port model of the antenna permits the use of any external electromagnetic solver, and the use of radiating structures other than wires. A free-of-charge classroom version of the optimizer can be requested from the authors (e-mail: marrocco@disp.uniroma2.it).

6. Acknowledgments

This work has been partially supported by SELEX Communications, a FINMECCANICA company. The authors wish to thank L. Folletto for the collaboration in the software implementation.

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