

A Novel Methodology for the Fast Design of Ultra-Wide Broadband Antennas

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Abstract

A novel approach for the fast evaluation of the performance of a loaded antenna exploiting the scattering matrix properties is presented. Starting from the scattering matrix calculated by using a generic full-wave solver, it is shown how to obtain the frequency response of the antenna loaded with lumped series/parallel RLC elements, properly applying short/open circuits, without recurring to repetitive and time consuming full-wave simulations. The procedure is also able to evaluate the power dissipated on the resistive elements and hence the overall efficiency of the loaded antenna. As an example of the usefulness and reliability of the proposed approach, this fast solver has been used in conjunction with a genetic algorithm (GA) for synthesizing a loaded wideband antenna with a 20:1 bandwidth.

1. Introduction

The design of antennas suitable for modern communications requires a significant effort in terms of computational resources, especially when stringent constraints on bandwidth, efficiency and radiation performance need to be satisfied. The tailoring of all the antenna parameters can hardly been achieved with analytical methods, particularly if the device is installed in a complex scenario, thus requiring the need of full wave solvers. A possible solution to mitigate the bottleneck of a time consuming evaluation of the antenna performance during the design process may be represented by a suitable interpolation procedure [1] or a more efficient numerical approach [2]. The aforementioned techniques are very useful especially in the case the antenna operates on a large bandwidth. Broadband and frequency agile antennas are employed in a variety of applications spanning from the high frequency range of naval and vehicular communications, to the microwave upper region of mobile communications [3]. To achieve a broadband behavior for wire or printed antennas, a matching network or insertion of lumped loads, with fixed or variable values, may be necessary. Within this framework, the synthesis of loaded wire antennas has received attention in recent years and different strategies have been proposed for providing radiators able to achieve the desired performance. In particular, most of the efforts relies on the synergy of a full-wave solver, generally the Method of Moments (MoM), and a stochastic algorithm, mainly the genetic algorithm (GA) [4], to drive the optimization toward the proper design.

In this paper we propose an approach based on the use of scattering parameters to properly loading the investigated antenna in order to achieve a broadband behavior of the radiator. This approach is solver-independent since it requires only the knowledge of the scattering matrix of the antenna considered as a multiple-source radiator. Moreover, the full-wave analysis is performed only once thus reducing the overall computational time necessary for the antenna design optimization. Finally, the considered loads can be a combination of any kind, and, more in general, a short or open circuit.

2. A Novel Fast Antenna Analysis

Let us consider the scattering matrix \bar{S} of the N -port network which completely describes a microwave device without any source inside. The matrix \bar{S} has dimension $N \times N$.

Let us suppose now to terminate one of its port with a load Z_i with a reflectance ρ_i , where a_i and b_i represents the incident and the reflected power waves at the network port, respectively, and $a_i = \rho_i b_i$.

After the loading of one port, the network has $(N-1)$ ports and the new scattering matrix becomes \bar{S}^i , a $(N-1) \times (N-1)$ matrix. In order to express \bar{S}^i , it is convenient to sort the columns and rows of the original \bar{S} matrix by renaming the i -th port as the N -th port and appropriately rewriting the relation between the matrix \bar{S} partitioned into four blocks and the incident/reflect waves, as reported hereafter:

$$\begin{bmatrix} \bar{b}' \\ b'' \end{bmatrix} = \begin{bmatrix} \bar{\bar{S}}_{11} & \bar{\bar{S}}_{12} \\ \bar{\bar{S}}_{21} & S_{22} \end{bmatrix} \begin{bmatrix} \bar{a}' \\ a'' \end{bmatrix}. \quad (1)$$

More in detail, in (1) the single primed quantities refer to waves related to the $(N-1)$ unloaded ports whereas double primed ones to waves at N -th port. It is therefore apparent that $\bar{\bar{S}}_{11}$ is a $(N-1) \times (N-1)$ matrix, $\bar{\bar{S}}_{12}$ and $\bar{\bar{S}}_{21}$ are $(N-1) \times 1$ and $1 \times (N-1)$ ones respectively, whereas S_{22} is a complex scalar. Then the matrix $\bar{\bar{S}}$ that describes the relation between \bar{a}' and \bar{b}' can be expressed as:

$$\bar{b}' = (\bar{\bar{S}}_{11} + \bar{\bar{S}}_{12} (\rho^{-1} - S_{22})^{-1} \bar{\bar{S}}_{21}) \bar{a}' = \bar{\bar{S}}' \bar{a}'. \quad (2)$$

If we suppose to load m ports we can reorganize the rows and columns of the $\bar{\bar{S}}$ matrix in order to have the unloaded ports as the first $(N-m)$ ports whereas the last m indexes refer to the loaded ones. In this case it is suitable to define the diagonal matrix $\bar{\bar{\rho}}$ as:

$$\bar{\bar{\rho}} = \begin{bmatrix} \rho_{N-m+1} & 0 & 0 & 0 & 0 \\ 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & \dots & 0 & 0 \\ 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & 0 & \rho_N \end{bmatrix}. \quad (3)$$

Then equation (2) can be generalized to an arbitrary number of loaded ports and rearranged to manage also the case of a singular $\bar{\bar{\rho}}$ matrix:

$$\bar{b}' = (\bar{\bar{S}}_{11} + \bar{\bar{S}}_{12} \bar{\bar{\rho}} (\bar{\bar{I}} - \bar{\bar{S}}_{22} \bar{\bar{\rho}})^{-1} \bar{\bar{S}}_{21}) \bar{a}' = \bar{\bar{S}}' \bar{a}', \quad (4)$$

where $\bar{\bar{I}}$ is the identity matrix. It is worthwhile to point out that (4) is always definite since in a real network $\bar{\bar{S}}_{22} \bar{\bar{\rho}}$ cannot be equal to $\bar{\bar{I}}$ due to the presence of losses in the structure.

It is important to highlight that expression (4) is independent from the numerical method that has been employed to compute the scattering parameters; therefore the full-wave analysis can be performed with the most suitable solver and not only with MoM, as in the aforementioned approaches. Moreover, the analysis of the device when some of its ports are terminated into known loads does not require any further full wave analysis. It has also to be remarked that, it is possible to determine the amount of power that has conveyed to the loads and how much of it has been dissipated in their resistive component.

3. Optimization Strategy

Let us consider the problem where an antenna is loaded and equipped with an impedance transformer in order to achieve a large operating bandwidth. The aim is to select the configuration of the loads and their values as well as the matching network.

The antenna dimensions are considered fixed. The set of all the available locations for the loads are defined whereas the set of available loads comprises series RLC and parallel RLC circuits, open and short circuits. The matching network consists of a simple impedance transformer with ratio equal to n . Unlike other approaches, short and open circuits can be employed since the undefined terms that may affect the Z or Y matrix are avoided by employing the scattering parameters. Moreover, the introduction of shorts and opens also provides a certain degree of shape optimization, as it will be illustrated in the following design example.

The optimization is performed by employing a genetic algorithm (GA) that has proved to be a valuable tool for electromagnetic design. The fitness function to be minimized is the following:

$$fitness = \frac{1}{N_f} \left(\sum_{i=1}^{N_f} c_1^i K_{VSWR}^i + c_2^i K_{eff}^i \right) + c_3 K_{RLC} \quad (5)$$

where N_f is the total number of samples within the considered frequency range and $c_{1,2}^i$ are variable weighting coefficients which provide a tailored tune of the performances in different parts of the operating bandwidth. The two terms K_{VSWR} and K_{eff} refer to the antenna matching and antenna efficiency, respectively, while the term K_{RLC} represents the number of lumped RLC loads and c_3 is a constant weight.

4. Design Example and Verification

In order to prove the effectiveness of the proposed approach the optimization of an antenna with a 20:1 bandwidth has been addressed. In this case the antenna to be optimized is illustrated in Fig. 1 and consists of a microstrip antenna printed on a bare FR4 substrate ($\epsilon_r = 4.4$, $\text{tg } \delta = 0.025$) of thickness equal to 0.8 mm. The dimension of the dielectric slab are $W = 25$ cm and $H = 35$ cm whereas the overall antenna dimensions are 16.4 cm \times 32.2 cm ($s = 8.2$ cm, $h = 6$ cm, $t = 3.6$ cm, $w = 4$ mm). The radiator is placed orthogonally on the xy -plane which is supposed to be an infinite PEC ground plane. This geometry provides multiple different paths along the antenna for the radiating currents and it is an interesting example to prove the ability of the method in achieving a broadband behavior by selecting the proper loads.

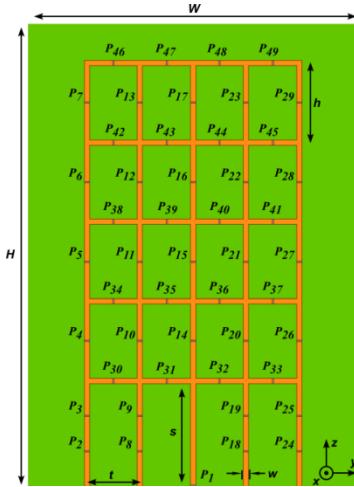


Fig. 1 – The antenna to be optimized is printed on a FR4 dielectric substrate and placed orthogonally on the xy infinite PEC ground plane.

The total number of ports, as well as their locations within the antenna, is set at the beginning of the optimization process, when the scattering matrix is computed. In this case the overall number of ports N is 49 hence the scattering matrix evaluated by the full-wave solver has 49 rows and columns. The designated source port is P_1 whereas the other 48 ports will be terminated into loads whose values and topology need to be optimized, as well as the impedance transformer ratio n , to obtain an antenna that fulfills the specifications. By following the fitness function (5), the GA will try to find the solution with the minimum number of lumped RLC loads. The requirements are given in terms of a VSWR threshold as well as a frequency-dependent lower bound for the radiation efficiency within the operating bandwidth. More in detail, the antenna design is required to operate over a 20:1 bandwidth ranging from 100 MHz up to 2.0 GHz, featuring a VSWR less than 3.5 and a minimum radiation efficiency of 5%, 30% and 50% respectively in the frequency intervals 100-200 MHz, 200-800 MHz and 800-2000 MHz.

Once the scattering matrix of the antenna shown in Fig. 1 is ready, the evaluation of the performance of a single configuration of loaded antenna by using the described fast scattering matrix approach takes less than 0.4 sec. The antenna in Fig. 1 has been optimized by minimizing (5) and the results of the evolutionary process have been summarized in Table I. The transformer ratio n has been set equal to 1.6.

TABLE I
TYPE, LOCATION AND VALUE OF THE LOADS DISTRIBUTED ON THE ANTENNA

Load	Port# and value
R	14 (402 Ω), 25 (150 Ω), 48 (30 Ω)
L	31 (6.8 nH)
C	13 (15 pF)
Short	4-7, 9-12, 15, 16, 20-24, 26, 29, 30, 33, 40-44, 46, 47
Open	2, 3, 8, 17-19, 27, 28, 32, 34-39, 45, 49

A comparison of the performances in terms of VSWR and efficiency evaluated by the proposed fast antenna analysis procedure and the full wave simulation is reported in Fig. 2. The fulfillment of the desired requirements is apparent and the agreement between the two procedures is quite good.

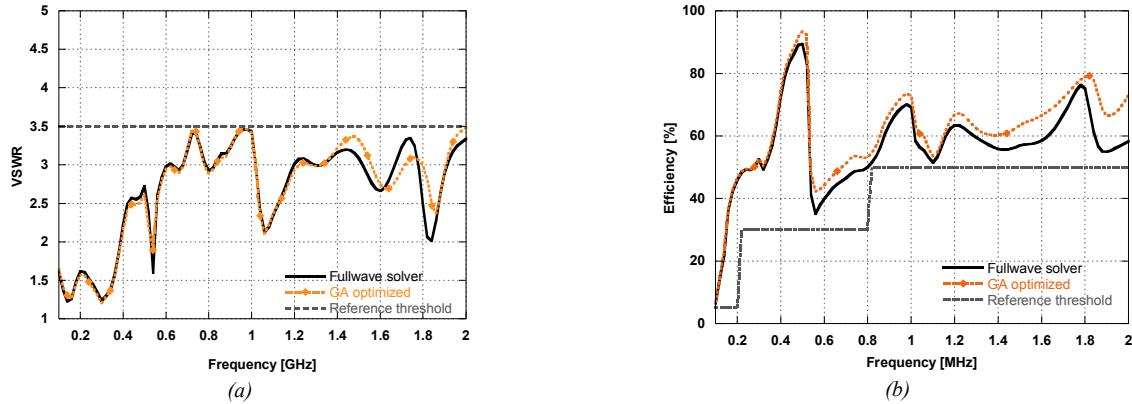


Fig. 2 – Comparison between the results obtained by using the fast antenna analysis procedure and the full wave simulation: a) VSWR; b) Efficiency.

The ϕ -averaged system gain has been also investigated and reported within the whole frequency range for three different directions ($\theta = 45^\circ, 60^\circ, 90^\circ$) in Fig. 3. The system gain is almost always greater than 0 dB in the horizontal plane ($\theta = 90^\circ$) up to 1.8 GHz whereas for higher frequencies the gain is more than 3 dB for the other two directions.

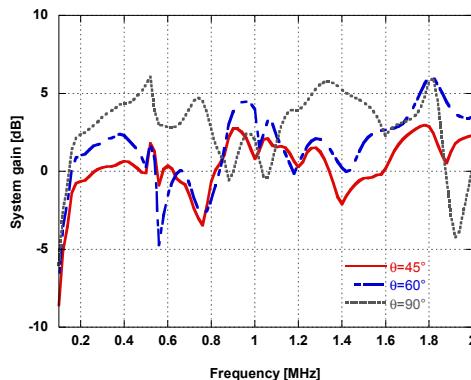


Fig. 3– System gain averaged over phi for the optimized antenna along three different directions ($\theta = 45^\circ, 60^\circ, 90^\circ$).

5. Conclusion

A novel technique based on the fast evaluation of the frequency response of a loaded antenna, starting only from the knowledge of scattering matrix of the unloaded antenna, has been described. The initial scattering matrix can be evaluated by using any numerical solver and this can be considered as an advantage with respect to other approach that relies only on numerical solvers, as for instance MoM. A quite reliable estimate of the loaded antenna efficiency can be obtained as well. This fast approach has proved to be particularly suitable to be exploited in an optimization process for designing wideband antennas. As an example, a printed antenna operating over a wide 20:1 bandwidth with a VSWR less than 3.5 and a predefined minimum efficiency has been designed.

6. References

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