Algorithm and modeling for fast optimization and design of large log-periodic array antennas with commercial EM solvers

Algorithm and Modeling for Fast Optimization and Design of Large Log-Periodic Array Antennas with Commercial EM Solvers

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***Abstract*—This paper presents two useful algorithms for efficient numerical simulations in design of large log-periodic array antennas by using commercial EM Solvers. Both algorithms take into account the finite size of large log-periodic array and make use of the periodicity to achieve faster numerical computations. The Eleven antenna is taken as an example to demonstrate the algorithms. Simulated and measured results are presented in the paper.**

I. Introduction

Many applications require wideband or ultra-wideband antennas, such as in radio astronomy and ultra-wide band (UWB) communication systems [1] [2]. Two examples of radio astronomy applications are the future SKA (SKA = Square Kilometer Array) and the VLBI2010 (VLBI = Very Long Baseline Interferometry) projects. Both projects have reflector antennas as candidates for the frequency range of approximately 1 - 13 GHz, whereas the UWB communication systems require small direct radiating antennas covering typically 3 - 10 GHz. Thus the frequency ranges are similar, although the requirements are quite different.

One way to achieve antennas with decade bandwidth or more is to use log-periodic arrays, being introduced 50 years ago [3] [4]. However, due to the desired decade frequency band, the size of the whole log-periodic array antenna becomes often very large in terms of wavelengths at the highest frequency, which makes numerical optimization and therefore the design a very challenging task because of the large computation time. In this paper, we will present a review of algorithms for fast optimization and design of large log-periodic array antennas with commercial EM solvers. The algorithms have been used during the development of different versions of the Eleven antenna described in [5]- [11].

II. Algorithm I - Partial Array Method

We have for the large log-periodic Eleven antenna array made two observations:

1) Scaled S-parameter Performance: If the log-periodic array is large, the S-parameters are frequency scaled due to the log-periodicity, except for the edge elements, according to

$$S_{i(l+n)j(m+n)}(f) = S_{i(l)j(m)}(f/k^n) \tag{1}$$

where $S_{i(l)j(m)}$ is the S parameter between the port i of dipole l and port j of dipole m, f the frequency, k the scaling factor for the log-periodic array and n an integer. The port definitions for an example array can be seen in Fig. 1, where D1 represents dipole 1 and so on. A 6-element-pair Eleven antenna has been modeled in CST MS (time-domain finite integration method solver) [12] with two discrete ports on each dipole and with all dipoles located in their correct log-periodic positions, as shown in Fig. 1. The reference impedance of the ports is 200 Ohms in this case. Fig. 2 shows simulated $S_{1(3)1(3)}(f)$, $S_{1(4)1(4)}(f)$ and scaled $S_{1(3)1(3)}(f/k)$ for the 6-element-pair Eleven antenna. It can be observed that $S_{1(4)1(4)}(f) \approx S_{1(3)1(3)}(f/k)$, which indicates that there is a frequency scaling between the S parameters of the two centrally located dipoles.

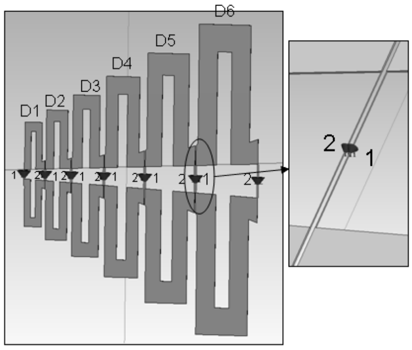

Fig. 1. Port definition of cascaded log-periodic array antenna.

2) Low Mutual Coupling between Far Separated Elements: For a properly functioning log-periodic array, the mutual coupling between elements separated far apart is much lower than that between the neighboring elements, see Fig. 3. This property is necessarily only present if the array is fed from the high-frequency end (smallest elements), and requires that frequencies must be stopped from propagating further along the array after they have reach the radiating element. This requires that the cascaded log-periodic elements must work as low pass filters, which is the case for the Eleven antenna when realized with folded dipoles [9].

Algorithm I makes use of these two properties to get a very efficient method for numerical simulations. The algorithm procedure is then as follows. We calculate the S parameters of

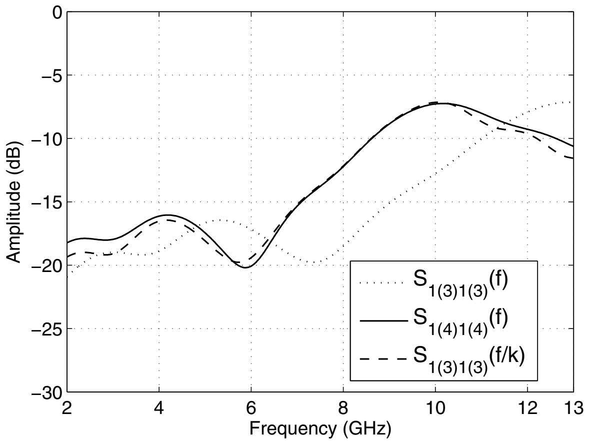

Fig. 2. Illustration of frequency scaling of S-parameters by a 6-element Eleven antenna simulated with all mutual couplings included.

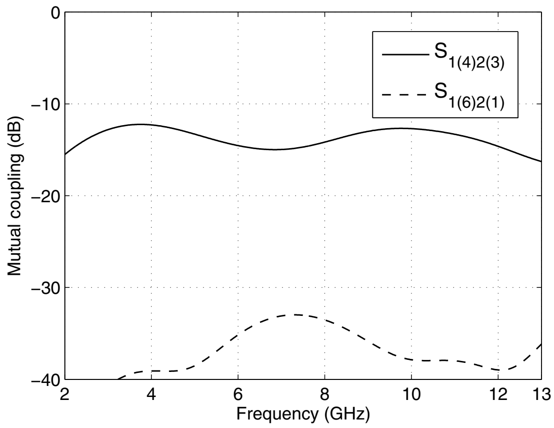

Fig. 3. Mutual coupling between neighbored elements and between far-separated elements in a 6-element Eleven antenna.

the small partial array, for example, the innermost M-element partial array. Then, by using frequency scaling, we can get all S parameters between all the elements of the complete large array that are separated by up to $M-2$ elements, for example,

$$S_{i(l)j(l+M-1)}(f) = S^{PA}_{i(1)j(M)}(f/k^{l-1}),\ \ (1 \le l \le N-M+1)$$

where S^{PA} is the S parameter of the partial array. For the non-edge elements, we always use the S-parameters for the centrally located elements in the partial array, for example,

$$S_{i(l)j(l+1)}(f) = S^{PA}_{i([M/2])j([M/2]+1)}(f/k^{l-[M/2]}).$$

where $[M/2]$ is the greatest integer less than or equal to $M/2$. For the edge elements, we use the S-parameters of the edge elements in the partial array, for example,

$$S_{i(1)j(2)}(f) = S^{PA}_{i(1)j(2)}(f)$$

$$S_{i(N-1)j(N)}(f) = S^{PA}_{i(M-1)j(M)}(f/k^{N-M}).$$

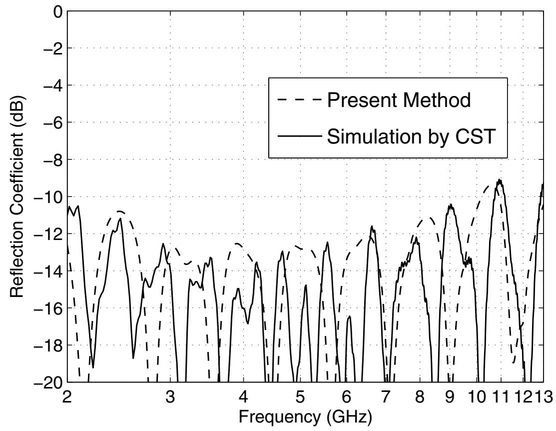

Fig. 4. Reflection coefficient of the optimized 14-element linearly polarized Eleven antenna by using the present partial array method (dashed) and a full wave simulation of the whole array by CST (solid).

We also choose to neglect the S parameters between the elements that are separated by more than $M - 2$ elements, so that

$$S_{i(l)j(l+m)}(f) = 0,\ if\ |m| \ge M.$$

Using these approximations we now know all S parameters for the whole array. Then the reflection coefficient of the whole large array after cascading can be obtained.

As an example, the method is applied to minimize the input reflection coefficient of a 14-element-pair Eleven feed over 2-13 GHz by calculating only a part of the array with 6-elements. Fig. 4 shows the reflection coefficient of this Eleven feed by partial array method and full wave simulation of the whole array by CST. The models of the complete array and the partial array in CST need 12.8 million meshes and 2.5 million meshes, respectively. One can observe that the present method provides a quite accurate result down to -10 dB. The computation time using the present method is about 30 minutes while it is about 2 hours to simulate the whole array in CST. It is quite obvious that the larger the complete array is, the more efficient the partial array method becomes.

III. Algorithm II - Input Impedance Periodicity Theorem

Input impedance of an in?nite large log-periodic array is periodic. For a realistic truncated ?nite log-periodic array, the purely periodic performance will not hold any more. We have derived a more accurate formula for the periodicity that will be presented in a future journal article, but we will here briefly describe it.

We assume that the excitation (feeding) port is at the input of the smallest radiation element in the array, which is also the case for most log-periodic array in practice. If we use $\mathbf{T}_1(f)$ to present the ABCD matrix of the first element in the array at frequency f, we have the following periodicity theorem for a finite log-periodic array :

$$Z_{in}(f) = \mathbf{T} \ominus Z_{in}(f/k^n) \tag{2}$$

where

$$\mathbf{T} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \prod_{i=0}^{n-1} \mathbf{T}_1(f/k^{n-i}), \tag{3}$$

operation $\ominus$ means that

$$\mathbf{T} \ominus Z_{in}(f/k^n) = \frac{D \cdot Z_{in}(f/k^n) - B}{A - C \cdot Z_{in}(f/k^n)}. \tag{4}$$

and k is the scaling factor for the array. From the above, we can calculate the input impedance at high frequency by using the value of the impedance at low frequency, which leads to a very efficient computation for numerical simulation.

Fig. 5 shows a 14-folded-dipole-pair Eleven antenna. It should be noted that in order to verify (2), we use an Eleven antenna of randomly chosen dimensions. Fig. 6 shows comparison of the input reflection coefficients obtained through the simulation over 2 - 18 GHz by using CST, and obtained first through the simulation over 2 - 5 GHz by using CST, then by using (2) to calculate the input impedance values at high frequency up to 18 GHz. From the figure, it can be seen that the agreement between the two methods is quite good, and the computation time for the present method is less than one third of the full simulation up to 18 GHz by CST. Therefore, by using the present formula of the periodicity for the input impedance for a finite log-periodic array in (2), a more efficient calculation of the reflection coefficient is obtained.

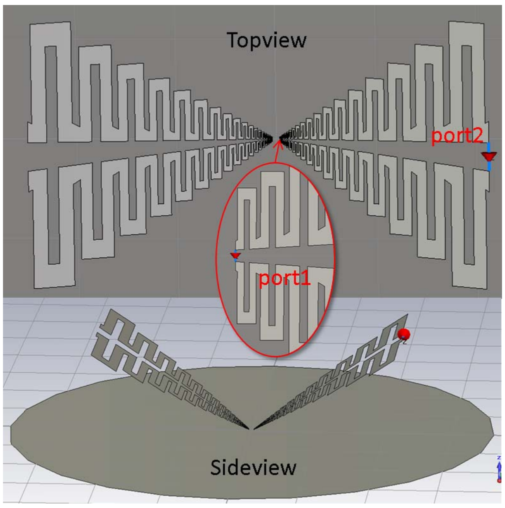

Fig. 5. The Eleven antenna of 14 folded dipole pairs.

IV. Modeling in CST MS

In order to implement the partial array method, a careful modeling of the log-periodic array is critical. Fig. 2 shows the modeling of the partial array of the 2-13 GHz Eleven antenna in CST MS, where port definition and the gaps between ports have been handled carefully for better accuracy. The output port of one dipole and the input port of the next are separated by a narrow air gap which does not exist when the dipoles are cascaded together but has to be there for modeling the ports in CST. The gap is also modeled periodically and the maximum gap for designing the Eleven feed of 2-13 GHz is 0.26 mm which corresponds to a phase change of 4 degree at 13 GHz. Then, when cascading all elements, we need to take the phase shift due to the small gap between the elements into account. φ_l is the phase shift due to the gap $l_{g,l}$ between dipole l and dipole $l+1$ in the partial array, and S^{gap} is the S parameter simulated with ports defined with gaps in the partial array. Therefore, the S parameters of the partial array should be corrected as

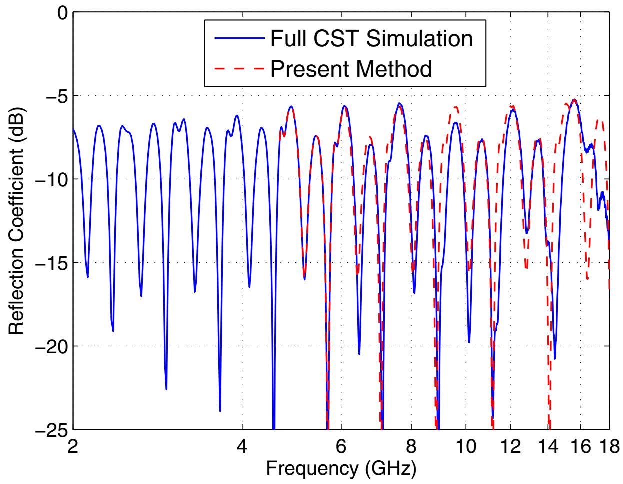

Fig. 6. CST simulated S parameters of the first folded dipole in the Eleven antenna shown in Fig. 5.

$$S^{PA}_{i(l)j(m)} = S^{gap}_{i(l)j(m)} \cdot e^{-\mathbf{j}[(i-1)\varphi_l + (j-1)\varphi_m]} \tag{5}$$

where $\varphi_l = 2\pi \cdot l_{g,l}/\lambda$ and the bolded $\mathbf{j}$ is the sign of an imaginary number.

V. Conclusions

We have presented two algorithms for large log-periodic array antennas in order to have more efficient numerical simulations with commercial EM Solvers. With these algorithms, optimization can be performed efficiently. The algorithms have been verified by using examples from the development of the Eleven feed, which has resulted in several successful hardware versions.

Acknowledgment

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