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GRID-BASED GLOBAL ELECTROMAGNETIC SIMULATION TOOL FOR PARAMETRIC DISTRIBUTED ANALYSIS OF ARRAY ANTENNAS

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Abstract—Full-wave electromagnetic solver based on the Transmission Line Matrix Method has been deployed on Grid test-bed. This Grid-based electromagnetic approach exploits the availability of computing node at disposal through the Grid to face the demand of arbitrary large simulations by allocating a corresponding amount of resources hence minimizing the overall elapse time. In order to highlight the benefits of using computing Grids in electromagnetic simulations, a parametric study of planar reflectarray antennas based on microstrip technology has been carried out. The efficiency of distributed computing when a very large number of computation units (nodes) are involved in the computation of large and non-uniform reflectarray antennas is reported.

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1. INTRODUCTION

The Grid computing environment provides a safe and pervasive access to dynamically distributed computing resources. Grids can be used to execute any of a variety of jobs across multiple resources, transparently to the user, providing greater availability, reliability, and cost efficiencies than may exist with dedicated servers [1, 2]. In addition to Central Processing Unit (CPU) and storage resources, it can provide access to increased quantities of other (shared) resources and to special equipment, software, licenses, and other services. These large-scale multi-site infrastructures provide the needed support for e-Science. Applications include, among others, scientific and engineering simulations of complex physical phenomena. Examples include weather prediction, earthquake models, interacting black holes and neutron stars, as well as medical and business applications.

Nowadays, microwave engineers can rely on highly specialized full-wave electromagnetic (EM) field solvers to develop and optimize their designs. Computer-aided analysis and optimization have replaced the design process of iterative experimental modifications of the initial design (namely the cut-and-try technique). Applications based on a parametric distributed study are now a good candidate to execute in a Grid environment [3]. However, such study in the framework of the EM simulation of complex structures has not yet been reported. For the first time, at least at the authors' knowledge, a large scale Grid-based approach for the parametric distributed analysis of EM structures is presented.

A complete, highly portable, free, open source package for full-wave EM computations called YATPAC [4] has been used here to simulate the test-case structures. This software is based on the Transmission Line Matrix (TLM) Method, a general purpose time-domain technique suitable for the EM simulation of structures of arbitrary shape [5]. An advantage of the TLM method resides in the large amount of information in one single computation. An example of parallel distributed computing using YATPAC on maximum six available computers has been demonstrated in the past [6] by one of the authors of the present paper. However, this precursory work does not grasp the efficiency of distributed computing when a very large number of computation units (nodes) are involved in the computation of large structures and it does not address the problem of parametric studies based on Grid environment.

In this article, it is described for the first time how computational Grids can be, with its high resources availability and reliability, a powerful tool for electromagnetic simulation of non-uniform antenna reflectarrays (e.g., the arrays are composed of non-identical cells) Different dimensions of a planar microstrip reflectarray antenna have been simultaneously simulated on Grid computing nodes in order to minimize the simulation time. Overall computation time for deriving radiation pattern of arrays was significantly reduced comparing to sequential computation while keeping the solver accuracy by deploying these simulations on up to 64 computing nodes.

2. GLOBAL ELECTROMAGNETIC SIMULATION OF REFLECTARRAY ANTENNAS

A microstrip reflectarray combines both advantages of a conventional reflector and a planar array of microstrip patches [7]. This flat reflector antenna consists of an array of resonant elements illuminated by a primary source, typically a feed horn [7–9]. Each element is designed to re-radiate the incident field with a phase shift defined to steer the main beam in a specified direction. Reflectarray analysis relies on the computation of the phase diagram from a unitary cell. The classical approach usually assumes that this unitary cell is extracted from an infinite periodic array [9]. It results in fast simulations, as only a single cell must be analyzed thanks to Floquet boundary conditions. This approach also accounts for mutual coupling but only gives the behavior of a reflectarray with identical cells. In this paper, we propose an alternative approach, where the global simulation of the structure is performed without approximations and for non-identical cells (see Figure 1(a)).

For the sake of demonstration, the reflectarray of various rectangular microstrip patches loaded with slots, proposed in [10], is simulated in Ku Band (see Figure 1(b)). The non-uniform planar array is illuminated by a normally and linearly polarized incident plane wave (in [10], the primary source is a 12–18 GHz feed horn). (see Figure 1). The center-to-center distance between elements is 0.7λ. The dimensions of the reflectarray are $7\lambda \times 7\lambda$ where λ is the free-space wavelength. Since the slot aperture lengthens the path of the electric currents on the metallic patch of the array cell, a phase shift is introduced locally for the reflected wave and the main-lobe direction of the backscattered field is then controlled. In order to choose the slot and patch dimensions, and consequently adjust the phase distribution, parametric simulations of the reflectarray can be performed in the design process.

The TLM Method developed here for the full-wave EM simulation of such reflectarray uses a uniform mesh grid cell dimensions of $\Delta x = \Delta y = \Delta z = 500\,\mu\text{m}$. Absorbing boundary conditions are assigned to a

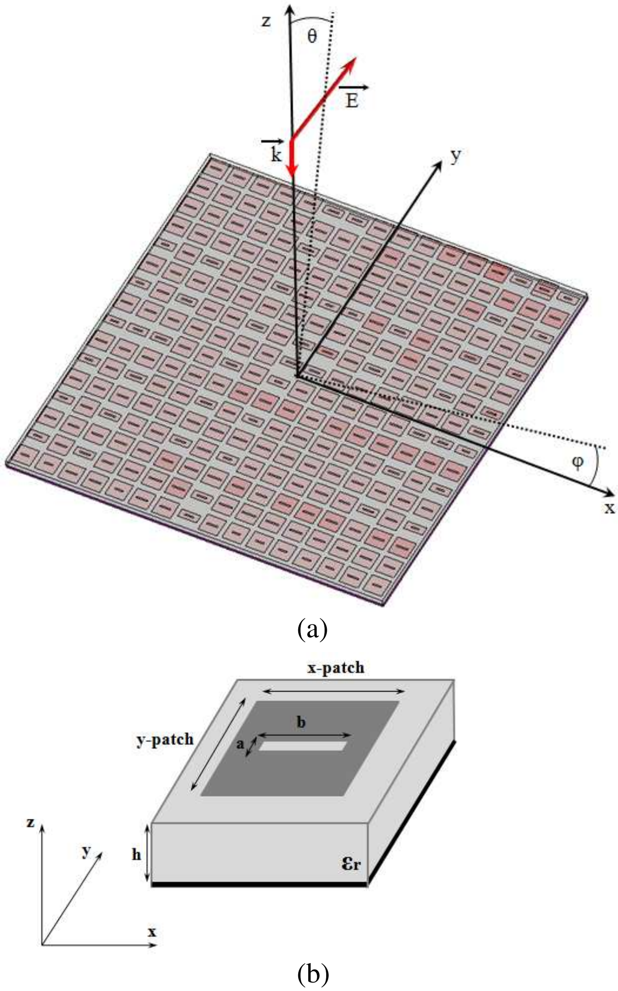


Figure 1. (a) Non-uniform reflectarray antenna [10] illuminated by a normally and linearly polarized incident plane wave ($\boldsymbol{\varphi}$ = Azimuth angle/+ or − rotation away from the x-axis; $\boldsymbol{\theta}$ = Elevation Angle/+ or − rotation away from the z-axis). In this figure, **E** denotes the incident electric field and **k** the free-space wave number; (b) Elementary cell: Patch structure loaded with a slot The patches are printed on one side of a single dielectric slab of 4mm thickness with relative permittivity of $\varepsilon_r = 2.17$. The other side of the slab is completely metalized. The elementary cell is a $16.8\,\mathrm{mm} \times 16.8\,\mathrm{mm}$ square containing rectangular metallic patch loaded with a centered slot.

large box $7\lambda \times 7\lambda \times \lambda$ that artificially encloses the structure.

3. THE GRID-BASED ELECTROMAGNETIC SIMULATION

Full-wave EM software based on the TLM Method has been deployed on a Grid large-scale test-bed named Grid'5000, a highly reconfigurable, controllable and monitorable experimental Grid platform of 9 sites geographically distributed in France [11]. Each site comprises one or several clusters, for a total of 22 clusters. Sites are interconnected with a 10 GB/s link. A variety of modern processor families and architectures can be found in the Grid clusters. The basic idea is that we shall apply a parallel distributed approach for the EM simulation. Instead of computing the different models simulation one after another on the same local computer, they will be computed in parallel on centralized facilities operated by third-party compute and storage utilities. There are two prerequisites for this scenario. First, the application (EM software) must be executable remotely. Second, the remote machine must meet any special hardware, software, or resources requirements imposed by the application.

An experiment could be resumed in following six steps:

1. Connect to the platform on a site
2. Reserve the needed computing resources
3. Configure the resources
4. Run experiment
5. Grab the results
6. Free the resources

A Grid'5000 Experiment Workflow is sketched in Figure 2.

In order to execute the different simulations (jobs), the first step is to reserve computing nodes. Note that the number of reserved nodes is relative to the number of simulations to run. As sketched in Figure 3, this task is performed by the resource management system OAR (OARSUB command) [12]. The user accesses the Grid by a Secure SHell (SSH) network connection, get to the frontend machine, and reserve its computing nodes. Then, input files, executables and script files (batch jobs) are sent to the computing environment to be remotely launched for execution. This execution is performed by using the specific software named KADEPLOY [13]. The last step of the experiments is to retrieve the results from the computational nodes and to store them on the local Network File System (NFS) servers. Once the EM simulation has been performed for the antenna array, the far-field is finally computed in order to derive the radiation pattern.

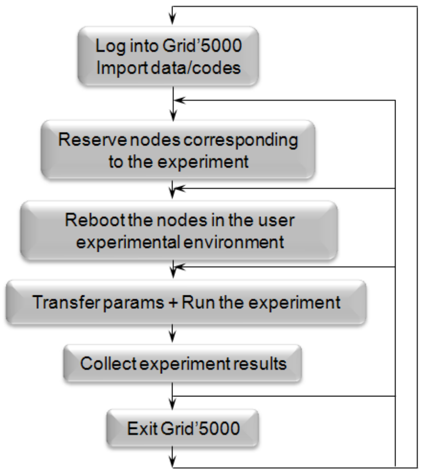


Figure 2. Experiment workflow.

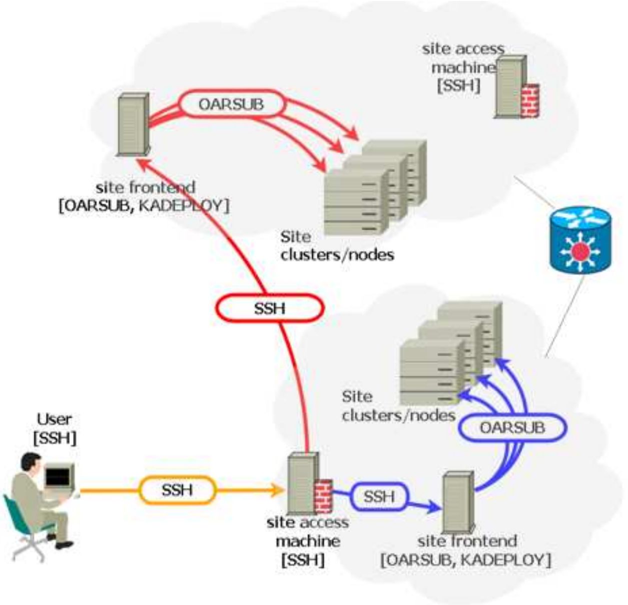


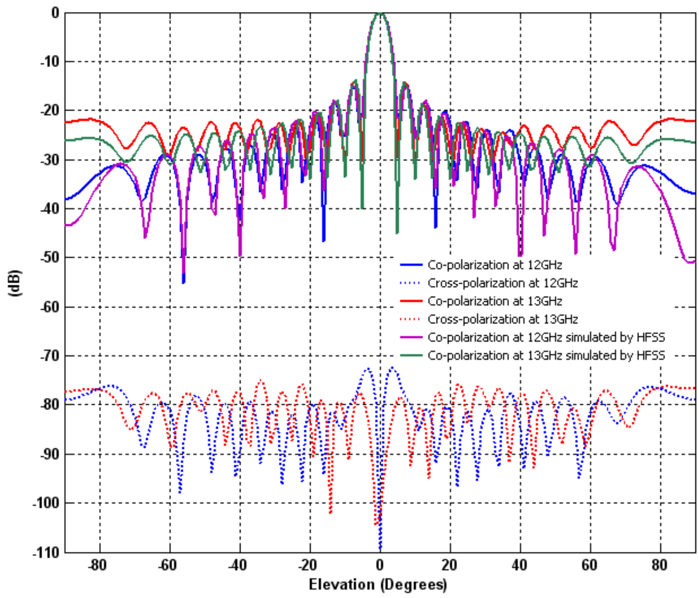
Figure 3. Simplified view of the platform: The user (1) accesses safely (**SSH** connection) the Grid via the *site access machine* of a Grid computing site (sites are sketched by clouds in this figure), (2) gets to the *frontend* node, (3) reserves nodes by OARSUB command, and (4) deploys its codes with KADEPLOY software.

4. RESULTS AND DISCUSSIONS

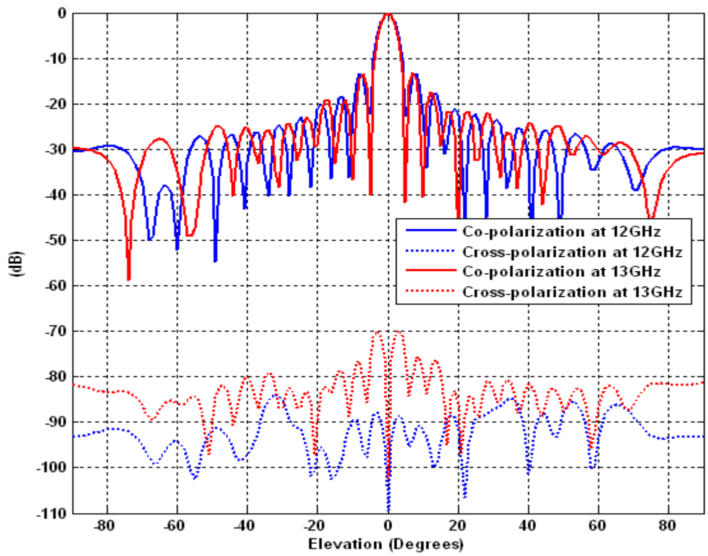
In this section, applications of the Grid-based EM simulation tool for the parametric analysis of the reflectarray shown in Figure 1 in are presented. Parametric studies are used here on geometrical dimensions as well as frequency points of interest to help the designer choosing the most appropriate elementary cell dimensions.

Common plots of the *E-phi* and *E-theta* components of the backscattered electric field are used to visualize the radiation pattern. As an example, in Figure 4, plots are shown in the case of a uniform reflectarrays composed of 81 identical metallic patches (x_patch = 13.5 mm, y_patch = 6 mm) with slot dimensions $b = 6$ mm, $a = 1$ mm. (Note that this paper is not focused on the design of reflectarrays but only on the computation time required for the parametric analyses of such arrays). Frequency sweep is interesting for parametric distributed cases in order to calculate, e.g., the bandwidth of the reflectarray. For reasons of clarity, only two frequency points are presented here. Figure 3 shows the radiation patterns for co-polarization and cross-polarization in the H-plane and E-plane at 12 GHz and 13 GHz (as expected from the symmetry of this first illustrative structure, the cross-polarization level is very low compared with the co-polarization level). For these EM simulations, by using only two computers, overall simulation time is reduced from about 75 minutes (on one computer) to 37 minutes. Results are found to be in good agreement with HFSS [14] simulation results (for the sake of readability of the figures, only two comparison to HFSS simulation results are reported here (see Figure 4(a), curves in green and purple)).

Figure 5 shows the radiation patterns in the case of 9×9-element non-uniform reflectarrays shown in Figure 1 simulated at a single point of frequency. This reflectarray has the same cell geometries as above but with patch dimensions configurations (x_patch = 13.5 mm, y_patch = 2 mm to 12 mm), while varying slot width b from 2 mm to 12 mm and keeping on $a = 1$ mm. The asymmetry of this second structure generates a cross-polarization level higher than one observed in the symmetric case considered in Figure 4. The simulated radiation patterns show that the main beam position steers toward 5° and 10° (Figure 5(b)) ($\Phi = 0°$ cut). In order to grasp the efficiency of distributed computing in such cases, the simulation of 64 arbitrarily chosen configurations (all with different patch and slots dimensions) of this structure are distributed on the Grid computing platform. The total simulation time is about 40 hours on an Intel Xeon 5140 @ 2.33 GHz with 4 GB memory computer. Figure 6 shows the time reduction reached with respect to the number of nodes used in the

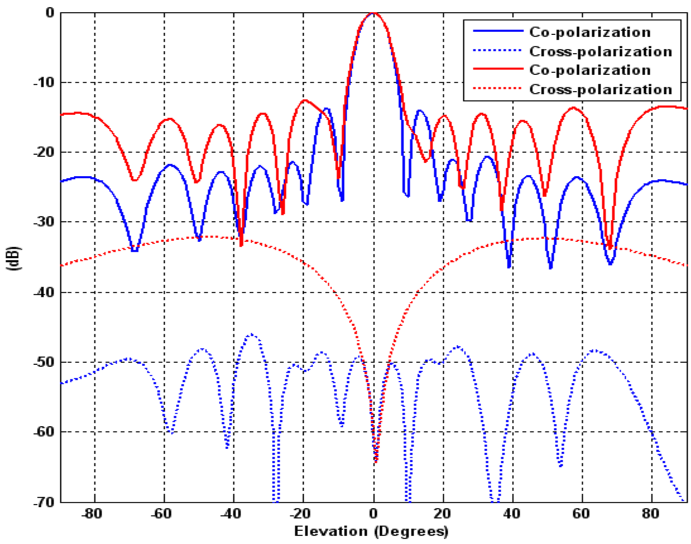


(a)

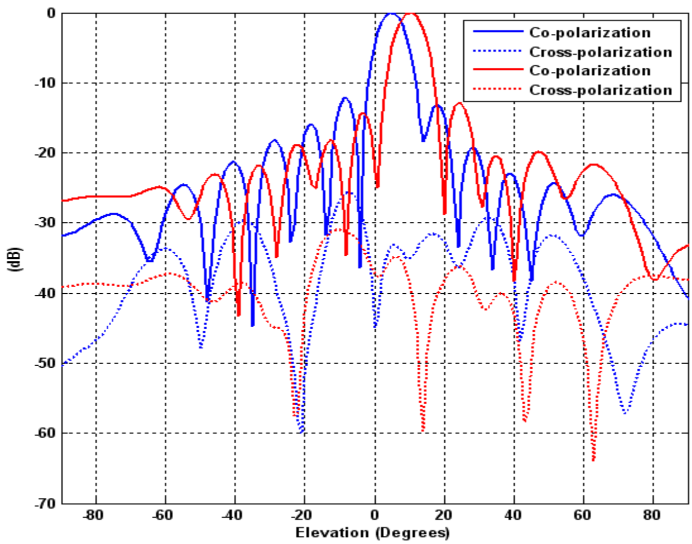


(b)

Figure 4. The simulated radiation patterns for a uniform reflectarray composed of 81 identical patches loaded with one centered slot in (a) E-plane and (b) H-plane at 12 GHz (blue lines), and 13 GHz (red lines).



(a)



(b)

Figure 5. The simulated radiation patterns in (a) E-plane and (b) H-plane at 12.5 GHz for two non-uniform reflectarray composed each of 81 cells with $x\_patch = 13.5$ mm, $y\_patch = 2$ mm to 12 mm, while taking slot dimension $b = 2$ mm to 13 mm and $a = 1$ mm. (Blue lines: first non-uniform array; red lines: second non-uniform array).

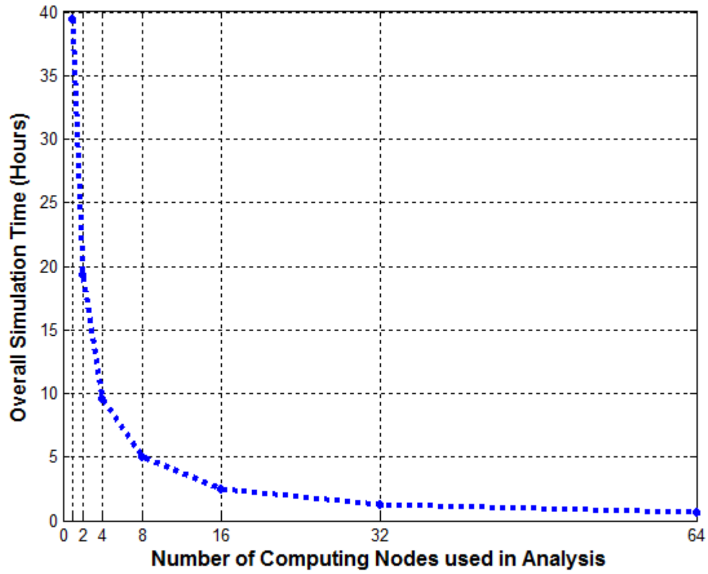


Figure 6. Time reduction with respect to number of nodes for the Grid-based global electromagnetic simulation of non-uniform reflectarray shown in Figure 1.

analysis. As expected, the overall execution time of the simulations depends on the number of nodes that are used, or more precisely, on the number of simulations that are executed on each node. A speed-up of 1.88 (compared to the time needed for the computation on one computer only) is reached by using two computers. Increasing the number of computing nodes to solve the problem increases the speed-up. User must choose for advance the number of Grid nodes reserved in order to accommodate heavier or lighter electromagnetic simulation requests. The best performance is obtained while distributing the simulations in a way to execute one simulation per computing node. These results point out the benefit from using a large number of computational nodes for running TLM simulations.

5. CONCLUSION

The use of Grid Computing to solve electromagnetic problems was presented in an example of distributed parametric simulation for planar microstrip antenna arrays. The modeling platform is based on a Transmission Line Matrix solver which is license-free.

Regardless from the number of possible parametric configurations antenna elements may have, their full-wave analysis can be carried out at the computational costs of a single one, by distributing them over a corresponding number of nodes. Currently this grid parametric approach is being applied to more evolved solvers such as emGine Environment able to support Genetic Algorithm (GA) [15].

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