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Modular modeling and optimization for large antenna arrays

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Abstract— **In the next-generation phased-array systems, a closely packed system of RF functions and electronics is expected. This creates a need for both accurate and flexible design tools. We employ the generalized scattering matrix (GSM) formalism to arrive at a flexible tool with modest computational costs to enable a computer-aided design trajectory. We employ an integral equation technique to generate the scattering matrices and discuss some optimization strategies that seem appropriate for the type design problem that is obtained via the GSM formalism.**

I. INTRODUCTION

Traditionally, large phased-array systems have been applied mainly in military radar systems. The main reason being the high costs associated to the high degree of complexity of the overall electronic system and the large number of individual antenna elements in the aperture. However, the advantage of full electronic beam steering over (partial) mechanical systems has generated wider interest in this technology. For instance, in radio astronomy the possibility to build a square kilometer array is under investigation for several years now. Also, in telecommunication applications, a similar trend is observed. So far, the main obstructions have been the cost per element and the system complexity. Whereas the latter is coming within reach for civil applications, owing to Moore's law, it is the former that has been persistent.

To reduce the cost per element, mass production technologies are being considered. As a consequence, antenna, system electronics, and packaging are merging into a highly integrated concept. Furthermore, pick-and-place technology is considered for assembling the entire phased-array system, to further reduce the cost. One of the major consequences is that certain types of closures, e.g. an iris plate, do not conform to this philosophy. Due to such manufacturing constraints, the array of antenna elements is not necessarily a layered medium in one direction, but tends to consist of a large number of non-connected dice. A typical example of the latter is shown in Figure 1. In such a highly integrated concept of antenna element and electronics, where also the elements themselves are closely packed, the design of a phased-array system becomes even more challenging. This design challenge can be considered as a large optimization problem of a cascade of RF functions consisting of the radome, the radiating element(s), the feed structure, connections and electronics. The focus of the design is mostly related to impedance matching between the separate RF functions as a function of frequency, for large bandwidth characteristics, and scan angle, to access a large scan volume. In this sense, there is a large difference between RF functions at the perimeter of the system and connected to the outside world, such as the radome and the radiating element, and RF functions at the interior of the system and fully isolated, in the sense that scan angle only plays an explicit role in the former functions. In the development of a suitable design strategy, there exists a strong interaction between choices made in the antenna modeling and the type of optimization strategy. For example, for antenna characterization tools with low computational costs a brute-force optimization may be conceivable, whereas for computationally expensive tools a high degree of efficiency of the optimization strategy is required. For the case that we consider here, we aim at numerical characterization tools with a modular structure to reach a high degree of flexibility at modest computational cost.

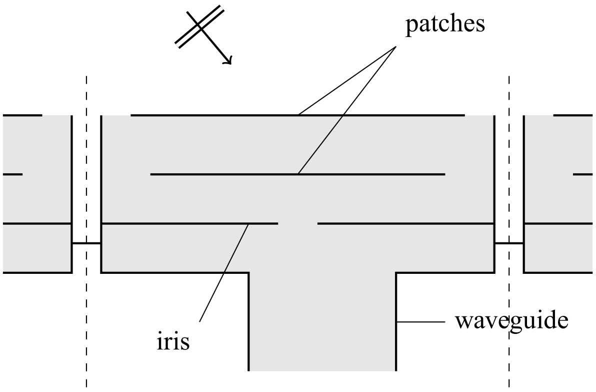

Fig. 1. Cross-section of a cavity backed patch with slits

II. ANTENNA MODEL

To approach the antenna design problem as an optimization problem, one of the key aspects is to arrive at a flexible and efficient modeling tool to evaluate the antenna performance. For a large class of antenna arrays, including patch antennas on layered media, waveguide arrays, and cavity-backed patch antennas (see Figure 1), the generalized scattering matrix (GSM) formalism leads to a particularly versatile scheme, in which also the physical wave behavior is accessible to the designer. The GSM formalism does not suffer from numerical breakdown that is sometimes observed in impedance or admittance formalisms, owing to the fact it separates outwards traveling waves from incident waves [1], [2]. In this formalism, uniform waveguide sections are connected by waveguide discontinuities, e.g a patch or an iris. The behavior of the uniform waveguide sections is described by the modal representation of the waveguide, whereas the waveguide discontinuities are characterized as converters that transform a set of modes in one connecting waveguide section into the modes of the other connecting section.

For the class of antennas under consideration, it assumed that each waveguide section has either perfectly electrically conducting (PEC) or quasi-periodic boundaries. Further, each section is filled with a homogeneous and isotropic dielectric. The antenna elements that we consider have a rectangular cross section and are placed in a large regular rectangular (possibly staggered, see Figure 2) grid. For a large part, the elements can be built from rectangular waveguide sections and the array behavior is well described by an infinite-array assumption. For this type of setup the modal representations are well-known and available analytically [3], [4]. To characterize a waveguide discontinuity between to waveguide sections, we first close the waveguide sections at the position of the discontinuity by a PEC screen. Subsequently we apply Schelkunoff's equivalence principle, e.g. [5], [6], and introduce equivalent magnetic currents at the former aperture between the sections (see Figure 3). For each waveguide section we can represent the total electric and magnetic field in terms of the incident fields and the fields originating from the magnetic currents. The latter representation takes the form of an integral representation in which the Green's function is constructed from the modal representation of the pertaining waveguide section. In the final step, the continuity of the tangential electric and magnetic fields across the opening, which leads to a direct relation between the magnetic currents in both sections for the electric fields and an integral equation for the magnetic field. In this particular case, the typical problem of Schelkunoff's equivalence principle connected to interior resonances do not occur, owing to the fact that there are no enclosed regions, i.e. each waveguide section has radiation conditions at one of its ends. Further, by employing an integral equation technique, we avoid the problem of relative convergence that has been observed in mode-matching techniques [7], [8]. To characterize the mode-transformation properties of the waveguide discontinuity, we have to solve the integral equation for multiple right-hand sides, i.e. for all incident waves that can reach the discontinuity by passing through the waveguide section with a certain minimum length. To solve this integral equation for the waveguide discontinuity, we employ either transverse waveguide-mode functions or rooftop functions to span the magnetic currents across the aperture. The mode functions are appropriate for the case where the aperture equals the cross section of one of the two waveguide sections, whereas rooftop functions are typically applied for other discontinuities such as patches or more exotic types of irises. To arrive at a matrix equation, we employ testing functions equal to the basis functions of the magnetic currents (Galerkin).

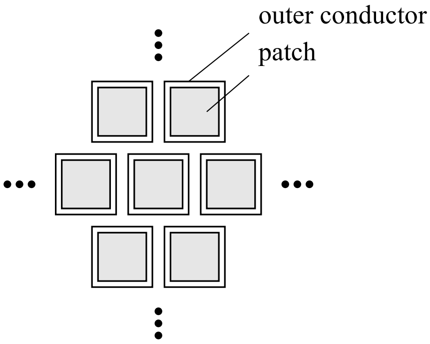

Fig. 2. Array elements distributed according to a staggered grid

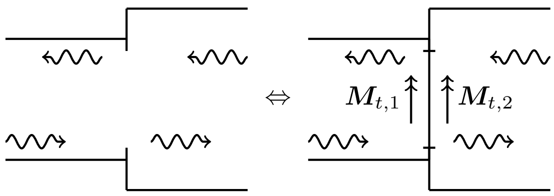

Fig. 3. Two magnetic current densities near a PEC sheet

As a first example, we show the behavior of a thick iris connected to two standard rectangular WR90 waveguides. The setup and the corresponding dimensions of the iris are given in Figure 4. For this case, we have used rectangular waveguide modes to span the magnetic currents at the aperture of the iris. To validate the simulation result, we have conducted measurements. In Figure 5, the modulus and phase behavior of S_{11} for this connection are shown for both the simulations and the measurements. Except for a slight shift in frequency, we observe very good agreement between simulations and measurements.

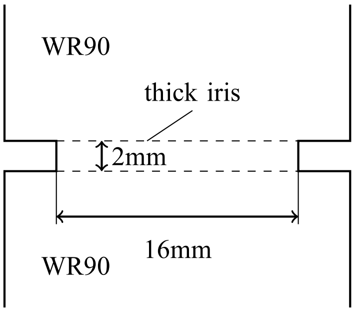

Fig. 4. Rectangular waveguides connected by a thick iris. The width of the iris is 1.5 mm.

A second validation example is a thick grating. In this example, two periodic half-spaces are connected by a periodic array of square holes in a PEC plate. The setup is presented in Figure 6. We compare the results to those published in [9]. In this case, the magnetic currents at the position of the hole have been expanded in terms of rooftop functions.

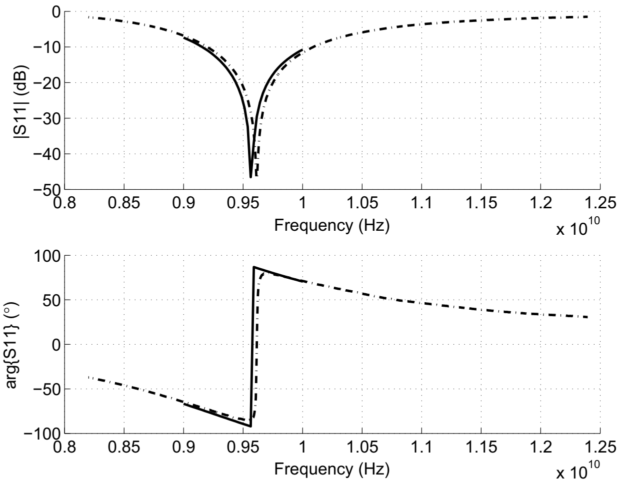

Fig. 5. Modulus and phase of S_{11} for the thick-iris configuration. The simulation results are indicated by the solid line and the measured results by the dash-dotted line.

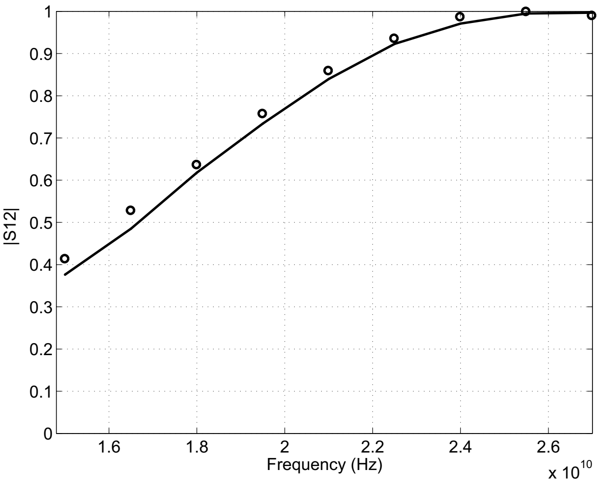

Fig. 7. Modulus of S_{12} for the PEC grating configuration. Our simulation results are indicated by the solid line and the results of [9] are indicated by bullets.

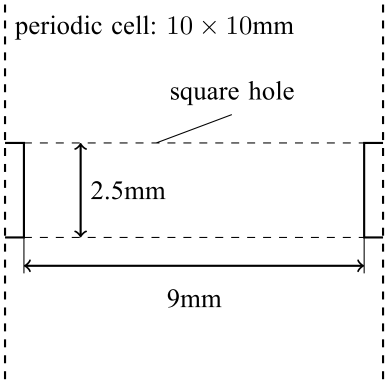

Fig. 6. Geometrical setup of a thick PEC grating.

Apart from the standard discontinuities shown above, we have extended our numerical tools. For example, we have included the case in which two or more waveguides are connected to a third via a planar discontinuity. Such a case is observed in Figure 1, where the periodic half space above meets the aperture of the patch and a waveguide created by the spacing between the antenna elements. We can also include junctions between a rectangular waveguide and a non-canonical one, where we employ a 2D finite element method to construct a modal representation. Finally, a frequency extraction technique is employed to obtain results over a range of frequencies for limited extra costs.

III. OPTIMIZATION

The modeling approach described above exhibits some characteristics that can be exploited to arrive at an efficient optimization scheme. Typically, changes in the length of a waveguide section can be analyzed efficiently, owing to the modal structure of the waveguide section. Owing to the modular structure of the GSM approach, changes in a single layer result in a marginal cost in evaluating the total performance of the antenna, once the scattering matrix of the pertaining layer has been determined. Hence, the characterization of the waveguide discontinuities tend to dominate the total computation time.

Besides the modeling approach, the formulation of the design problem turns out to be important for the efficiency and the strategy with which the design problem is approached. As an example, we consider the formulation of impedance matching as a function of frequency and scan angle. By representing the frequency and scan angle as a discrete set of points, one obtains the VSWR on this set. Then the task is to minimize the highest peaks, such that an overall acceptable VSWR level is obtained. Such a formulation takes the form of a minimax problem, for which very few algorithms are available. Alternatively, if one introduces slack variables for the maximum VSWR value, one obtains a standard nonlinear programming problem, i.e. a constrained optimization problem, for which a large number of strategies are available. We have considered several continuous-optimization strategies and problem formulations and evaluated the success and efficiency of these strategies [10], [11] for a number of antenna design problems.

These observations bring much freedom in approaching the design problem as an optimization problem. A possible approach is to build a library of generalized scattering matrices for predefined waveguide discontinuities. Then the optimization problem becomes one in which we have a number of discrete parameters, i.e. choices from the library, and a set of continuous parameters for the waveguide sections. Although the characterization of the antenna performance for each parameter setting is modest in computation time, it is not clear in which way the optimization problem is attacked in the most efficient way. The optimization community, this type of problem is indicated as mixed-integer optimization [12] and is traditionally dealt with via branch-and-bound techniques. The core of such a strategy is an alternation between integer and continuous optimization. In the integer optimization, a tree is constructed and by bounding the optimal results, e.g. via continuous optimization, one can discard certain parts of the tree. In many engineering disciplines an alternative route is often taken by making the continuous parameters discrete as well and then apply some form of stochastic optimization technique such as a genetic algorithm (GA) [13] or a particle swarm optimization (PSO) [14], [15]. Such stochastic approaches are only viable when the computational costs of the underlying performance evaluation of the antenna are sufficiently low.

We are currently exploring the viability of these optimization strategies and problem formulations for the type of antennas described above and we will give a detailed account on the results of this study.

IV. CONCLUSION

For next-generation phased-array antennas, electronics and RF components are brought together in a single package. Such a setup calls for accurate and flexible design tools to accommodate the daunting design tasks. The generalized scatting matrix formalism provides such an efficient and flexible way to analyse and design antenna elements. In our approach, the scattering matrices are determined by solving a set of integral equations that are obtained via Schelkunoff's equivalence principle. This approach is both efficient and numerically robust. To approach the design problem, we have discussed several alternative optimization strategies and have indicated the importance of a proper formulation of the design problem.

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