Advances on multi-scale MbD synthesis of WAIMs for advanced phased arrays

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Abstract. The most recent advances on the synthesis of wide-angle impedance matching (WAIM) devices for next-generation phased arrays are discussed. Towards this end, the WAIM design problem is formulated within the Material-by-Design (MbD) framework with the objective of minimizing the antenna input reflections caused by mutual coupling (MC) effects arising at the antenna aperture when steering the main beam in a wide angular region. Accordingly, the degrees-of-freedom (DoFs) are represented by the constituent materials of the synthesized structure and/or the micro-scale geometrical descriptors of the considered unit cells. Selected illustrative results will be shown in order to assess the effectiveness and the potentialities of leading-edge MbD solutions for the design of reliable and easy-to-implement WAIMs.

1. Introduction

Active electronically-scanned arrays (AESAs) represent nowadays a key-technology in many applicative domains ranging from radar to space communications [1]. Moreover, they will cover a fundamental role for the successful deployment of fifth-generation (5G) mobile communication systems [2]. However, the increasing demand of wide scanning angles and broadband functionalities are involving unprecedented design challenges in order to meet several conflicting requirements, which become particularly critical when aperture radiators (such as, for example, horns or truncated waveguides) are needed to allow high-power transmissions. Indeed, the scanning capabilities of such architectures are limited by the unavoidable mutual coupling (MC) effects arising between adjacent elements, causing non-negligible deviations of the reflection coefficient at the air-aperture interface when directing the main beam far from the broadside [3]-[8].

Several strategies can be adopted to reduce MC and enhance the array steering capabilities. Just to mention a few examples, non-uniform arrangements could be exploited to mitigate the inter-element interactions, with the main undesired drawback of decreasing the antenna efficiency [1]. Otherwise, low-profile multi-layer dielectric structures covering the array aperture, often indicated as wide-angle impedance matching (WAIM) devices can be designed to significantly reduce the amount of reflected power towards the feeding network in a wide range of steering angles and frequencies [3]-[8].

Within this context, artificially-engineered materials (such as, for instance, meta-materials/meta-surfaces) clearly represent one of the most appealing and competitive technologies to address the synthesis of WAIMs. Indeed, thanks to their capability of manipulating "at will" the propagation of electromagnetic (EM) waves, meta-materials are enabling the design of complex devices exhibiting unconventional features in many applicative fields [9]-[14], including (but not limited to) Luneburg lenses [11], mutual blockage reduction [13], and cloaking [9].
The efficient realization of multi-layer and multi-frequency WAIMs has been recently proposed within the Material-by-Design (MbD) paradigm, an instance of the System-by-Design (ShD) framework [7], [8], [14], defined as the "application-oriented synthesis of field-manipulating systems whose constituent electromagnetic properties are driven by the device functional requirements". According to the MbD vision, the material electromagnetic (EM) properties [7] and/or the micro-scale structure of the elementary cell (when printed WAIMs are considered to simplify the realization process [8]) become the actual degrees-of-freedom (DoFs) to be properly tuned through effective and efficient optimization strategies, as briefly resumed in the following.

2. Multi-scale MbD approaches for the synthesis of WAIMs

Following the MbD paradigm [7], [8], [14], the problem of synthesizing a WAIM device providing the desired features is effectively addressed by decomposing the whole design process into elementary functional blocks, each solving rather "simple" tasks. More precisely, the solution is obtained by combining (i) a computationally-efficient EM modeling block for accurately modeling the reflections at the air-aperture interface, (ii) a physical linkage block devoted at assessing the fitting of all user-defined/application-driven constraints and objectives, and (iii) a solution-space exploration block for the effective search of the global optimum of a suitably defined cost function [7], [8].

To these functional blocks, a fourth homogenization one can be added to determine the equivalent permittivity/permeability tensors of each layer when considering the design of printed WAIMs over off-the-shelf dielectric substrates [8], [15]. As a matter of fact, the first MbD attempts to synthesize high-performance WAIMs involved the direct optimization of the constituent materials of each layer [3], [7]. However, despite the very promising results, those strategies rely on the availability (hopefully real in the near future) of manufacturing technologies able to reproduce arbitrary anisotropic permittivity and permeability distributions [7]. To overcome such a feasibility limit of the obtained solutions, multi-scale MbD approaches have been proposed [8], in which the WAIM is a printed meta-surface [16] rather than a set of homogeneous dielectric layers. In this case, the synthesis problem is re-formulated as the optimization of the micro-scale structure (i.e., the geometrical descriptors of the elementary cells), instead of the macro-scale equivalent permittivity/permeability tensors [8].

Concerning the actual implementation of each functional block, the modal analysis method [7] allows to derive an accurate but computationally efficient EM modeling block without recurring to time-consuming full-wave simulations. Regarding the physical linkage block, the WAIM macro-scale requirement is the minimization of the integral power reflection across all the considered steering angles (i.e., allowing a sufficiently large scan cone \( \vartheta \in [\vartheta_{\text{min}}, \vartheta_{\text{max}}] \cup \varphi \in [\varphi_{\text{min}}, \varphi_{\text{max}}] \)) and operative frequencies (i.e., enabling a proper matching over the user-defined frequency range \( f \in [f_{\text{min}}, f_{\text{max}}] \)).

Such a requirement is typically mathematically translated into the following cost function [8]

\[
\Phi(\Omega) = \int_{f_{\text{min}}}^{f_{\text{max}}} \int_{\varphi_{\text{min}}}^{\varphi_{\text{max}}} \int_{\vartheta_{\text{min}}}^{\vartheta_{\text{max}}} \left| \Gamma(\vartheta, \varphi, f; \Omega) \right|^2 d\vartheta d\varphi df
\]

where \( \Omega \) is the set of design DoFs (i.e., the layers thicknesses, the permittivity/permeability tensors [7] or the meta-surface unit-cell descriptors [8], etc...) and \( \Gamma(\vartheta, \varphi, f; \Omega) \) is the voltage reflection coefficient at the planar aperture. Of course, additional terms could be added to (1), as well, to include multi-physics requirements depending on the applicative scenario (e.g., thermal, aerodynamic, etc...).

As for the solution-space exploration block, remembering the no-free-lunch theorem on evolutionary optimization [17], [18] and given the highly non-linear/multi-modal nature of (1) and the real-nature of the DoFs, the Particle Swarm (PS) [7], [8], [18] represents a particularly suitable candidate to effectively and efficiently reach the global optimum. Finally, the homogenization block can be easily implemented through homogenization formulas linking the macro-scale WAIM EM properties (i.e., permittivity/permeability tensors) to its micro-scale features (i.e., the geometrical descriptors of the surface elementary cells) and the frequency [8], [15].
3. Conclusions

The most recent advances on the MbD-based synthesis of WAIM layers for enhancing the scanning capabilities of phased arrays have been discussed. The recently proposed methodologies allow unprecedented flexibility and effectiveness in realizing single-/multi-layer and single-/multi-frequency devices. Moreover, the development of multi-scale MbD approaches allowed the simplification of the manufacturing process through suitably designed microstrip printed surfaces. Further research is still needed to address the synthesis of complex unit-cells, as well as to generalize the existing strategies to any kind of phased array/elementary-radiator, and to conformal antennas. Furthermore, the integration of powerful interval-analysis (IA)-based techniques [19]-[24] in the WAIM design process is envisaged to predict and improve the robustness of the obtained layouts to several manufacturing uncertainties.

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