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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 (*DoF*s) 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 *WAIM*s.

1. Introduction

Active electronically-scanned arrays (*AESA*s) 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 *WAIM*s. 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].

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The efficient realization of multi-layer and multi-frequency *WAIM*s has been recently proposed within the Material-by-Design (*MbD*) paradigm, an instance of the System-by-Design (*SbD*) 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 *WAIM*s are considered to simplify the realization process [8]) become the actual degrees-of-freedom (*DoF*s) 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 *WAIM*s

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 *WAIM*s over off-the-shelf dielectric substrates [8], [15]. As a matter of fact, the first *MbD* attempts to synthesize high-performance *WAIM*s 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 $\vartheta \in [\vartheta_{\min}, \vartheta_{\max}] \cup \varphi \in [\varphi_{\min}, \varphi_{\max}]$) and operative frequencies (i.e., enabling a proper matching over the user-defined frequency range $f \in [f_{\min}, f_{\max}]$). Such a requirement is typically mathematically translated into the following cost function [8]

$$\Phi(\mathbf{\Omega}) = \int_{f_{\min}}^{f_{\max}} \int_{\vartheta_{\min}}^{\vartheta_{\max}} \int_{\varphi_{\min}}^{\varphi_{\max}} \left|\Gamma(\vartheta, \varphi, f; \mathbf{\Omega})\right|^2 d\varphi\, d\vartheta\, df \tag{1}$$

where $\mathbf{\Omega}$ is the set of design *DoF*s (i.e., the layers thicknesses, the permittivity/permeability tensors [7] or the meta-surface unit-cell descriptors [8], etc...) and $\Gamma(\vartheta, \varphi, f; \mathbf{\Omega})$ 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 *DoF*s, 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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