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Learning based direction of arrival estimation using a programmable metasurface

Estimation de la direction d'arrivée fondée sur l'apprentissage à l'aide d'une métasurface programmable

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Mots clés : métasurface, reconfigurabilité, direction d'arrivée, réseau neuronal multicouche.

Abstract

A metasurface solution for the estimation of direction of arrival of electromagnetic waves is presented. The metasurface, which is programmable, is used as a reflector with an adjustable pointing direction to scan the azimuth plane for sensing and reflecting incoming waves to a focal point. A processing layer based on a pre-trained multilayer neural network is then exploited to interpret the measured power signatures and provide fast and accurate DOA estimation.

Une solution à base de métasurface est proposée pour l'estimation de la direction d'arrivée (DOA) d'ondes électromagnétiques. La métasurface, programmable, est utilisée comme un réflecteur dont la direction de pointage peut être ajustée afin de balayer le plan azimutal, capter les ondes incidentes et les réfléchir vers un point focal. Une couche de traitement fondée sur un réseau neuronal multicouche pré-entraîné est ensuite exploitée pour analyser les variations des niveaux de puissance mesurés et fournir une estimation rapide et précise de la DOA.

1 Introduction

In a general manner, DOA is estimated through the use of phased array antennas and various calculation methods [1], ranging from beamforming with Fast Fourier Transform (FFT) technique to algorithms such as MUSIC and ESPRIT [2]. In spite of their remarkable resolution and accuracy, these algorithms present limitations in terms of computational and storage resources, and their performance is significantly degraded for non-ideal conditions and imperfect antenna arrays. Metasurfaces, with their ability to manipulate electromagnetic waves at a subwavelength scale, have brought significant advances in DOA estimation. A metasurface, interacted with artificial intelligence, has also been applied for efficient and accurate DOA estimation [3]. However, large amounts of data are still required and computation remains time-consuming.

Here, we present a programmable flat metasurface reflector where the pointing direction can be adjusted by varying its voltage-controlled phase profile to scan the azimuth plane for DOA estimation [4]. By continuously varying the pointing direction of the metasurface reflector, a series of power levels received by the detector is measured and recorded. A processing layer based on a pre-trained multilayer neural network is exploited to interpret the measured power signatures, enabling fast and accurate DOA estimation from a limited number of measurements, without requiring fine angular scanning of the metasurface reflector [5,6].

2 Experimental validation of DOA estimation

For the experimental study, a series of 19 parabolic phase configurations is applied to the metasurface reflector in order to perform a coarse angular scanning over the azimuth plane. A microwave horn antenna is placed at the transmitter side on a semi-circular rail to launch electromagnetic waves toward the metasurface reflector within an azimuth angular range from -60° to 60°. For each considered angle of incidence, the power of the reflected signal is measured for all metasurface configurations using an RF detector positioned at the focal point (Fig. 1a).

The experimental measurements thus obtained are used to construct a supervised dataset, in which each sample is represented by a power-level vector corresponding to the 19 metasurface configurations, associated with the corresponding direction of arrival. This dataset contains a large number of samples acquired over the entire angular range and is subsequently divided into training, validation, and test sets, enabling model learning and performance evaluation on previously unseen data.

The training performance of the Multilayer Perceptron (MLP) model is analyzed using the learning curve shown in Fig. 1b. The monotone decrease of the root mean square error (RMSE) on the training set, together with a progressive and stable reduction of the validation error, indicates proper convergence of the model. The limited gap between the training and validation curves confirms the absence of overfitting and demonstrates good generalization capability.

The angular estimation accuracy is evaluated on the test set and illustrated in Fig. 1c, which compares the DOA values predicted by the model with the corresponding ground-truth values. The data points are distributed almost linearly along the ideal diagonal over the entire angular range considered, confirming the fidelity of the learned relationship between power signatures and directions of arrival. This performance results in a mean absolute angular error (MAAE) of 0.5°, demonstrating the ability of the proposed system to estimate the DOA from acquired power signatures, despite the use of a coarse angular scanning strategy.

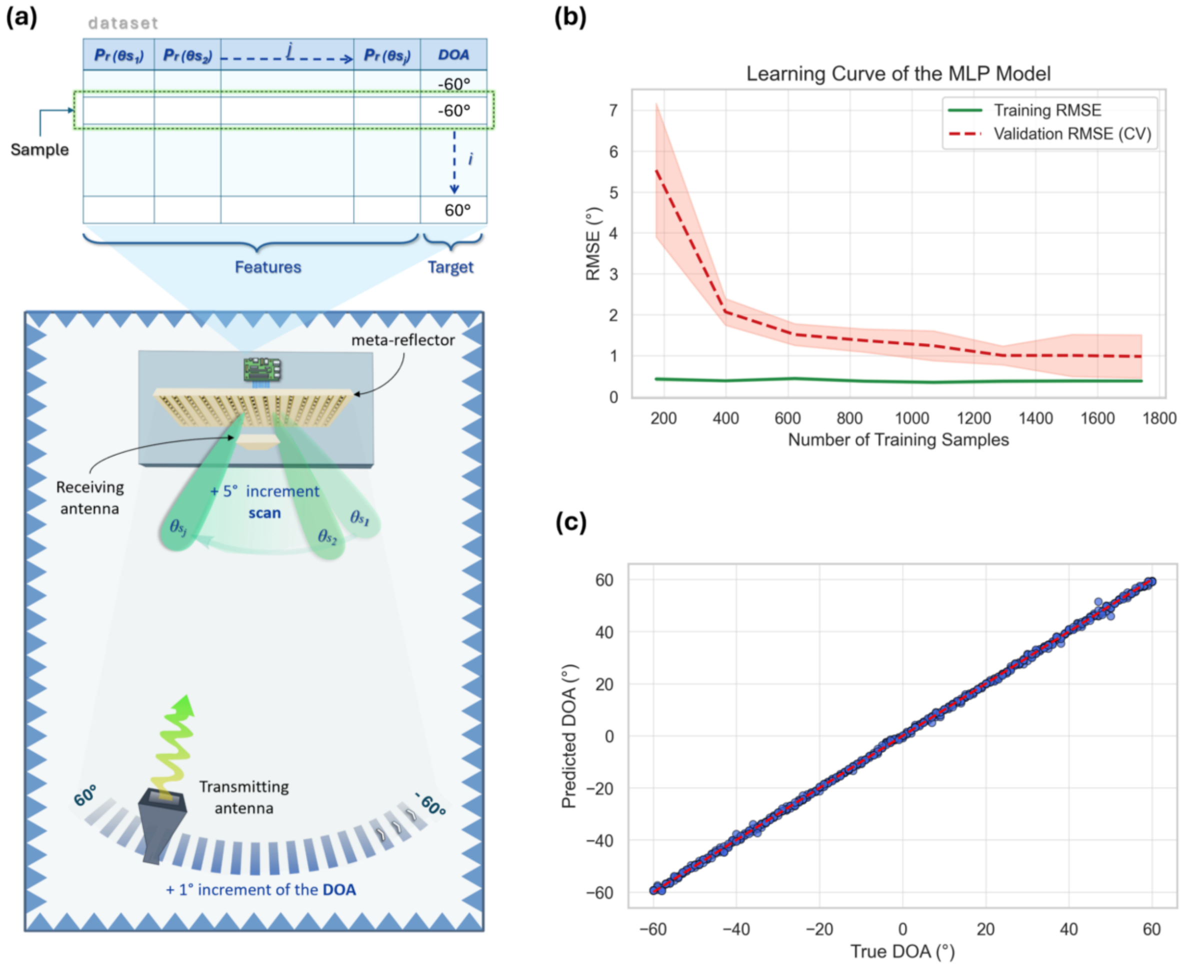

Figure 1: (a) Schematic principle of the metasurface-based platform for DOA estimation. (b) Learning curve of the MLP model for the DOA estimation. (c) Comparison of predicted vs. real DOA values.

3 Extension to multipath scenarios

Although the experimental validation presented in the previous section focuses on a single-source scenario, the proposed detection approach, based on a programmable metasurface, naturally lends itself to an extension toward more realistic propagation environments, in which multiple signals may arrive simultaneously from different directions. Such scenarios commonly occur in practice, either due to multipath propagation induced by reflections and diffractions from the surrounding environment, or in the presence of multiple active transmitters operating at the same frequency.

In such multipath scenarios, the incident field at the metasurface can no longer be described by a single plane wave, but rather by a superposition of multiple contributions, each associated with a distinct direction of arrival and power level. The response measured by the metasurface under different configurations therefore contains richer angular information, which can no longer be interpreted through a single-direction estimation.

Nevertheless, the fundamental principle of the proposed approach remains unchanged: angular information is still encoded in the power signatures measured across the different metasurface configurations. By exploiting a learning-based processing layer, the estimation problem can be reformulated as the reconstruction of an angular spectrum, in which multiple peaks may coexist, each corresponding to a distinct incident path, as illustrated in Fig. 2. The dominant directions of arrival can then be identified from the main maxima of the reconstructed spectrum. These results highlight the ability of the proposed approach to capture the main angular characteristics of multipath scenarios and to reliably identify multiple dominant directions of arrival, even when several signals are present simultaneously. Preliminary numerical results further show that the angular spectrum can be reconstructed with an average reconstruction error on the order of 0.03°, emphasizing the potential of programmable metasurfaces combined with learning-based techniques for DOA estimation in dense and multipath propagation environments, while maintaining a compact hardware architecture relying on a single receiving antenna.

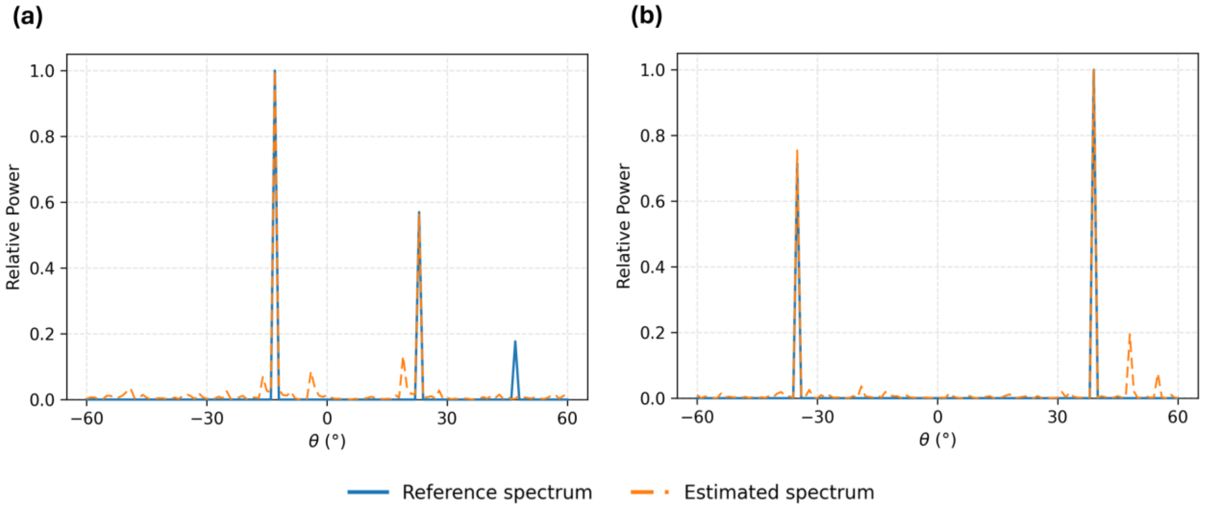

Figure 2: Angular spectrum reconstruction in multipath scenarios, showing accurate identification of dominant directions of arrival in cases (a) and (b).

4 Conclusions

In this work, a fast and accurate method for DOA estimation has been presented, based on the combination of a programmable metasurface and a learning-based processing layer. By exploiting power signatures measured over a limited number of metasurface configurations, the proposed system enables DOA estimation using a single receiving antenna, despite the use of a coarse angular scanning. Experimental results in a single-source condition demonstrate excellent accuracy, with a mean absolute angular error of 0.5°. In addition, preliminary results in multipath conditions indicate a reliable reconstruction of the angular spectrum, with an average reconstruction error on the order of 0.03°, highlighting the potential of the proposed approach in more complex propagation environments.

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