2024 IEEE International Symposium on Antennas and Propagation and INC/USNC-URSI Radio Science Meeting (AP-S/INC-USNC-URSI) | 979-8-3503-6990-8/24/$31.00 ©2024 IEEE | DOI: 10.1109/AP-S/INC-USNC-URSI52054.2024.10686871

Deep Learning Aided Modelling and Inverse Design for Multi-Port Antennas

Emir Ali Karahan, Zijian Shao, Kaushik Sengupta
Department of Electrical and Computer Engineering, Princeton University, Princeton, USA
{karahan, zijianshao, kaushiks}@princeton.edu

***Abstract*—With the prevalence of multiple-input multiple-output (MIMO) systems, multi-port antenna design has become an important research area. In this work, we approach the multi-port antenna design problem to accelerate the design cycle, expanding design space, and finding non-intuitive designs that can potentially yield better performance than existing template-based designs. To achieve these, we rely on the optimization of a discretized surface, which can implement near-arbitrary antenna shapes. However, performing an electromagnetic (EM) optimization with a large number of variables is prohibitively costly. On the other hand, if EM simulations can be replaced by a machine learning (ML) based approach, antenna optimization could be accelerated greatly. To this end we utilize a convolutional neural network (CNN) for the modeling of multi-port pixelated structures. A genetic algorithm (GA) in conjunction with CNN is used to perform inverse design. Example designs for various optimization targets have been shown in support of the proposed approach.**

***Index Terms*—Deep neural networks, antenna design, electromagnetic, mmWave, genetic algorithm, machine learning**

I. Introduction

As we enter the next-G era, the number of antennas is increasing rapidly, leading to a growing concern regarding the coexistence and miniaturization of variable antennas. As a result, multi-port antennas have gained more and more attention as they offer more functionality or flexibility with a compact appearance [1]. On the other hand, the challenge of antenna decoupling in MIMO and full-duplex systems has emerged as a prominent area of research focus [2]–[4]. For example, in portable antenna design, imposed by the size limitations of mobile terminals, two primary objectives are consistently pursued. One involves maximizing the placement of patch antennas, while the other entails achieving high isolation and low correlations among distinct antennas [5]. However, the growing complexity of system integration in specific small areas makes it increasingly challenging to attain the aforementioned goals through conventional antenna design methods with optimized template-based geometries. Therefore, developing ML-based methods for passive design has become more and more attractive in recent years [6]–[8]. In this study, we investigate the deep learning (DL) based inverse design of multi-port antennas to enable dual-band and MIMO operations.

II. DL-Based Modeling and Inverse Design

The main component of the inverse design approach is the CNN-based EM predictor. As shown in Fig. 1, the input of the CNN is a pixelated multi-port antenna structure divided into 12×12 pixels. Antenna ports are placed randomly to the left and right halves. Amplitudes of S_{11}, S_{22} and S_{21} were converted to dB and clipped between -20 and 0 for the training. The output of the CNN covers the frequency range of 20-40 GHz with 81 linearly placed points. As 3 terms are predicted at a given frequency, the output has 243 neurons. For the preceding layers, hyper-parameters are decided in accordance to [6]–[8].

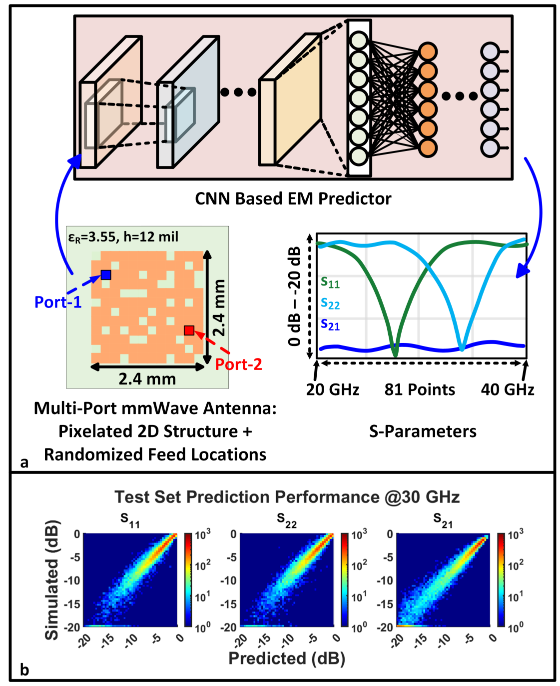

Fig. 1. a: CNN-based forward model can predict S-Parameters of 2-port planar mmWave antennas. This model can then be used in conjunction with an optimization algorithm to synthesize desired characteristics. As CNN inference is orders of magnitude faster than an EM simulation, optimization takes mere minutes even with modest computational resources. b: Prediction accuracy of the CNN needs to be adequately well to characterize never-seen-before antenna structures. We use the test set to evaluate this requirement. Here, predicted and simulated values of S-Parameters at the center frequency of 30 GHz are shown with a heat map. CNN predictions concentrate around $y = x$ line, indicating good accuracy.

It is worth noting that a two-step training approach was adopted for efficient use of computational resources [8]. A total of 300K fast simulations and 128K accurate simulations were conducted. These datasets were augmented with geometrical transformations. In the first step of training, a randomly initialized network was trained with a test-validation-training split of 38K-38K-375K over 30 epochs. The second step

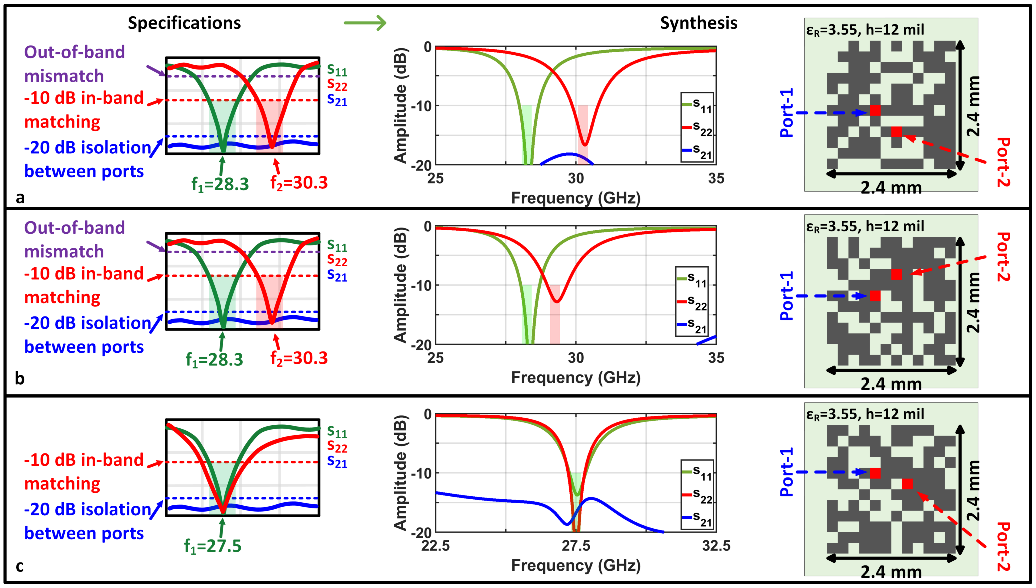

Fig. 2. CNN aided genetic algorithm optimization results. a-b: Antenna ports are matched at different frequencies while being isolated from each other. c: Antenna ports are matched at 27.5 GHz with more than 15 dB isolation.

essentially carries on the training of the first model for another 30 epochs with the dataset of accurate simulations. This set of data is divided into 15K-18K-175K test-validation-training splits. Once the training was complete, we deployed the network with a genetic algorithm (GA) to optimize for different antenna properties. With the help of a GPU, prediction of S-Parameters for the population size of ≈4000 structures takes less than 1 second, and optimization concludes within ≈2 minutes for 100 generations.

III. Example Designs

To demonstrate the effectiveness of the modeling approach and the inverse design methodology, we present synthesis results antennas and their measured properties in Fig. 2. Fig. 2-a shows an example of a dual-band 2-port patch antenna on a 12 mil RO4003C substrate operating at 28.3 and 30.3 GHz. It should be noted that the goal here is to match S_{11} and S_{22} at 2 distinct frequencies while ensuring isolation (S_{21}). Furthermore, it was aimed that S_{11} and S_{22} should be mismatched outside of the target band. The resulting EM structure implements these requirements. Fig. 2-b implements similar functions at a slightly different frequency range of 28.3 and 29.3 GHz. Fig. 2-c shows the simultaneous matching of 2 antenna ports while providing more than 15 dB isolation at 27.5 GHz. These examples illustrate that CNN-based multi-port EM modeling for antenna synthesis is a promising method for optimizing various aspects of multi-port antennas.

IV. Conclusion

The presented approach with deep CNN carries out an extension of the previous works by providing greater design freedoms. For example, as we allow a single antenna to be excited from multiple ports, the bandwidth of the antenna can be compositely extended. Moreover, a single radiating structure can be used for both transmit and receive chains by isolating antenna ports. While typically such functionalities require considerable engineering effort, CNN-based modeling and inverse design could synthesize a solution rapidly, as shown in example designs. In addition, once trained, CNN can be repeatedly utilized for antenna design to compensate for the initial computational investment. These aspects can make CNN-based modelling a viable design tool.

References

[1] X. Lu, C. Chappidi, X. Wu and K. Sengupta, "Antenna Preprocessing and Element-Pattern Shaping for Multi-Band mmWave Arrays: Multi-Port Receivers and Antennas", *IEEE J. Solid-State Circuits*, vol. 55, pp. 1455–1470, 2020.

[2] Z. Shao, L. Ma, C. Gu and K. Sengupta, "Decoupling of Wideband Closely-Spaced Patch Antennas for MIMO Applications," in *2023 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/URSI)*, Portland, OR, USA, 2023.

[3] L. Ma, Z. Shao, J. Lai, C. Gu and J. Mao, "A Compact Dual-Decoupling Scheme for Aperture-Coupled and Probe-Fed Closely Spaced Wideband Microstrip Antennas," *IEEE Trans. on Antennas and Propag.*, vol. 71, no. 11, pp. 9072-9077, Nov. 2023.

[4] L. Ma, Z. Shao, J. Lai, C. Gu and J. Mao, "Bandwidth Enhancement of H-Plane MIMO Patch Antennas in Integrated Sensing and Communication Applications," *IEEE Open J. Antennas Propag.*, 2023.

[5] A. Zhang, K. Wei, Y. Hu and Q. Guan, "High-Isolated Coupling-Grounded Patch Antenna Pair With Shared Radiator for the Application of 5G Mobile Terminals," *IEEE Trans. on Antennas and Propag.*, vol. 70, no. 9, pp. 7896-7904, Sept. 2022.

[6] E. A. Karahan, A. Gupta, U. K. Khankhoje and K. Sengupta, "Deep Learning based Modeling and Inverse Design for Arbitrary Planar Antenna Structures at RF and Millimeter-Wave," in *2022 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/URSI)*, Denver, CO, USA, 2022.

[7] A. Gupta et al., "Tandem Neural Network Based Design of Multiband Antennas," *IEEE Trans. on Antennas and Propag.*, vol. 71, no. 8, pp. 6308-6317, Aug. 2023.

[8] E. A. Karahan, Z. Liu and K. Sengupta, "Deep-Learning-Based Inverse-Designed Millimeter-Wave Passives and Power Amplifiers," *IEEE J. Solid-State Circuits*, vol. 58, no. 11, pp. 3074-3088, Nov. 2023.