

Machine Learning Techniques for Multi-Objective Antenna Optimization (Invited)

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Abstract- Different types of microstrip antennas with non-uniform metasurfaces are designed and optimized using statistical methods with various formulations. The design objectives include impedance matching bandwidth, realized gain, and axial ratio bandwidth for linearly polarized antennas and circularly polarized antenna, respectively. The designed antennas are to operate in the sub-6 GHz frequency band of the 5G New Radio system.

I. INTRODUCTION

The 5G era is shaping the future of wireless communication and posing unprecedented demands for electromagnetic designs tailored to stringent application-specific requirements. Conventional antenna designs mainly rely on the designers' experience and exhaustive parameter sweepings, which are extremely time-consuming, and the truly optimum result is rarely obtained. Therefore, the increasingly complicated applications pose serious challenges on antenna designs, particularly when a large number of design parameters and multiple performance metrics are involved.

Patch antennas have long been a popular choice for various communication systems because of the advantages of low profile and easy integration with systems. However, the applications of classical microstrip antennas are limited by their inherent narrow bandwidth. Nevertheless, it was shown in study that in order to further increase the bandwidth, the height of substrate needs to be increased significantly [1]. Therefore, it is desirable to find solutions to further increase the bandwidth of the microstrip patch antenna without increasing the antenna profile. One effective approach to enhance the bandwidth is to utilize non-uniform or non-periodic metasurface that are able to excite multiple resonances. Traditional design methods include applying dispersion analysis [2] and characteristic mode analysis [3], but it is difficult to explore the full potential of non-uniform structures, which typically form a huge design space because of the non-periodicity.

In this paper, microstrip antennas with various types of non-uniform metasurfaces are designed and optimized with machine learning techniques and statistical approaches with different formulations. The problems targeted to solve are with complex physical models and expensive evaluation functions, which are the cases of antenna designs with a large number of design parameters. Another important aspect of antenna design and optimization is that there are typically multiple conflicting

objectives which may not be optimized at the same time without any compromise with complex physical models and expensive evaluation functions. In this sense, multi-objective optimization method is particularly suitable to solve the problems of antenna design and optimization.

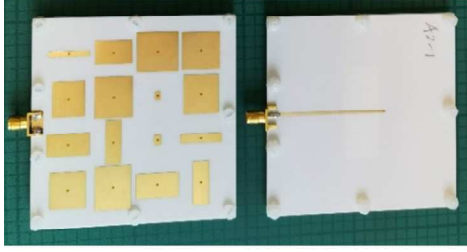
II. OPTIMIZATION METHODS

Nature-inspired optimization methods like genetic algorithms are capable of solving complex design problems and handling a large number of design parameters. Such metaheuristic algorithms have been widely applied in antenna design and optimization. Nevertheless, it was pointed out that one of the major disadvantages of the nature-inspired algorithms is the insufficient usage of all the available heuristic data, which form the essential core values and cost most computational resources in the optimization process [4]. On the other hand, Bayesian optimization (BO) fully utilizes all the available heuristic data to form the probabilistic distribution of solutions. BO is particularly suitable for solving global optimization of black-box functions in arbitrary forms, which typically involve complex physical models and are expensive to evaluate [5]. In recent years, BO has been frequently applied in machine learning for hyper parameter tuning. It is also widely utilized in other areas for design optimization. However, BO has rarely been explored in the antenna community, with only a few recent studies [6-8].

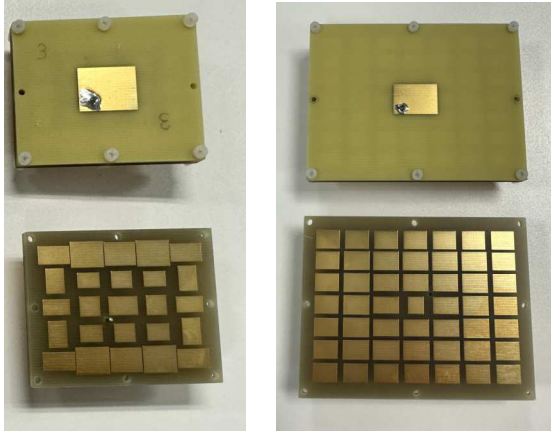
When solving multi-objective antenna problems, BO can be formulated by aggregating multiple design objectives into a single weighted sum [9]. However, determining these weighting coefficients can be challenging and has the potential to significantly impact the outcomes of the optimization process. An alternative method involves utilizing a genuine multi-objective BO (MOBO) method [10], which enables the acquisition of the Pareto optimal set without the need to grapple with the determination of weighting coefficients.

III. ANTENNA DESIGNS

This section presents three microstrip antennas with non-uniform metasurfaces. All the three antennas are designed and optimized via the genuine MOBO method.



(a)



(b)

(c)

Figure 1. Fabricated samples of: (a) optimized 4×4 non-uniform mushroom antenna (Ant. I); (b) optimized 5×5 non-uniform metasurface antenna (Ant. II); (c) optimized 7×7 non-uniform concentric metasurface antenna (Ant. III).

As shown in Figure 1(a), the 4×4 non-uniform mushroom antenna is designed by tuning 36 physical design parameters automatically. The mushroom antenna is fed by the microstrip line at the back of the ground plane. In measurement, the optimized design achieves a 63% enhancement in bandwidth as compared with its periodic reference, while keeping the same size. The linearly polarized antenna achieves the measured bandwidth of 3.36–4.19 GHz with $|S_{11}| < -10$ dB, or fractional bandwidth of 22.0% and maximum boresight realized gain of 6.32 dBi.

Figure 1(b) presents a microstrip antenna with the patch radiator placed on top of the 5×5 non-uniform metasurface, where 20 design parameters have been optimized via MOBO. The antenna is with a measured impedance bandwidth of 26.5% (3.40 – 4.44 GHz) with $|S_{11}| < -10$ dB, circular polarization bandwidth of 17.9% (3.55 to 4.25 GHz) with axial ratio less than 3 dB and maximum boresight realized gain of 4.49 dBi.

Figure 1(c) shows a 7×7 non-uniform metasurface antenna, where the metasurface consists of concentric rings of patches with the same size. Ten parameters are optimized for this design. The circularly polarized antenna has the measured impedance bandwidth of 39.5% (3.25 – 4.85 GHz) with $|S_{11}| < -10$ dB, circular polarization bandwidth of 29.5% (3.75 to 5.05 GHz) with axial ratio, and maximum boresight realized gain of 7.15 dBi.

TABLE I
SUMMARIZED PERFORMANCES OF THE ANTENNAS

Ant.	Size (λ_0^3)	Imp. BW (%)	CP BW (%)	Operating BW (%)	Boresight Realized Gain
Ant. I	$1.11 \times 1.11 \times 0.029$	22.0	N. A.	22.0	6.32 dBi
Ant. II	$0.70 \times 0.57 \times 0.062$	26.5	17.9	17.9	4.49 dBi
Ant. III	$1.12 \times 0.86 \times 0.069$	39.5	29.5	25.6	7.15 dBi

λ_0 is the free-space wavelength at the center frequency of the corresponding operating bandwidth (BW).

The measured performances of the three antennas are summarized in Table I. The operating bandwidth of the two circularly polarized antennas Ants. II and III are the overlap of the impedance and circular polarization bandwidths.

IV. CONCLUSION

In this paper, three microstrip antenna designs with non-uniform metasurfaces have been presented. The three antennas were designed and optimized via a genuine multi-objective Bayesian optimization method. All the three antennas can function in the in the sub-6 GHz frequency band of the 5G New Radio system.

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