An automated approach for pixelated antenna topology design incorporating multi-objective optimization algorithms

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***Abstract*-This paper proposes an approach for pixelated antenna topology design using multi-objective optimization algorithms. The MOBPSO algorithms are applied to investigate the relationship between the pixelated structures and their corresponding performances. A compact dual-band planar antenna design is presented, showing that the proposed approach can provide flexible candidate designs with satisfactory antenna performances without any structural analysis and parametric study and depends only weakly on the initial antenna geometry.**

I. INTRODUCTION

With the development of modern wireless communications, antennas have been widely used in handset and portable devices for 4G/5G, wireless sensor networks, and Internet of Things (IoT) applications. In these scenarios, antenna designs are usually required to achieve design goals such wideband or multiband, high gain or efficiency, compact size, and etc. Conventionally, antenna designs rely on geometric shape optimization of a given initial layout via optimization algorithms, such as genetic algorithm (GA) and Particle Swarm Optimization (PSO). However, such approaches could fail to provide a satisfactory design if the detailed initial guess is incorrect.

Instead of adjusting the geometric parameters of a given initial layout, topology optimization, also known as a pixelated design technique, does not require a detailed predefined shape, yet it automatically generates a suitable antenna topology fulfilling design requirements. It discretizes the design space into several rectangular pixels representing by a matrix with elements “1” (metal) and “0” (air). During the optimization process, the distribution of conductor is varied until design goals are achieved. Usually, topology optimization provides an unexpected antenna shape, thereby avoiding designer’s improper biases and developing innovative layouts. Moreover, topology optimization is particularly suitable for the miniaturized antenna design in handset and portable communication products as the antenna design space in these products that are usually confined in a specific space. Therefore, automated topology optimization of pixelated antenna design shows great competence in practical design situations, leading to a shorter design cycle and a lower design cost [1], [2].

Several searchers used GA to design topology structure of UHF RFID tags [3] and monopole antennas [4] for single band or multiband operation. Compared to GA, the PSO’s simplicity, ease of implementation, and flexibility make it highly appealing for multi-dimensional antenna designs for WLAN or software-defined radio applications [5], [6]. All the above work has some drawbacks such as involving only one objective or a few number of design variables, achieving few functions, or inefficient algorithm or antenna performance. In this paper, an automated approach for pixelated antenna topology design incorporating multi-objective optimization algorithms is proposed for high-dimensional, multi-functional, and compact internal antenna designs. The results of a planar multiband antenna design validate the effectiveness of the proposed approach.

II. PROBLEM FORMULATION

Pixelated antennas discretize a design space into many small rectangular pixels, and each pixel could be filled with either air or conductor. Fig. 1 illustrates the mapping procedure, where the small rectangular pixels of antenna structure filled with conductors or air are encoded as 1 or 0, respectively. Therefore, the pixelated antenna designs can be formulated as a binary multi-objective optimization problem:

$$\begin{aligned} &\mathit{find}\ \boldsymbol{x}^* = \arg\ \min_{\boldsymbol{x}}\ (f_1(\boldsymbol{x}), f_2(\boldsymbol{x}), \ldots, f_m(\boldsymbol{x}))^{\mathrm{T}} \\ &\qquad s.t.\ \ \boldsymbol{x} \in \{0,1\}^n \end{aligned} \tag{1}$$

where $\boldsymbol{x}=[x_1,x_2,\ldots,x_n]$ is an n-vector of binary design variables, representing the encoding bit string mapped from a specific antenna geometry; $\boldsymbol{x}^*$ is the optimal design to be found; $f_k(\boldsymbol{x})$, $k=1,2,\ldots,m$ is the kth design objective, which is related to the desired antenna performances, such as reflection coefficients, size, gain, and efficiency. In multi-objective antenna design, the target is to obtain the Pareto front (PF) [7],

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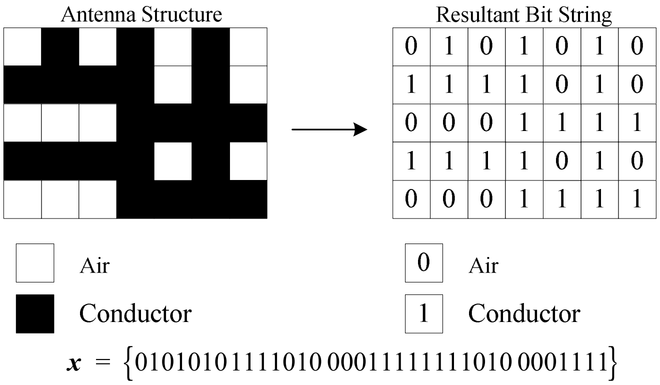

Fig. 1. The relationship between the physical antenna structure and the resultant bit string.

[8], i.e., multiple designs representing the trade-off between various characteristics of the antenna under consideration.

For multi-objective optimization, any two designs $\boldsymbol{x}$ and $\boldsymbol{y}$ for which $f_k(\boldsymbol{x}) < f_k(\boldsymbol{y})$ and $f_l(\boldsymbol{x}) < f_l(\boldsymbol{y})$ for at least one pair $k \neq l$, are not commensurable, i.e., none is better than the other in the multi-objective sense. We define the Pareto dominance relation $\prec$ saying that for the two designs $\boldsymbol{x}$ and $\boldsymbol{y}$, we have $\boldsymbol{x} \prec \boldsymbol{y}$ ($\boldsymbol{x}$ dominates $\boldsymbol{y}$) if $f_k(\boldsymbol{x}) \leq f_k(\boldsymbol{y})$ for all $k = 1, 2, \ldots, m$ and $f_k(\boldsymbol{x}) < f_k(\boldsymbol{y})$ for at least one k. The multi-objective optimization aims to find a representation of a Pareto front $\boldsymbol{X}_p$ (viz. Pareto-optimal set) of the design space, such that for any $\boldsymbol{x} \in \boldsymbol{X}_p$, there is no $\boldsymbol{y} \in \boldsymbol{X}$ for which $\boldsymbol{y} \prec \boldsymbol{x}$ [7], [8].

III. DESIGN METHODOLOGY

The binary PSO (BPSO) algorithm proposed by Kennedy and Eberhart [9] is a good candidate for automated topology designs addressing 0/1 optimization problems. Different from continuous version of PSO, a transfer function is used in BPSO to map a continuous space to a binary one, and a new position-updating procedure is designed to switch particles' positions between 0 and 1 in a binary design space.

In a multi-objective PSO, each location in the solution space is mapped into a candidate design. Its performance is denoted by K fitness functions that represent K factors considered in a specific problem. The MOPSO algorithm [10] is formulated based on the concept of *Pareto dominance*. By applying the swarm behavior, the particles are attracted to the temporary Pareto front, and explore a new Pareto front in the next iteration. If the optimization is executed for a large number of iterations, the Pareto front will be no longer expanded. All the nondominated solutions on the ultimate Pareto front show the best trade-off between the two considered factors, $f1(x)$ and $f2(x)$. This principle applies to the binary PSO algorithms and the resulted multi-objective PSO algorithms are denoted as MOBPSO.

In the pixelated antenna designs, different pixelated structures (i.e., the bit strings) corresponds to different antenna performances. The MOBPSO algorithms is therefore applied to investigate the relationship between the pixelated structures

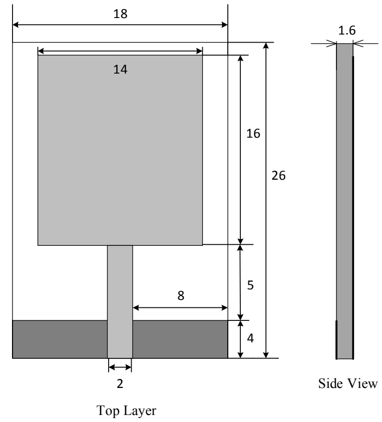

Fig. 2. Initial geometry of planar dual-band antenna model (unit: mm).

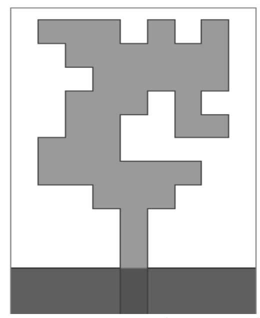

Fig. 3. One optimized antenna geometry, i.e., one selected Pareto-optimal design

and their corresponding performances. The main steps of MOBPSO for pixelated antenna designs are summarized as:

Step 1) Initialize the population in antenna design space;

Step 2) Initialize MOBPSO parameters and generate an initial set of non-dominated solution stored in the archive;

Step 3) Evaluate the fitness value of each individual design;

Step 4) Update the velocities and positions of the population;

Step 5) Update the archive;

Step 6) Stop when termination condition is satisfied; otherwise, turn to step 3).

IV. DUAL-BAND ANTENNA DESIGN AND DISCUSSIONS

Here we present a dual-band planar antenna design from an initial antenna geometry shown in Fig. 2, which consists of a 14mm×16mm rectangular patch and a 18mm×4mm rectangular ground plane. The design goals are: i) to minimize the S_{11}<-10dB of two bands, covering entire 2.4/5.2/5.8GHz WLAN band applications (F_1); and ii) to maximize the realized gain (F_2). The objective function F_1 can be described as:

$$F_1 = \frac{1}{n}\sum_{i=1}^{n}(Q(f_i)) \tag{2}$$

$$Q(f_i) = \begin{cases} -10, & S_{11}(f_i) \leq -10 \\ S_{11}(f_i), & S_{11}(f_i) > -10 \end{cases} \tag{3}$$

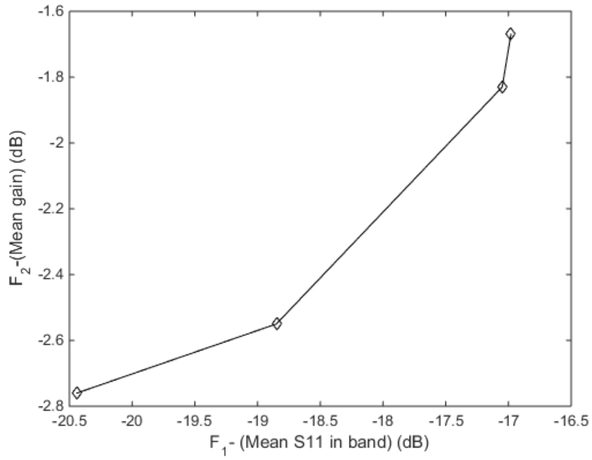

Fig. 4 The selected representations of the Pareto set for the planar multiband antenna.

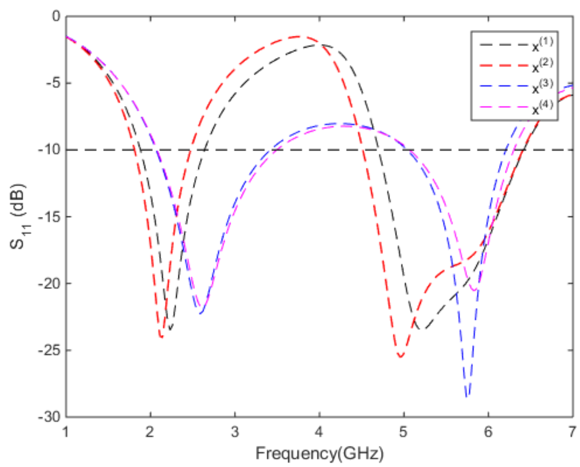

Fig. 5. Reflection responses at the selected Pareto-optimal designs.

where f_i is the ith sampling frequency points within the given operating bands; $S_{11}(f_i)$ is the reflection coefficient of sampling point f_i; n is the total number of sampling points; F_1 is the fitness value. The objective function F_2 can be described as:

$$F_2 = \frac{1}{2}\sum_{i=1}^{2} G_{\min}(f_{ci}) \tag{4}$$

where f_{ci} denotes the center frequency of the ith working band; $G_{\min}(f_{ci})$ denotes the minimum gain of the radiation pattern at the frequency point f_{ci}.

The patch is discretized into 8×7 small rectangular pixels and optimized by the MOBPSO algorithm. In this case, the pixelated antenna design is mapped into a 56-dimensional binary optimization problem. Fig. 3 depicts an optimized antenna geometry (i.e., one selected Pareto-optimal design). The selected representations of the obtained Pareto set are shown in Fig. 4. The obtained results indicate that the design objectives considered for this problem are indeed conflicting. their corresponding reflection responses are shown in Fig. 5. All these designs provide flexible choices for practical antenna engineering.

V. Conclusion

In this paper, we propose an automated approach for pixelated antenna topology design incorporating multi-objective optimization algorithms. The proposed approach can provide flexible candidate designs with satisfactory antenna performances without any structural analysis and parametric study and depends only weakly on the initial antenna geometry. Although it usually provides an unexpected antenna shape, such a feature is suitable for novel antenna design, especially for antenna design with a limited surrounding environment or an unexplored area.

Acknowledgment

This work was supported in part by the HUAWEI research project under Grant No. YBN2017110019, in part by the Natural Science Foundation of Hunan Province under Grant No. 2018JJ2533, and in part by the Fundamental Research Funds for the Central Universities under Grant No. 2018gczd014.

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