Metaheuristic Optimization Techniques for an Electromagnetic Multilayer Radome Design
Trung Kien Nguyen¹ · In-Gon Lee¹ · Obum Kwon² · Yoon-Jae Kim² · Ic-Pyo Hong¹,*

Abstract

In this study, an effective method for designing an electromagnetic multilayer radome is introduced. This method is achieved by using ant colony optimization for a continuous domain in the transmission coefficient maximization with stability for a wide angle of incidence in both perpendicular and parallel polarizations in specific X- and Ku-bands. To obtain the optimized parameter for a C-sandwich radome, particle swarm optimization algorithm is operated to give a clear comparison on the effectiveness of ant colony optimization for a continuous domain. The qualification of an optimized multilayer radome is also compared with an effective solid radome type in transmitted power stability and presented in this research.

Key Words: Ant Colony Optimization, Electromagnetic Multilayer Radome Design, Metaheuristic Optimization Algorithm, Particle Swarm Optimization, Transmission Coefficient Maximization.

I. INTRODUCTION

The problem of an electromagnetic multilayer dielectric design optimization for a frequency band and a desired range of incident angles has been introduced in recent years using such metaheuristic optimization algorithms as the genetic algorithm [1, 2], particle swarm optimization (PSO) [3, 4], or a hybrid algorithm that combines ant colony optimization (ACO) with the microgenetic algorithm [5]. In this study, an effective algorithm presented by Socha and Dorigo [6] in 2008 called ant colony optimization for a continuous domain (ACOR) is applied to design a C-sandwich radome [7] with an applicable range of incident angle (0°–70°) in both the transverse electric (TE) and transverse magnetic (TM) modes for the X- and Ku-bands. To validate the ACO_R algorithm in a multilayer radome design optimization, the performance of the transmission coefficient characteristics of the C-sandwich radome design optimized by ACO_R has been compared with a conventional analysis method (i.e., a simpler and lower-cost analysis) that approximates multilayer radomes by a solid radome with an effective medium approximation (EMA) [8, 9]. Then, the performance of ACO_R is compared with a general optimization algorithm used in electromagnetic characteristic design (i.e., PSO). This study is organized as follows: Section II is an overview of the ACO_R algorithm, which uses a boundary value method to evaluate the transmission coefficient of a multilayer radome. Section III examines the fitness function and compares the optimization results obtained by ACO_R and PSO. The simulation results and the transmitted power stability are compared with an effective solid radome, and the results are discussed. The conclusion is

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provided in Section IV.

II. METHODS

1. Ant Colony Optimization for a Continuous Domain

Originally, ACO was introduced in 1992 by Dorigo [10], and it has been used to solve many combinational optimization problems consisting of a set of discrete decision variables. The idea of applying ACO in solving the continuous optimization problem was presented in 2008 by Socha and Dorigo [6]. The flowchart of the ACO algorithm is illustrated in Fig. 1.

In ACO, the solutions are kept and sorted in a solution archive (Fig. 2), in which the associated weight of solution \( l \) defined in Eq. (1) represents the strength of the solution in producing new solutions.

\[
\omega(l) = \frac{1}{qk^{\epsilon/2}} e^{-\frac{(l-1)^2}{2qk^2}}.
\]

(1)

To generate new solutions, a kernel is selected by probability that is computed for each group as in Eq. (2).

\[
p(l) = \frac{\omega(l)}{\sum_{k=1}^{k} \omega(k)}.
\]

(2)

Roulette wheel selection [11] is applied to select a solution kernel. Each probability \( p(l) \) is presented as a proportion of the wheel (Fig. 3), and a random selection process is made similarly to rotate the roulette wheel. An \( m \) new random number group according to the parameterized normal distribution is used with mean \( \mu_l \) and standard deviation \( \sigma_l \) for ant \( i \) in group \( l \).

\[
\mu_l = s_l^i.
\]

(3)

\[
\sigma_l = \xi \sum_{k=1}^{k} \frac{|s_l^i - s_l^j|}{k-1}.
\]

(4)

\( \xi > 0 \) is a constant parameter that is similar to the pheromone evaporation rate in ACO [10]. Then, \( m \) new solutions are added to the solution archive and re-ordered. Non-fit solutions are removed, and only the \( k \) best ones are kept after each iteration.

2. Transmission Coefficient Characteristic of the C-Sandwich Radome

A C-sandwich radome, which is a multilayer radome (style d) [7], is considered in this work. The sandwich wall has five layers that were developed to cover an antenna array operating in a wide-band frequency range. The C-sandwich construction consists of three skins that are interleaved by two cores. Typically, the relative permittivity of skin is greater than that of the core. To guarantee that the input and output of the propagation wave...
are equal, a C-sandwich wall is designed with the first and last skins having the same thickness, and the widths of the two cores are the same as well. To fabricate a radome, the thickness of each layer is designed as the multiple of plies. The propagation wave on the radome with layer \( i \) has thickness \( d_i \), relative permittivity \( \varepsilon_i \), loss tangent \( \tan \delta_i \), and refractive index \( n_i \).

The propagation waves are related by the Fresnel equation. If one uses the formula in Eq. (5) and simplifies it to Eq. (6), the transmission coefficient can be obtained by Eq. (7).

\[
\begin{align*}
[F_1 \ B_1] &= \prod_{i=1}^{n} \begin{bmatrix} 1 & e^{-j k d_i} \\ r_i & e^{j k d_i} \end{bmatrix} \begin{bmatrix} F_2 \\ B_2 \end{bmatrix} \\
T &= \frac{F_2}{F_1} = \frac{1}{A_{11}}.
\end{align*}
\] (5)

The first optimized radome of this study is the design for the X-band (8–12 GHz) frequency. According to a comparative analysis with 30 execution times (Table 2), ACO\(_R\) requires less time (56.69 seconds) to reach the convergence than PSO (70.18 seconds). Fig. 4 presents the comparison of transmitted power stability between the optimized multilayer radome and the effective solid radome with the stability of a multilayer radome in various angles, with both TE and TM modes being under 10% change. The transmission coefficient characteristic of the C-sandwich radome after optimization is presented in Fig. 5 in the X-band.

To give a more effective decision, the same design properties of the multilayer radome are applied in the Ku-band (12–18 GHz). Table 3 shows the same result to demonstrate that ACO\(_R\) has better performance than PSO. Fig. 6 illustrates that the stability in the transmitted power of the optimized multilayer structure is less than 10%, which is outstanding compared with that of the effective solid radome. Fig. 7 shows the transmission coefficient of the optimized radome for the TE and TM modes in the Ku-band.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Permittivity</th>
<th>Loss tangent</th>
<th>Thickness (mm)</th>
<th>Step/ply (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin 1</td>
<td>4.4</td>
<td>0.016</td>
<td>0.48–2.4</td>
<td>0.24</td>
</tr>
<tr>
<td>Core 1</td>
<td>1.1</td>
<td>0.001</td>
<td>2–9</td>
<td>0.1</td>
</tr>
<tr>
<td>Skin 2</td>
<td>4.4</td>
<td>0.016</td>
<td>2.4–9.6</td>
<td>0.24</td>
</tr>
<tr>
<td>Core 2</td>
<td>1.1</td>
<td>0.001</td>
<td>2–9</td>
<td>0.1</td>
</tr>
<tr>
<td>Skin 3</td>
<td>4.4</td>
<td>0.016</td>
<td>0.48–2.4</td>
<td>0.24</td>
</tr>
</tbody>
</table>

The thickness of the effective half-wavelength solid-type radome at a resonant frequency of 10 GHz for the X-band and 15 GHz for the Ku-band with an angle of incidence \( \theta = 70^\circ \).

\[
\varepsilon_{eff} \sum_{i=1}^{n} d_i = \sum_{i=1}^{n} \varepsilon_i \cdot d_i.
\] (9)

\[
d_{eff} = \frac{\lambda}{2 \sqrt{\varepsilon_{eff} \cdot \sin^2(\theta)}}.
\] (10)
According to the computed result, ACO\textsubscript{R} gives a promising value in optimizing multi-objective problems applied in the electromagnetic multilayer radome design.

**IV. CONCLUSION**

A comparative study of two metaheuristic optimization algorithms, PSO and ACO\textsubscript{R}, for an electromagnetic multilayer radome design with various angles of incidence (0°–70°) in the perpendicular and parallel polarizations for the X- and Ku-bands was presented. The simulation results obtained by ACO\textsubscript{R} were compared with those of a trusted optimization, PSO. The results strongly confirm that ACO\textsubscript{R} can be useful in the electromagnetic multilayer radome characteristic optimization. The stability for the transmission coefficient of the optimized structure is also guaranteed by ACO\textsubscript{R}. In future works, the ACO\textsubscript{R} algorithm will be improved to solve more complex frequency-selective surface design optimization problems such as the 3D frequency-selective surface screen design.

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**REFERENCES**

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