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RESEARCH ARTICLE

Chameleon Swarm Algorithm Assisted Optimization of U-Slot Patch Antenna for Quad-Band Applications

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ABSTRACT Existing optimization algorithms are insufficient in the face of problems with difficult measurement functions as well as a large number of design parameters. Therefore, to achieve such challenging applications, the Chameleon swarm algorithm and its variants, which belong to the family of meta-heuristic algorithms that have not been used in any antenna optimization study before, are used together with 3 different objective functions fitted from mathematical models. Then, a U-slot antenna application with 12 different variable design parameters with resonance frequencies of 3.5 GHz, 3.7 GHz, 5.2 GHz and 5.8 GHz is considered as a multidimensional and single-objective optimization problem. In this study, first of all, the success of the algorithm is reinforced by comparing the performance with other commonly used single and multi-objective optimization algorithms. In addition, the results obtained with different population parameters, weight coefficients, objective functions and variant models were compared. All these processes are compared within themselves, and the antenna results of the most successful result are displayed as 3D electromagnetic simulation. The results show that the optimization processes proposed for an antenna designer are a safe, practical and efficient solution for multidimensional and single-objective antenna optimization applications. In addition, any optimization problem with a large number of variable design parameters can undoubtedly be adapted to the Chameleon swarm algorithm.

INDEX TERMS Quad-band, eCSA, patch antenna, multidimensional optimization, optimization techniques, chameleon swarm algorithm, evolutionary algorithms, swarm intelligence algorithms.

I. INTRODUCTION

Wireless communication is frequently used in today's technology products. The most common wireless communication technologies use electromagnetic communication methods. In wireless applications, there are many antenna models such as monopole, dipole, horn, parabolic reflector and millimeter wave [1]. New generation wireless communication systems require smaller antennas with high data rates. Reducing the size of the antenna increases the compatibility of the antenna with wireless communication systems. In addition, there is a high level of interest in dual, triple and even multi-band operations in a single device. Although microstrip antennas were first proposed by Decamps in 1970, their first development was made by Munson in 1980 [2]. In today's communication systems, microstrip antennas are preferred frequently due to their planar profile and robustness as well as their low cost [3], [4]. Microstrip antennas consist of 3 layers, the substrate above the ground plane and a patch etched onto the substrate above it. Recently, three or four band antenna designs with different segments on the patch of a microstrip antenna have attracted the attention of researchers and have been the subject of many studies [2], [5]–[9]. These designs have a numerous of variable. All these situations, such as the ground plane dimensions and patch shapes and sizes, contain many complexities. U-slot patch antennas, one of these cutting shapes, are preferred in multi-band applications with small and wide frequency ratios as well as wideband applications [3], [10]. One of the most important applications of microstrip antennas is Wi-Fi (WLAN) and Wi-Max. Multiple broadband

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frequency ranges in data communication are created by the IEEE 802.16 WiMAX standard. Of these, the 2-11 GHz range was created for the lower frequency range of 802.16d for data transmission. The first effective design with a low frequency ratio was made by Long and Walton [11]. The U-slot patch antenna was first designed by Huynh and Lee in 1995 with a single layer and a single patch [3]. Since its design in 1995, U-slot patch antennas have been involved in many studies with circular polarization [12], [13] with multi-band applications as well as wideband applications [14]–[19].

Although there are many empirical equations for antenna designs, their inconsistency and the fact that the technique is not suitable for practical designs due to the old age led the designers to antenna simulation programs [20], [21]. In addition, optimization processes can be performed by combining different programs. In a study, the performance analysis of the parameters of the rectangular patch antenna was performed using Genetic algorithm optimization and CST software. In this study, the Genetic algorithm is embedded in the CST environment using MATLAB [22]. In the developed antenna, the surface current path is meandering and therefore the electrical length of the antenna is increased. This means that for an antenna with the same resonant frequency, the total surface is greatly reduced [22]. In this way, up to 82% reduction in patch size was achieved with a radiation pattern specific to our proposed microstrip patch antenna, compared to a conventional microstrip patch antenna resonating at the same frequency [22]. Here, the dual band of the antenna facilitated the optimization, and the study could be supported by comparing with different algorithms instead of a single algorithm [22].

In another article with a similar method, the effects of antenna design of Substrate integrated waveguide (SIW) structures on radiation and return loss properties were investigated by simulation in different situations and optimized using Differential evolutionary algorithm (DEA) [23]. In the simulated results, it is shown that the optimized antenna with SIW structure achieves simulated gain level of 7 and 7.13 dB at 12 and 24 GHz, respectively, while the other two antenna design cases without SIW design can reach a maximum of 6 dB. Here, by comparing different algorithms instead of a single algorithm, more successful results could be obtained or the success of the proposed algorithm could be confirmed. [23]. In another study, a SIW hollow slot antenna structure was designed and optimized with the Particle swarm optimization (PSO) algorithm by automating EMS HFSS from the MATLAB code [24]. The measured gain reached a maximum value of 8.8dBi, which can be considered a very high gain compared to conventional planar antennas [24]. In addition, the S_{11} parameter is too low to be underestimated [24].

In the past few years, scientists have developed many optimization methods based on linear or non-linear methods to overcome multidimensional and various optimization problems in many fields and especially in engineering [25]–[27]. Many existing optimization problems consist of a simple objective function and the weighting coefficients in it, as well as a cost function adapted from these objective functions. In many problems, the relationship between design variables and objective functions is mostly linear [27]. Non-linear, that is, non-convex, are complex in nature and have many limitations [28]. Often, nonlinear problems contain many local optima as well as sharp and multiple peaks [29]. The main purpose here is to find the global optimum. There are problems that require a complex objective function for complex and decision-variable problems with a large number of performance parameters. Meta-heuristic algorithms are very successful in both preventing the local optimum and finding the global optimum. For this reason, problems that have not yet been addressed or newly found algorithms can be addressed and more successful results can be obtained. In addition, these algorithms meet the 'no-free-lunch' (NFL) theory advocated in a study [30]. Chameleons are mostly creatures that live in forests or deserts and are constantly searching for food. There was no optimization algorithm in the literature that mimicked the behavior of chameleons in nature, until a study covered last year [31]. In the aforementioned study, a meta-heuristic algorithm called Chameleon swarm algorithm (CSA) is presented to solve global optimization problems [31]. The inspiration for this algorithm is the dynamic behavior of chameleons looking for food in nature. The algorithm basically adapts its behavior while foraging to the mathematical model. This includes chameleons catching prey by throwing their tongues out quickly. When all these behaviors are applied to create an optimization algorithm, a model that finds suitable solutions is obtained. From what has been described so far, the idea has emerged that the challenging optimization problem of multiband microwave antenna design can be overcome with the CSA, which belongs to the family of meta-heuristic algorithms, found in the last year and has not been used in any antenna design to the best of the author's knowledge.

Here, a successful study is revealed by combining these two issues mentioned so far. Both the multiplicity of antenna geometric design parameters and the quad-band antenna make optimization very difficult. This challenging problem will be overcome by CSA optimization supplemented with original objective functions. In addition, the study was not limited to the existing CSA, but was expanded with variants of the existing CSA by adding innovation to the algorithm. With this aspect, the study contains more than one innovation. There are many U-slot antenna studies in the literature [5]–[9]. There are not many studies where both S_{11} and directivity gain are improved simultaneously, although many are single or dual band. In addition, such a large study has not yet been encountered.

The following chapters of this article are organized as follows: Chapter II, information about antenna design is given. The objective and cost functions used together with the optimization algorithm variants used are mentioned in Chapter III. The results analyze of the study were done in Chapter IV. The article ends in Chapter V.

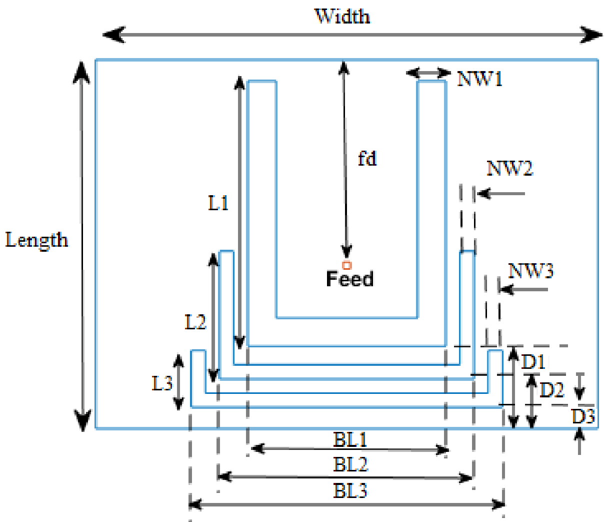

FIGURE 1. U-slot antenna.

II. ANTENNA DESIGN

Some applications used in wireless communication require designs that cover two or three or even four frequency bands [32]–[34]. For example, a base station antenna design that can provide wireless access services at the same time may be required for the WiMAX 2.5-5.8 GHz band. Here, a quad band antenna design with four resonant frequencies such as 3.5 GHz, 3.7 GHz, 5.2 GHz and 5.8 GHz with U-shaped patch that can meet such requirements will be designed. The proposed antenna consists of substrate material on a plane and multiple U-shaped patches on it. Also, the antenna has a coaxial feed. Figure 1 shows the schematic of the antenna design. The design parameter values specified in the diagram are given in Table 1 in detail. Of the 18 design parameters specified here, 12 were chosen as variable and 6 as fixed values. In the algorithm validation optimization processes, PEC was chosen as the conductor and air was chosen as the substrate. Although there are many empirical equations and methods for slot antenna design, it has been mentioned that it is not suitable for practical designs due to the inconsistency of the equations and the old technique [20], [21]. For this reason, the antenna toolbox of MATLAB 2021 was used in the optimization processes and antenna simulations in the study. All these processes were performed by a computer with 8th generation Intel Core i7 CPU, 3.20 GHz processor and 8 GB RAM. In addition, the results were verified in the 3D electromagnetic (EM) simulation program CST Microwave studio environment. In the design part of the CST Microwave studio environment, the conductor was arranged as copper and the substrate as vacuum in the first part, and the success of the most successful optimization was confirmed. In addition, the substrate RT/Duroid 5880 was selected and optimized again and the most successful result was presented in the CST Microwave studio environment.

III. CHAMELEON SWARM ALGORITHM

Classical optimization and search algorithms are not effective for nonlinear, complex, dynamic large-scale problems with incomplete information [35]. Therefore, in some cases, the difficulties of design problems as well as the desire to find better solutions, combined with the inadequacy of existing meta-heuristic algorithms, lead researchers to develop new meta-heuristic algorithms. Among these studies, one of the nature-inspired algorithms developed in recent years is CSA [31]. Meta-heuristic algorithms work by integrating them into real simulations to mimic some properties of commodities existing in nature [38]. General-purpose metaheuristic methods are evaluated in nine different groups as biology-based, physics-based, social-based, music-based, chemical-based, sports-based, mathematics-based, and herd-based [36]. Combinations can also be considered as hybrid category. Genetic algorithm, ant colony algorithms and differential evolution algorithm are biologically based models [37]. Swarm intelligence (SI) falls under the category of collective behavior of organisms found in nature that is of interest to researchers [38]. The CSA to be used belongs to this class. This algorithm is inspired by the methods of survival, finding food and hunting in areas where chameleons live. The balance between these two is very important, since discovery-use are the two most basic features in meta-heuristic algorithms.

TABLE 1. Antenna design parameters.

Parameter	Value	Definition
fd	14.5 (mm)	Feed distance
h	6 (mm)	Board thickness
GPLength	71 (mm)	Ground plane length along x-axis
GPWidth	52 (mm)	Ground plane width along y-axis
Length	26 (mm)	Patch length along x-axis
Width	35.5 (mm)	Patch width along y-axis
BL1	11.2 - 16.8 (mm)	1st patch bottom length along x-axis
BL2	14.4 - 21.6 (mm)	2nd patch bottom length along x-axis
BL3	17.6 - 26.4 (mm)	3rd patch bottom length along x-axis
L1	14.96 - 22.44 (mm)	Length of 1st patch along the y-axis
L2	7.2 - 10.8 (mm)	Length of 2nd patch along the y-axis
L3	3.2 - 4.8 (mm)	Length of 3rd patch along the y-axis
D1	4.64 - 6.96 (mm)	Distance of 1st patch to base along y-axis
D2	2.8 - 4.2 (mm)	Distance of 2nd patch to base along y-axis
D3	1.2 - 1.8 (mm)	Distance of 3rd patch to base along y-axis
NW1	1.6 - 2.4 (mm)	1st patch notch width along x-axis
NW2	0.8 - 1.2 (mm)	2nd patch notch width along x-axis
NW3	0.8 - 1.2 (mm)	3rd patch notch width along x-axis
WD	CW	Direction of helix turns (windings)
Conductor	PEC / Copper	Type of metal material
Substrate	Air / Vacuum / RT/Duroid 5880	Type of dielectric material

Chameleons are in all areas of the search area to find their prey and use their spherical eyes to scan the search area. When they find their prey, they use their very long and sticky tongues to catch their prey with a fast performance. For a safer performance, the algorithm includes a parameter that can be adjusted throughout the entire iteration, which can balance the discovery-use balance, which are the two main features of the previously mentioned meta-heuristic algorithms. The algorithm used is the first meta-heuristic algorithm that mimics the foraging strategy of chameleons in nature with all these described aspects [31]. The Chameleon algorithm proposed in another previous study is completely different from the CSA algorithm used [39]. This study is a very limited model used for data clustering. The CSA algorithm used is an algorithm that has proven its success in both constrained and global optimization problems. In addition, in a study using CSA algorithm, it is seen that more successful results are obtained when compared with other meta-heuristic algorithms such as GWO, PSO, especially GA [31].

A. MATHEMATICAL MODEL OF CSA

The inspiration for the CSA proposed in the study, in short, consists of following the prey, chasing the prey with its eyes, and attacking the prey. If we briefly summarize the steps of the algorithm used.

1) INITIALIZATION AND FUNCTION EVALUATION

Since CSA is a population-based algorithm, the process starts from this part. For a d-dimensional search space, each chameleon represents a solution to a problem, so if we call n candidate solutions, the $n \times d$ dimensional two-dimensional y-matrix can be defined as the chameleon population. If we were to define it as a vector:

$$y_t^i = \left[y_{t,1}^i, y_{t,2}^i, \ldots, y_{t,d}^i\right] \tag{1}$$

where $i = 1, 2, 3 \ldots, n$ and t are valid iterations, $y_{t,d}^i$ represents the position in the d^{th} dimension [31].

2) IN SEARCH OF PREY

The mathematical model of position update of chameleons' behavior and movements while searching for food can be given as follows.

$$y_{t+1}^{i,j} = \begin{cases} y_t^{i,j} + p_1\left(P_t^{i,j} - G_t^j\right) r_2 + p_2\left(G_t^j - y_t^{i,j}\right) & r_1 r_i \geq P_p \\ y_t^{i,j} + \mu((u^j - l^j)\, r_3 + l_b^j) sgn\,(rand - 0.5) & r_i < P_p \end{cases} \tag{2}$$

where $y_{t+1}^{i,j}$, is the new position of the i^{th} chameleon in the j^{th} dimension in the iteration step.

$y_t^{i,j}$ is the current position of the chameleon in the j^{th} iteration step in the t^{th} iteration step.

$P_t^{i,j}$ represents the best position ever taken by the j^{th} size chameleon in the t^{th} iteration loop.

G_t^j, represents the global best position in the j^{th} dimension achieved by any chameleon in the t^{th} iteration.

p_1 and p_2, are two positive numbers that control exploration ability,

r_1, r_2 and r_3, are random numbers that are evenly spaced from 0 to 1.

r_i, is a uniformly generated random number in the index i between 0 and 1.

P_p, represents the chameleon's probability of detecting prey, equal to 0.1.

$sgn(rand - 0.5)$ has an effect on the exploration direction and can be 1 or -1.

μ is a parameter defined as a function of decreasing iterations [31].

3) ROTATION OF CHAMELEON EYES

Chameleons have the ability to determine the position of their prey by using the ability of their eyes to rotate independently of each other. Let's summarize this part step by step. First, its position is translated to the center, that is, the origin, then the rotation matrix is defined and the position is updated according to this matrix. Finally, it is returned to the original position [31].

4) PREY HUNTING

Chameleons conclude the hunt by attacking when they are very close to their prey. We can say that it is the best chameleon that comes closest to its prey, and it is assumed to be optimal. Chameleons use their tongue to attack their prey. For this reason, tongue lengths can extend up to 2 times, which requires updating the position of the chameleon. We can give all these as a mathematical model as follows.

$$v_{t+1}^{i,j} = \omega v_t^{i,j} + c_1\left(G_t^j - y_t^{i,j}\right) r_1 + c_2\left(P_t^{i,j} - y_t^{i,j}\right) r_2 \tag{3}$$

where $v_{t+1}^{i,j}$ represents the new speed of the chameleon in j.

In iteration, size $t + 1$ represents the current speed of $v_t^{i,j}$. $\omega v_t^{i,j}$ represents the current position of the chameleon in the t^{th} dimension. $P_t^{i,j}$ is the current chameleon's best known position and G_t^j is the best known spherical position ever known to chameleons, $P_t^{i,j}$ is the current chameleon's best known position and G_t^j is the best global position ever known to chameleons, c_1 and c_2 are the two positive constants controlling the effect of $P_t^{i,j}$ and G_t^j falls while chameleon's tongue, r_1 and r_2 are two random numbers, distributed in the range 0 to 1 and ω is the inertia weight [31].

All these processes and mathematical models are outlined in Figure 2 as a flow chart.

B. VARIANTS OF CSA

1) VARIANT 1

The first variant is inspired by a trait possessed by chameleons. Chameleons can turn 180 degrees to the right or left to identify their prey. This feature gives them the ability to find their prey more easily. In addition, each eye can move independently of each other. This allows him to

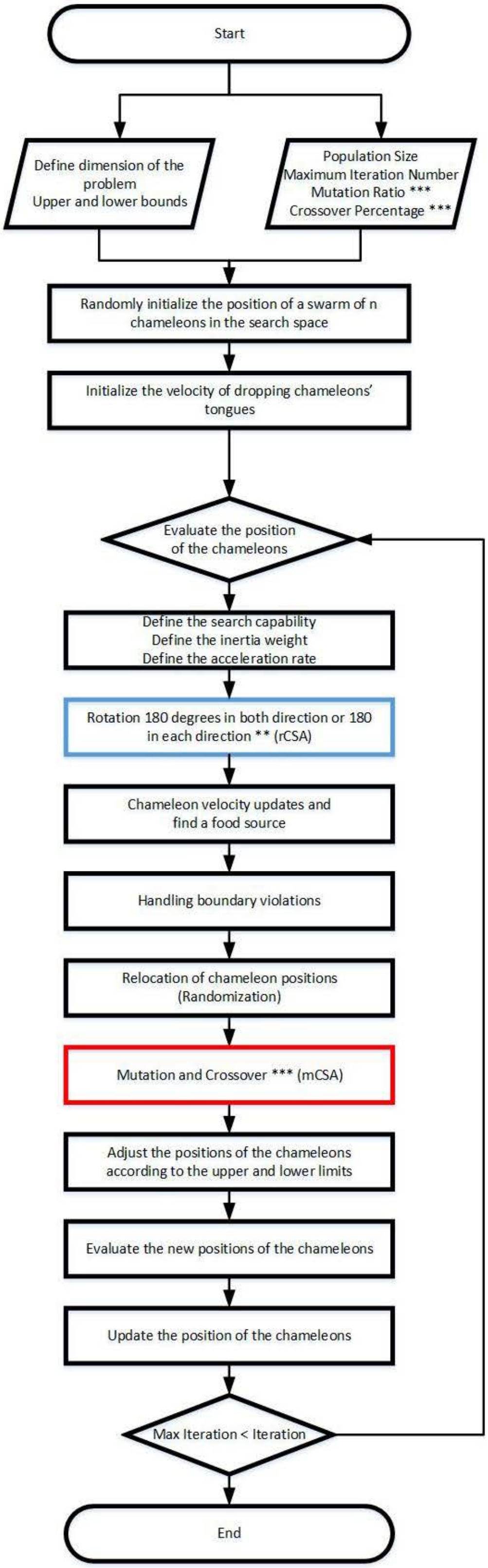

FIGURE 2. Block diagram showing the basic steps of the original and variant algorithm.

observe different objects at the same time. This part was not included in the mathematical modeling in the original CSA. Considering the advantages described above, adding this part to the original code suggests that it may lead to improvement in the optimization results found.

The $y_t^{i,j}$ expressed in the prey part of the chameleons represents the position of the chameleons in the second iteration. If we add the change mentioned above to this part, the rotation matrices on the relevant axis are expressed with R.

$$v = R(\Phi, y_t^{i,j}) \tag{4}$$

here the rotation matrix in v is represented by Φ and can be defined as a mathematical model as follows.

$$\Phi = r\ sgn\,(rand - 0.5) \times 180 \tag{5}$$

where r is a random number generated in the range 0 to 1.

2) VARIANT 2

The basic operations that are frequently used in many optimization algorithms, especially genetic-based algorithms, are reproduction, crossover and mutation. It is made possible by these basic processes for the previous generation to transfer their characteristics to the new generations. Thus, it means that individuals with good traits that vary with the fitness of an individual are more likely to be selected for breeding. Due to these advantages, a second variant model was derived by adding the crossover and mutation stages that were not present in the current CSA to the original CSA.

3) CROSSOVER OPERATOR

Major crossover operators are single-point row crossover, two-point row crossover, and PMX. According to the two-point crossover, the two points to be crossed over in the chromosomes are determined and these parts are exchanged to obtain two new generation chromosomes. Other genes are inherited from the first parent to the first progeny chromosome, respectively. In the same way, transfer is made from the second parent to the second new generation chromosome. During the transfer, if the transferred gene is already present in the new chromosome, the other gene is passed on, if not, this gene is transferred to the new chromosome. In a single-point crossover, only one point is determined and the remaining steps are performed as in a two-point crossover. In the PMX crossover operator, two random points are selected and gene exchange takes place between these points. Each gene corresponding between these two points is addressed by marking and the next generation chromosomes are filled by looking at this marking list. In the study, the two-point crossover operator is preferred.

4) MUTATION OPERATOR

Three types of mutation operators have been studied. These are the 'Swap', 'Insert' and 'Shift' mutation operators. The swap operator swaps two randomly determined genes on a randomly determined chromosome. In insert mutation, a randomly determined gene is added after a randomly determined gene. In shift mutation, a point is determined on the chromosome and the next gene sequence is ordered from smallest to largest according to the value of the genes. In the study, the 'Swap' operator was preferred.

The mentioned variants are shown in Figure 2 as "** " and "*** ", respectively. These two innovations were added to the original algorithm separately and named as rCSA and mCSA, respectively, as the variant of the original CSA. In addition to the original CSA, these two variants are used in the study.

C. OBJECTIVE AND COST FUNCTIONS FOR ANTENNA OPTIMIZATION

With the innovation in the algorithm, the determination of the original objective functions will facilitate finding more performance results. For this study, three different pairs of objective functions, adapted from linear and nonlinear mathematical methods, were defined. These are named in one study as power, exponential and fourier models, respectively. To create these unique objective functions, two measurement functions, S_{11} and 90-degree directivity gain, were used as decision variables. Here, it is aimed to make S_{11} low and directivity value as high as possible. In addition, the weight coefficients (wc_{1-2}) of the measurement functions are also included in the objective function pairs as a product.

The objective function pair adapted from the power model is defined as follows:

$$OF_{11} = \sum\nolimits_{i=1}^{N} \left(\frac{wc_1}{directivity_i}\right)^2 \quad (6)$$

$$OF_{12} = \sum\nolimits_{i=1}^{N} \left(\frac{wc_2}{-S11_i}\right)^2 \quad (7)$$

Adapted from the exponential model, the objective function pair is defined as follows:

$$OF_{21} = \sum\nolimits_{i=1}^{N} wc_1 * e^{-directivity_i} \quad (8)$$

$$OF_{22} = \sum\nolimits_{i=1}^{N} wc_2 * e^{S11_i} \quad (9)$$

The pair of objective functions adapted from the Fourier model are defined as follows:

$$OF_{31} = \sum\nolimits_{i=1}^{N} wc_1 * \cos(directivity_i) \quad (10)$$

$$OF_{32} = \sum\nolimits_{i=1}^{N} wc_2 * \cos(S11_i) \quad (11)$$

where $i = 1, 2, \ldots, 4$ each represents a resonance frequency.

In addition to all these, 2 different cost functions have been defined. The first of these is obtained by collecting the 2 determined objective function pairs within itself and is defined as follows.

$$cost_1 = OF_{j1} + OF_{j2}, j = 1, 2, 3 \quad (12)$$

The second cost function is defined as follows in order to compare the objective functions on a common basis.

$$cost_2 = \sum_{i=1}^{N} \frac{wc_1}{directivity_i} + \frac{wc_2}{-S11_i}, i = 1, 2, \ldots, 4 \quad (13)$$

In the next chapter, a detailed working case will be presented on the optimization of the U-slot antenna with predetermined design parameters for the frequency bands 3.5 GHz, 3.7 GHz, 5.2 GHz and 5.8 GHz.

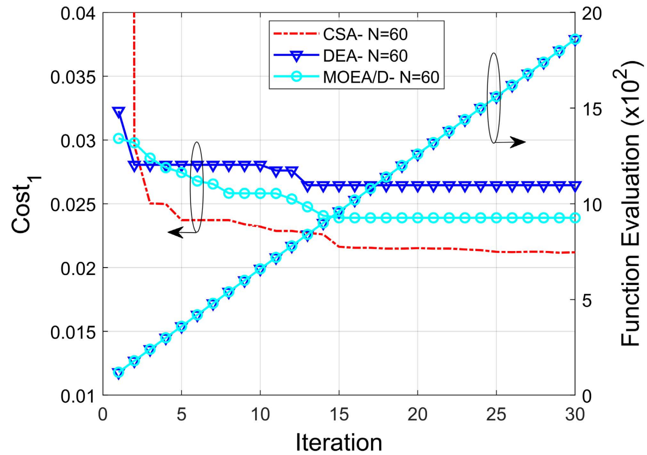

FIGURE 3. Typical cost$_1$ and FEN variations with iteration of the best performance selected from among 10 runs based on CSA, DEA and MOEA/D performance comparison.

IV. RESULTS ANALYZES

In the study part, first of all, the proposed algorithm will be compared with 2 different single/multi-objective algorithms that are commonly used in antenna optimization problems. Then, the optimal parameters that will be used in the continuation of the study will be determined for the selected algorithm. In addition to the original objective function pairs adapted from the mathematical models by using these selected parameters, since the requirements of the measurement functions included in the decision variable may be different, different weighting coefficients (wc_{1-2}) will also be tried. In the continuation of the study, the performances of CSA and its variants derived from CSA will be compared. The section will be concluded with the 3D EM simulation of the measurement functions selected as the decision variable obtained from the optimization process. The optimization methods to be used in the study are scholastic in nature. Therefore, different results can be obtained in each run. Therefore, before the optimization operations, the best performance selected from 10 different code studies for each optimization was taken into account by using the MATLAB "*rng(n)*" (n=1, 2, ...,10) command. In addition, all the optimization and simulation processes were carried out independently of each other, under equal conditions, on the same environment, one by one. During the optimization process, no other operation was performed on the computer in order not to affect the performance.

A. PERFORMANCE COMPARISON WITH OTHER COMMON ALGORITHMS

The performance of CSA has been compared with single-objective DEA and multi-objective MOEA/D, which are widely used in optimization studies and are also used in existing antenna optimization problems [40], [41]. Performance comparison was made based on $cost_1$ (12) function by

TABLE 2. Statistical test results based on variation of typical $cost_1$ for 10 different runs (population (N) = 60, maximum iteration = 30).

Algorithm	Minimum	Maximum	Mean	Standard Deviation
DEA	0.0264	0.0311	0.0287	0.0016
MOEA/D	0.0239	0.0292	0.0274	0.0015
CSA	0.0212	0.0245	0.0230	0.0013

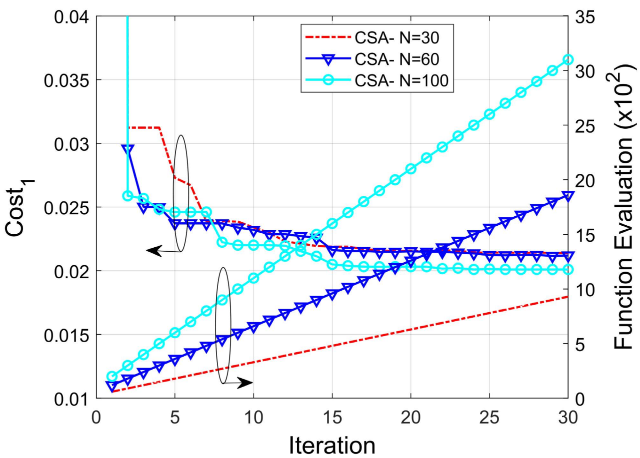

FIGURE 4. Typical $cost_1$ and FEN variations with iteration of the best performance selected from among 10 runs based on population parameter selection.

using OF_{11}-OF_{12} (6,7), one of the objective function pairs. In the algorithms used, the parameters used in the studies specified as reference were preferred. In addition, for all algorithms, the maximum iteration = 30 and the population (N) = 60. Figure 3 shows typical $cost_1$ and Function evaluation number (FEN) variations with best performance repeat of CSA, DEA, MOEA/D. For all, the $cost_1$ value was chosen as the minimum among 10 different studies. In Figure 3, it consists of 30 steps, with the number of steps (range) being 1. As can be seen in Figure 3, it is seen that all algorithms reach saturation after the 25th iteration, that is, there is no decrease in the cost value. Therefore, it can be concluded that the number of iterations is large enough. In addition, the results obtained from 10 different running processes are given in Table 2 as a numerical table with $cost_1$ (12) variations of minimum, maximum, mean and standard deviation. Optimization times were measured at 86 minutes for DEA, 90 minutes for MOEA/D, and 92 minutes for the recommended CSA. Since the antenna simulation rotation time does not affect the algorithm much, it is an expected result that similar times will occur in each of them. Based on the results, it can be concluded that the proposed algorithm is successful.

B. OPTIMAL PARAMETER SET SELECTION FOR OPTIMIZATION

The selection of population size is important because it aims to find the global optimum in optimization studies. As it is known, if this value is chosen smaller than it should be, the probability of the algorithm getting stuck in the local optimum is quite high [42]. Likewise, if this value is chosen high, undesirable situations such as wasting resources and taking a long time to solve the problem may be encountered [42]. In order for the study to progress smoothly, performance comparisons were made over the $cost_1$ (12) function using OF_{11}-OF_{12} (6,7), one of the objective function pairs determined with population = 30, 60 and 100 values. The results obtained are shown in Figure 4 as typical variations of $cost_1$ and FEN with the repetition of the best performance selected from 10 different studies. In addition, the $cost_1$ and FEN variations in Figure 4 are given in Table 3 as a numerical table. Just like in the previous process, it is seen that for all population values, it reaches saturation after the 25th iteration, that is,

TABLE 3. Performance evaluations of algorithm by population parameter for results in Figure 4 (maximum iteration = 30).

Population		Minimum	Maximum	Mean
30	$Cost_1$	0.0214	0,729	0.0469
	FEN	840	60	930
60	$Cost_1$	0,0211	0.729	0.0461
	FEN	1800	120	1860
100	$Cost_1$	0,0201	0.729	0.0452
	FEN	2500	200	3100

TABLE 4. Statistical test results based on variation of typical $cost_1$ for 10 different runs (maximum iteration = 30).

Population	Minimum	Maximum	Mean	Standard Deviation
30	0.0214	0.0253	0.0237	0.0012
60	0.0212	0.0245	0.0230	0.0013
100	0.0201	0.0238	0.0225	0.0011

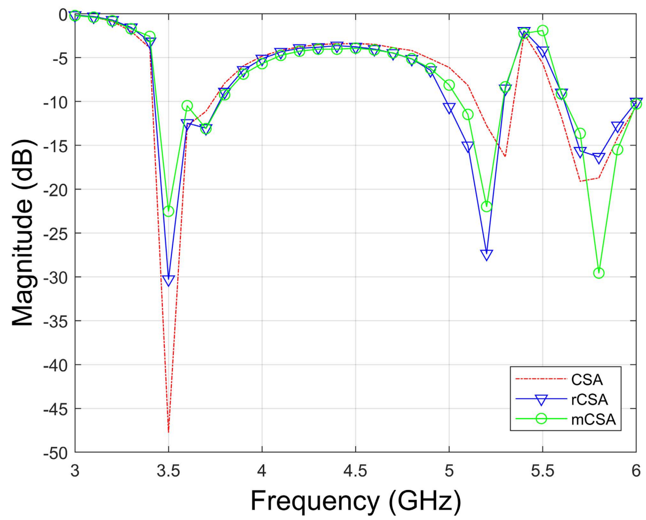

FIGURE 5. S_{11} of the antenna from the results in Table 8 obtained using MATLAB.

TABLE 5. Performance results of algorithm by different objective functions (wc_{1-2} = 0.3-0.7).

		3.5 GHz		3.7 GHz		5.2 GHz		5.8 GHz		$Cost_2$
		Gain (dB)	S_{11}(dB)	Gain (dB)	S_{11}(dB)	Gain (dB)	S_{11}(dB)	Gain (dB)	S_{11}(dB)	
OF_1	$Cost_{1\&2}$	9.00	-47.73	8.06	-11.12	8.99	-12.74	8.60	-18.71	0.3088
OF_2	$Cost_1$	8.18	-9.88	9.10	-12.79	9.23	-9.19	8.21	-11.58	0.4009
	$Cost_2$	8.75	-19.31	8.12	-9.14	9.26	-10.13	7.99	-11.14	0.3859
OF_3	$Cost_1$	8.87	-1.72	8.85	-10.15	9.30	-6.71	8.47	-108.07	0.7212
	$Cost_2$	8.57	-3.92	8.70	-85.31	9.30	-7.42	8.35	-17.23	0.4596

TABLE 6. Performance results of algorithm by different objective functions (wc_{1-2} = 0.5-0.5).

		3.5 GHz		3.7 GHz		5.2 GHz		5.8 GHz		$Cost_2$
		Gain (dB)	S_{11}(dB)	Gain (dB)	S_{11}(dB)	Gain (dB)	S_{11}(dB)	Gain (dB)	S_{11}(dB)	
OF_1	$Cost_{1\&2}$	8.88	-25.15	8.21	-13.66	8.87	-21.95	8.49	-25.10	0.3317
OF_2	$Cost_1$	8.42	-10.68	8.73	-10.52	9.21	-9.87	8.08	-11.97	0.4195
	$Cost_2$	9.08	-13.81	7.94	-11.88	9.28	-8.49	8.09	-13.83	0.4072
OF_3	$Cost_1$	8.41	-3.84	8.67	-48.79	9.30	-5.44	8.61	-87.79	0.4672
	$Cost_2$	8.65	-3.82	8.67	-60.14	9.33	-5.46	8.54	-76.58	0.4649

TABLE 7. Performance results of algorithm by different objective functions (wc_{1-2} = 0.7-0.3).

		3.5 GHz		3.7 GHz		5.2 GHz		5.8 GHz		$Cost_2$
		Gain (dB)	S_{11}(dB)	Gain (dB)	S_{11}(dB)	Gain (dB)	S_{11}(dB)	Gain (dB)	S_{11}(dB)	
OF_1	$Cost_1$	8.66	-11.93	8.64	-11.42	8.98	-11.74	8.81	-22.08	0.4099
	$Cost_2$	8.66	-12.26	8.64	-11.31	8.86	-13.21	8.81	-22.16	0.4076
OF_2	$Cost_{1\&2}$	8.67	-10.91	8.75	-11.22	9.11	-8.72	8.43	-18.55	0.4254
OF_3	$Cost_1$	8.75	-75.92	9.33	-0.64	9.24	-7.06	8.44	-53.87	0.8310
	$Cost_2$	8.49	-4.04	8.72	-26.18	9.37	-6.57	8.53	-80.55	0.4546

there is no decrease in the cost value. Therefore, there is no need to increase the maximum number of iterations after the study. In addition, the results obtained from 10 different runins are given in Table 4 as a numerical table with the variation of minimum, maximum, mean and standard deviation as $cost_1$ (12). Among the results obtained for this study, it is seen that the population (N) value that gives the result with the lowest minimum and average cost is 100.

C. PERFORMANCES OF DIFFERENT OBJECTIVE FUNCTIONS/WEIGHT COEFFICIENT

In the basic principle of the operation of optimization algorithms, it is tried to bring the objective functions closer to zero by giving priority in the ratio of the weight coefficients determined. From this, it can be concluded that one of the most important points of optimization is the correct determination of the objective function and weight coefficients. In this section, 3 different pairs of objective functions, adapted from the mathematical models mentioned in the previous section, were used to ensure that the directivity value is high and S_{11} is as low as possible. In addition, according to the 2 different cost functions determined in the previous section, a separate selection was made for each pair of objective functions. Accordingly, the results of the optimum cost value according to 3 different objective functions for the weight coefficients (wc_{1-2} = 0.3-0.7), (wc_{1-2} = 0.5-0.5) and (wc_{1-2} = 0.7-0.3), respectively given at Table 5, 6 and 7. In addition, the value calculated on the basis of $cost_2$ is given for each row at the far right of each table. According to the results from the tables, the results obtained with OF_{31}-OF_{32} (10,11) found very high S_{11} values, but were not successful in each of the 4 frequencies. The results found with OF_{21}-OF_{22} (8,9) are partially successful. It is seen in the tables that the most successful values are the results found using OF_{11}-OF_{12} (6,7). The results with the weight coefficients (wc_{1-2} = 0.3-0.7) in this objective function gave the most successful result, with a cost value of 0.3088.

D. PERFORMANCES OF CS VARIANT ALGORITHMS

Since the preferred CSA is a new optimization algorithm, variant models are also included in this study. In this context, performance comparisons of CSA, rCSA and mCSA were

TABLE 8. Performance results of algorithms by variants (OF_{11}-OF_{12} (6,7) & wc_{1-2} = 0.3-0.7).

		3.5 GHz		3.7 GHz		5.2 GHz		5.8 GHz		Cost₂
		Gain (dB)	S_{11}(dB)	Gain (dB)	S_{11}(dB)	Gain (dB)	S_{11}(dB)	Gain (dB)	S_{11}(dB)	
CSA	$Cost_{1\&2}$	9.00	-47.73	8.06	-11.12	8.99	-12.74	8.60	-18.71	0.3088
rCSA	$Cost_{1\&2}$	8.98	-30.28	8.17	-13.04	8.47	-27.36	8.68	-16.32	0.2854
mCSA	$Cost_{1\&2}$	9.03	-22.52	8.13	-13.09	8.44	-21.98	8.62	-29.56	0.2806

TABLE 9. Antenna design parameters found as a result of optimization (mm).

	wc_{1-2}=0.3-0.7			wc_{1-2}=0.5-0.5			wc_{1-2}=0.7-0.3			wc_{1-2}=0.3-0.7		
		CSA			CSA			CSA		CSA	mCSA	rCSA
	OF1	OF2	OF3	OF1	OF2	OF3	OF1	OF2	OF3		OF1	
BL1	16.406	16.739	12.742	16.232	14.589	13.825	16.693	11.225	11.845	16.406	16.249	15.736
BL2	19.823	19.008	16.578	18.602	17.957	18.735	15.672	17.046	19.826	19.823	18.582	18.303
BL3	22.366	26.339	23.749	20.785	26.033	23.817	26.295	26.359	24.327	22.366	22.151	21.514
NW1	1.822	2.383	1.902	2.017	2.161	2.306	2.400	1.601	2.182	1.822	2.058	2.044
NW2	0.894	1.121	0.968	0.920	1.071	0.964	1.200	0.801	1.167	0.894	1.055	1.169
NW3	0.809	0.801	0.914	0.886	0.906	1.099	0.982	0.946	0.903	0.809	0.899	1.051
L1	14.974	15.389	15.915	15.469	17.291	17.164	15.040	14.965	17.557	14.974	15.143	15.991
L2	9.734	7.209	9.421	9.589	10.126	8.547	7.747	10.795	10.386	9.734	9.584	9.859
L3	3.235	4.735	4.107	3.473	4.339	4.033	4.800	3.203	3.631	3.235	3.343	3.528
D1	6.680	4.656	5.826	6.200	5.383	6.528	5.463	5.034	5.472	6.680	5.189	6.184
D2	2.800	2.956	3.325	3.704	3.597	3.943	2.805	4.198	3.767	2.800	3.410	3.888
D3	1.609	1.263	1.393	1.388	1.601	1.681	1.800	1.658	1.652	1.609	1.249	1.218

made by using the objective function pair OF_{11}-OF_{12} (6,7) and weight coefficients ($wc_{1-2} = 0.3$-0.7), in which the best result determined in the previous section was obtained. The results obtained in Table 8 are given as a numerical table. The table shows the best results for each algorithm according to 2 different cost functions. Also, in Figure 5, the variation of S_{11} is given as typical magnitude-frequency. As can be seen from the results, mCSA is the most successful algorithm model. In addition to all these, the antenna design parametric dimensions for the most successful results obtained from the experimental results are given in Table 9 as a numerical table.

E. ANTENNA SIMULATIONS

Until this part of the study, experiments were made on various algorithm parameters, objective functions, weight coefficients and algorithm variants for the most optimal results, and the most optimum result has been found by using the MATLAB program. Now, the results of the decision variables (S_{11} and directivity) are obtained by using the 3D EM simulation tool CST Microwave studio with a total of 18 design parameters, 12 of which are variables, obtained from the optimum result found in the previous section using mCSA and given in Table 8. In Figure 6, the variation of S_{11} is given as typical magnitude-frequency. Also, the directivity at 3.5, 3.7, 5.2 and 5.8 GHz is shown in Figures 7A, 7B, 7C and 7D, respectively. The results obtained are in agreement with Table 8. In addition to all these, in terms of designing on a materialized surface, the surface dielectric material type RT/Duroid 5880 was selected using the mCSA algorithm in the MATLAB program and optimized again, and the most successful design parameter was obtained by using the 3D EM simulation tool CST Microwave studio. The antenna model drawn with the CST program is given in Figure 8. In Figure 9, the variation of S_{11} is given as typical amplitude-frequency.

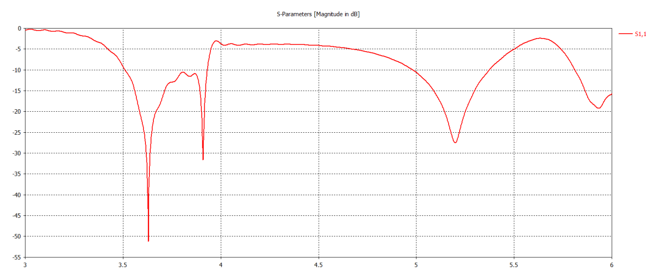

FIGURE 6. S_{11} of the antenna from the results in Table 8 obtained using CST (Substrate to vacuum).

V. DISCUSSION

There are many intelligent methods inspired by nature or based on physics and biology for antenna optimization

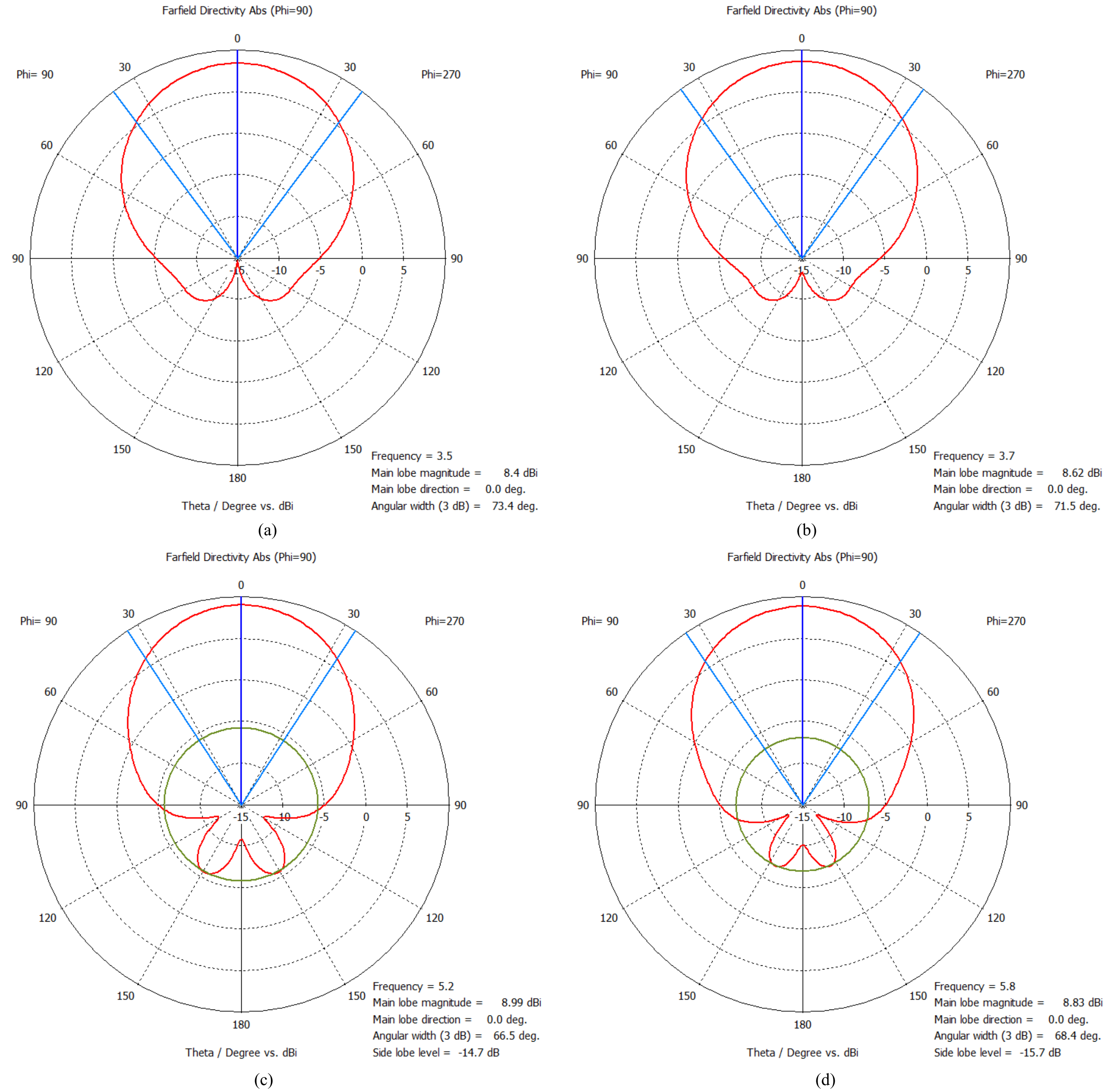

FIGURE 7. Directivity of antenna for the mCSA from the results in Figure 6 using CST (a) 3.5GHz, (b) 3.7GHz, (c) 5.2GHz, (d) 5.8GHz (Substrate to vacuum).

problems. Many of these methods work with a random selection and population-based search method. There are many methods in nature yet to be discovered. For this reason, problems that have not yet been addressed or newly found algorithms can be addressed and more successful results can be obtained. One of them is the newly developed CSA. The main inspiration was inspired by the hunting behavior of chameleons in nature. Thus, each feature of the chameleon's prey search is modeled with objective functions adapted from mathematical models to achieve the desired results. For the related problem between the original CSA and variant models, the mCSA is considered the best. In addition, these algorithms meet the NFL theory advocated in a study [30]. Good performance of a method depends on a properly selected objective function pair as well as balanced parameter settings. It is also useful to dwell on the possibility that the current CSA has a single-objective cost function, which may be limiting the algorithm. In addition to all these, the determination of more efficient objective functions is still an active area of research. Of course, modifications to the antenna model used may lead to more effective solutions. Therefore, in this study, it is aimed to give a different perspective to the antenna optimization design problems in the literature.

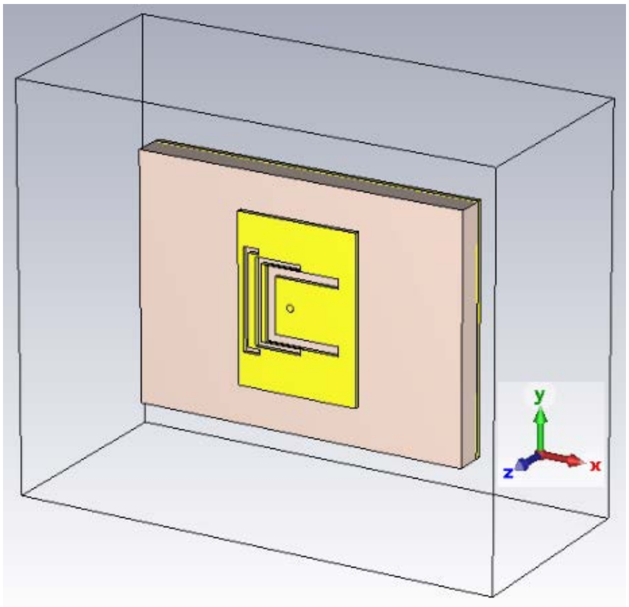

FIGURE 8. 3D view of the antenna designed with CST.

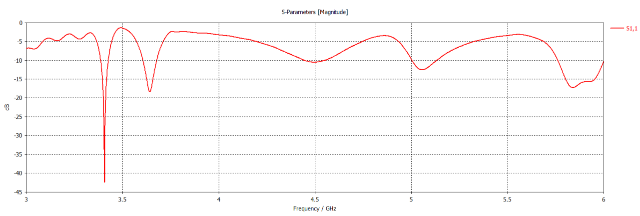

FIGURE 9. S_{11} of the antenna from the results using CST (Substrate to RT/Duroid 5880).

VI. CONCLUSION AND FUTURE WORKS

In antenna design optimizations, the increase in the number of design parameters and the high number of bands make it difficult to solve the problems encountered effectively. New and computationally efficient methods must be sought for such design optimization problems. The proposed CSA is one of the newest meta-heuristic-based algorithms that can be used effectively to solve such designs. In addition, the perfect algorithm that gives the most successful results for all problems has not been designed yet, so new artificial intelligence optimization algorithms are constantly proposed or variant models are derived by making some efficient additions or modifications to existing algorithms.

In recent years, researchers have proposed the CSA algorithm, inspired by the dynamic behavior of chameleons looking for food in nature. Although there are many meta-heuristic algorithms, CSA is effective in solving high-dimensional and difficult problems [38]. CSA gives more successful results than optimization methods such as GA, GWO, PSO, MFO, MVO and SCA [38]. In addition, the success of the CSA optimization algorithm has been experimentally proven by comparing it with DEA and MOEA/D in this study.

In this paper, a U-slot antenna with 4 resonance frequencies (3.5 GHz, 3.7 GHz, 5.2 GHz and 5.8 GHz) and a total of 18 design parameters, 12 of which are variable, is considered as a multidimensional and single- objective optimization problem by using variants developed in collaboration with CSA, which has just been proposed in the literature. The study was started with the selection of the optimum population parameter in order not to get stuck in the local optimum, not to waste resources and not to spread the solution of the problem for a long time. In the study, original complex linear and nonlinear objective functions adapted from mathematical models were used, supported by different weight coefficients of the decision variables. Since the preferred CSA model is a very new optimization algorithm, the study also included CSA variant models developed for the study. Variant models played an active role in finding more performance results. The aim of the study is to find the optimum antenna design parameters. More than one cost function was used separately in all these selections. The most successful results were obtained with variant mCSA using OF_{11}-OF_{12} (6,7) and weight coefficients ($wc_{1-2} = 0.3$-0.7) adapted from the power model. In the last part of the study, all these processes were compared within themselves and the antenna results of the most successful result were displayed. In addition, an example of design in a different substrate is given in terms of designing on a materialized surface. Considering all these aspects of the study, it contains more than one innovation.

This article allows researchers to quickly learn about the CSA algorithm and shows that it can be a safe, practical and efficient solution for any multidimensional optimization applications. Also, CSA is of course adaptable to any optimization problem with a large number of variable design parameters. Although CSA is a very new algorithm, the results obtained are promising. Better results can be obtained by suggesting new distributed and binary versions in future studies. New methods can be included in the algorithm to improve performance and reduce optimization time. It may also be possible to extend CSA applications to solve multi-objective problems in various fields.

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