Optimization and Comparative Analysis of Quarter-Circular Slotted Microstrip Patch Antenna Using Particle Swarm and Fruit Fly Algorithms

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Abstract: *This paper proposes a parametric study of modified rectangular microstrip antenna in the frequency range between 1.4-2.65 GHz for wireless communication applications, incorporating with optimization methods Particle Swarm Optimization (PSO) and Fruit Fly Optimization (FOA). To design an antenna using optimization methods a fitness function of required parameters is needed. The resonance frequency of Microstrip Patch Antennas (MPAs) depends on various parameters and a standard frequency function does not exist for MPAs. In this study, a rectangular patch antenna is designed for the required resonance frequency and modified with circular quarter slots. The frequency-shift with the change of design variables, which are the substrate thickness and the radius of the slots, is observed. The resonance frequency is obtained as a function of the design variables and it is used in the optimization process to minimize the difference between the target frequency and the calculated one. The original algorithms FOA and PSO have been adapted for its application to a modified rectangular patch antenna design problem: resonance frequency and design of antenna. The design parameter values obtained via optimization and the performances of the optimization methods are presented. The results showed that both PSO and FOA find the dimensions correctly. It is also observed that the sensitivity of the FOA increases with the fruit fly population and the convergence gets faster. The outcomes of this paper show that the PSO algorithm gives better results when compared to the FOA for the proposed antenna.*

Keywords: *Microstrip antenna design, particle swarm optimization, fruit fly optimization.*

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1. Introduction

Microstrip Patch Antennas (MPAs) have a wide range of application area in the modern wireless communication and sensor technology. MPAs are preferred in defense, aerospace, and global navigation industries due to their miniature structures, easy manufacturing, cost effectiveness, etc., [4, 9]. To solve the system requirements and improve its performance, a well-designed antenna operating at a certain frequency is needed. Antenna design parameters such as, physical dimensions, geometry, feeding technics, and the thickness of the substrate have essential effects on the resonance frequency of the antenna. The design of an antenna operating at the required frequency is an optimization problem [16].

The nature-inspired evolutionary algorithms such as Genetic Algorithm (GA) [10, 18, 20], Particle Swarm Optimization (PSO) [7, 16, 27, 31, 32] have better global search capabilities when compared with conventional ones and have gained more and more importance especially in recent years. Several swarm algorithms are inspired by the social behavior of insect or animal groups in nature such as bird flocking, fish schooling or ant colonies. The PSO algorithm based on how a group of birds adapt their paths to find their food [17], the Ant Colony Optimization (ACO) technique including the cooperative behavior of bee colonies [5, 23, 24], and Fruit Fly Optimization (FOA) algorithm based on the fruit fly's smell and visual features in foraging process [13, 14, 25, 26] have been widely investigated. In groups of these animals, individuals have memory and move as a whole to locate the desired locations in a restricted area. Both PSO and FOA were created based on this social behavior of the swarms and guide a population of particles to move towards the most promising location of the search space. These algorithms have been applied successfully to many problems requiring the optimization of a certain multidimensional function.

GA is widely used is used in antenna pattern synthesis of antenna arrays [2]. Desired antenna pattern is obtained via GA optimization of the excitation amplitude and phase weights of the array elements [30]. Abd Malik *et al*. [1] utilized PSO to optimize the Side

Lobe Levels (SLLs) of even-element linear arrays. SLL reduction, null control, thinning and directivity improvement of linear and planar array antennas via FOA [6, 19, 22] and ACO [24, 28, 29] is investigated and compared with other metaheuristic algorithm.

Since there is no exact frequency equation for each geometry of MPA [15] and metamaterial based antennas [3, 11], the optimization is performed by parallel computation of optimization method with the full wave Electromagnetics (EM) simulation software. However, in this method, the next optimization update of individuals is evaluated calling the simulation software again and again which leads to high calculation cost. A self-renewing fitness approach is introduced to overcome the time consumption of parallel computation [8]

The optimization of microstrip antennas with irregular geometries is performed by utilizing curve fitting followed by optimization methods [34, 35] or Artificial Neural Network (ANN) [33].

In this paper, a modified rectangular MPA with two quarter circular slots at the top corners of the rectangular patch is designed. PSO and FOA is used to optimize the modified rectangular MPA for wireless communication applications in the frequency range between 1.4 GHz and 2.65 GHz. The aim is to design an antenna that operates at the required frequency and compare the performance of the optimization algorithms. The correlation between substrate thickness *(h)* and radius of the slot *(r)* is investigated. The operating frequency of the proposed antenna is defined as a function of *h* and *(r)*, by utilizing curve fitting. The difference between the target frequency and the calculated frequency for the optimized dimensions is used as the fitness function.

2. Optimization Techniques

2.1. Particle Swarm Optimization

PSO is first introduced by Kennedy and Eberhart [17]. To optimize a specific fitness function of M variables, a swarm of N particles is defined. Each particle in the swarm is assigned a random position in the research area which are the initial candidate solutions for the fitness function. The position of the particles in a swarm is changed according to its current positions, its own memory and by the social behavior of the swarm [7].

Several techniques are proposed to handle constrained optimization problems and to maintain a feasible population with PSO. Fly-back mechanism is one of them which is proposed by He *et al.* [12]. According to this mechanism, the positions of each particle are initialized within the feasible search area considering the predefined constraint conditions. The particles move in the feasible area. If any of the particles move to the unfeasible area, it flies back to the previous feasible position and a feasible solution is guaranteed. Since the particle is most likely to be close to the boundary, the global minimum is obtained faster when fly-back mechanism is applied to PSO algorithm [12, 21].

The main steps of the PSO are as follows:

- *Step* 1 Define the variables of the fitness function. Initialize each particle's position within the constraint conditions. Assign the initial velocities of the particles as zero.
- *Step* 2 Calculate the fitness function value for each particle and obtain the local best position of each particle and the global best within the swarm.
- *Step* 3 Update the current position and velocity of the particles by Equations (1) and (2).

$$V_{i,j}^{k+1} = wV_{i,j}^{k} + c_1 r_1\left((X_{best})_{i,j}^{k} - X_{i,j}^{k}\right) + c_2 r_2\left((X_{global})_{i,j}^{k} - X_{i,j}^{k}\right) \quad (1)$$

$$X_{i,j}^{k+1} = X_{i,j}^{k} + V_{i,j}^{k+1} \quad (2)$$

Where the indices *i* and *j* represent the size of the swarm ($i=1,2,\ldots. M$), and variables, ($j=1,2,..N$), respectively. *V is* the velocity of the particles. *k* is the iteration number ($k=1,\ 2,\ \ldots.\ K$). *X* denotes the particle positions. The parameters X_{best} and X_{global} are the particles' best position and the global best of the swarm, respectively. The inertial weight factor *w* defines the effect of the previous velocity on the calculated one. The values r_1 and r_2 are random variables between (0, 1). The learning factors c_1 and c_2 are selected as 2.

- *Step* 4 Compare the values of fitness function for each particle, update X_{best} and X_{global}.
- *Step* 5 If the required conditions are satisfied, complete the program otherwise return to step 3.

2.2. Fruit Fly Optimization Algorithm

FOA is a global finding optimization algorithm which is inspired by the foraging behavior of fruit flies Figure 1. It was first introduced by Pan in 2011. Fruit flies' vision and smell capabilities are superior when compared to other species. They can smell the food within the 40 km and fly toward to the food according to the smell concentration. Then, they can find the food by using their vision capability [25, 26].

During hunting for food, each fruit fly keeps track of its location and the concentration of food. Fruit flies send and receive information from their neighbors and compare the smell concentration and the current best location. When fruit flies get close to the food location, they then fly to the current location from where they find the next best location by using their sensitive vision. Then, the process of smell-based and vision-based foraging is repeated until the termination criterion is satisfied.

The main steps of the FOA are as follows:

- *Step* 1 Initialize the random position of the swarm (*x*,*y*) within the predefined constraint conditions.

$$Init\ x\_axis \tag{3}$$

$$Init\ y\_axis \tag{4}$$

- *Step* 2 Define the random direction and position of the olfactory organ.

$$x_i = x\_axis + Randx \tag{5}$$

$$y_i = y\_axis + Randy \tag{6}$$

- *Step* 3 Estimate the distance to the origin ($Dist_i$) and the smell concentration S_i.

$$Dist_i = \sqrt{x_i^2 + y_i^2} \tag{7}$$

$$S_i = \frac{1}{Dist_i} \tag{8}$$

- *Step* 4 Estimate the value of the smell concentration judgement (fitness) function and determine the smell concentration of each local position of the swarm.

$$Smell_i = Function\ (S_i) \tag{9}$$

- *Step* 5 Determine the best smell concentration position within the swarm.

$$[bestSmell\ bestIndex] = \min(Smell) \tag{10}$$

- *Step* 6 Save the best smell value and the *(x,y)* coordinate to be used as vision knowledge to fly towards that location.

$$Smellbest = bestSmell \tag{11}$$

$$x\_best = x(bestIndex) \tag{12}$$

$$y\_best = y(bestIndex) \tag{13}$$

- *Step* 7 Start the iterative optimization for steps 2-5 and compare the values of judgement (fitness) function for each fly if the smell concentration is more than the previous one, if so repeat step 6 [26].

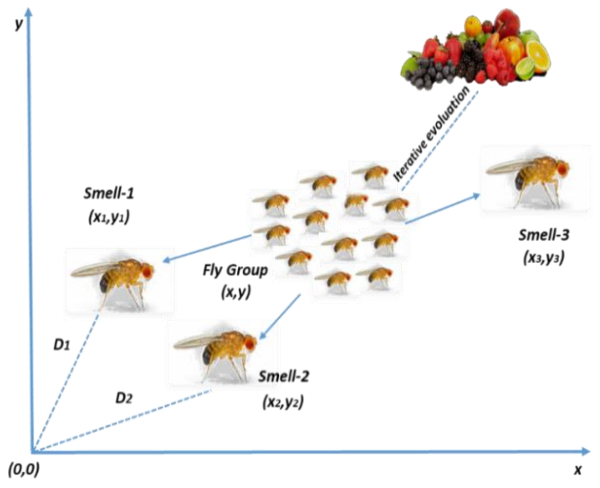

Figure 1. Schema of food searching approach of fruit fly.

3. Quarter-Circular Slotted Micropatch Antenna (SMPA) Design

In this section, a quarter-circular Slotted Microstrip Patch Antenna (SMPA) is designed for wireless communication applications. The SMPA is designed by cutting quarter-circular slots at the corners of the rectangular patch antenna as shown in Figure 2. RT/duroid 5880 with relative permittivity ε_r=2.2 is selected as substrate.

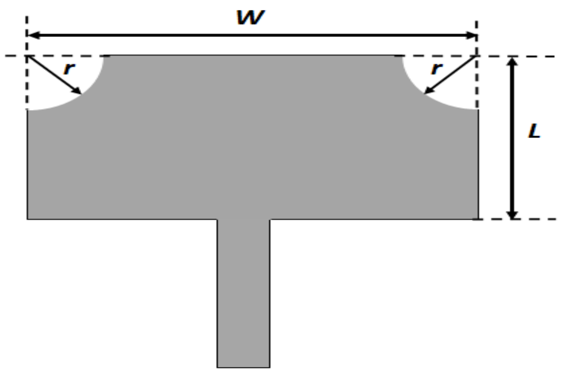

Figure 2. Rectangular microstrip antenna with quarter circular slots.

The simulations of the antenna are performed via ANSYS High-Frequency Spectrum Simulation (HFSS) a Finite Element Method (FEM) based numerical simulator. Frequency range is divided into six frequency band of 200 MHz and 20 simulations are performed for each band. Six conventional rectangular MPAs with resonance frequencies at 1.43 GHz, 1.63 GHz, 1.83 GHz, 2.03 GHz, 2.25 GHz, and 2.43 GHz have been designed according to Equations (14), (21). The substrate thickness *(h)* is calculated as 0.05λ_0 (h_{max}) to achieve the largest BW.

The dimensions of the rectangular patch are calculated for each frequency band via Equation (14) through Equation (21) [3, 4]. The initial dimensions of the patch for six different frequency value are given in Table 1.

$$L_{eff} = L + 2\Delta L \tag{14}$$

$$\Delta L = 0.412h\frac{(\varepsilon_{reff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{reff}-0.258)(\frac{W}{h}+0.8)} \tag{15}$$

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2} \tag{16}$$

The actual physical length is as follows:

$$L = L_{eff} - 2\Delta L \tag{17}$$

The resonance frequency of the MPA is calculated by the folloing:

$$f_r = \frac{c_o}{2L_{eff}\sqrt{\varepsilon_{reff}}} \tag{18}$$

$$W = \frac{1}{2f_c\sqrt{\varepsilon_0\mu_0}}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{c}{2f_c}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{19}$$

Ground layer dimensions are calculated as follows [2]:

$$L_g = 6h + L \tag{20}$$

$$W_g = 6h + W \tag{21}$$

Table 1. The initial dimensions of the patch antenna.

Frequency (GHz)	L (mm)	W (mm)	h (mm) ($h_{max}=0.05\lambda_0$)
1.43	79.02	57.14	10
1.63	69.72	50.42	8.82
1.83	62.38	45.11	7.89
2.03	56.44	40.82	7.14
2.25	51.53	37.27	6.52
2.43	47.41	34.28	6

The radii of the quarter-circular slots are changed between $0.1L$ and $0.5L$, where L is the length of the main patch. The effect of the radii of the slots on resonance frequency (f_r) are observed. The results showed that the f_r can be adjusted by varying the radius of the quarter-circular slots without changing the outer dimensions of the patch (*W and L*). The simulations for each radius are also repeated for five different substrate thicknesses (h) between ($0.6h_{max}$) and (h_{max}) where $h_{max}=0.05\lambda_0$. It is observed that, the same f_r value is obtained for different (r, h) pairs. It is concluded that the slotting approach may be used to compensate for the influence of h on f_r. In the light of aforementioned effects of r and h on resonance frequency, curve fitting is applied to obtain the frequency as a function of (r) and (h) Equation (22). Curve fitting process is performed by MATLAB and a third degree polynomial is obtained for each frequency range. The constants for each polynomial are listed in Table 2.

$$f_r(r,h) = A + Br + Ch + Dr^2 + Erh + Fh^2 + Gr^3 + Hr^2h + Irh^2 + Jh^3 \qquad (22)$$

The calculated frequency values are compared with the simulation values in Figure 3.

Table 2. The constants of the third-degree polynomial equation of the resonance frequency (f_r) given in Equation (22).

Equation Constants	Gr. 1 1.43-1.63 (GHz)	Gr. 2 1.63-1.83 (GHz)	Gr. 3 1.83-2.03 (GHz)	Gr. 4 2.03-2.25 (GHz)	Gr. 5 2.25-2.43 (GHz)	Gr. 6 2.43-2.65 (GHz)
A	1.379	2.223	1.914	2.461	2.562	2.649
B	0.01507	-0.003211	0.01544	0.01277	0.01872	-0.007235
C	0.09171	-0.1322	0.06238	-0.1031	-0.04735	0.05259
D	0.00003486	0.00004972	0.00006439	0.0002446	0.0001298	0.001289
E	-0.002532	0.002868	-0.002002	-0.001091	-0.002573	0.003471
F	-0.01528	0.008131	-0.01732	0.007066	-0.004215	-0.0286
G	0.0000085	-0.0000091	-0.0000228	-0.000038	-0.000048	-0.00007
H	0.00002938	0.00002413	0.00009694	0.0001322	0.0001954	0.0001166
I	0.0001111	-0.0002373	0.00003429	0.0001533	0.0001018	0.0005063
J	0.000651	-0.0001189	0.001026	-0.0001143	0.0005888	0.002299

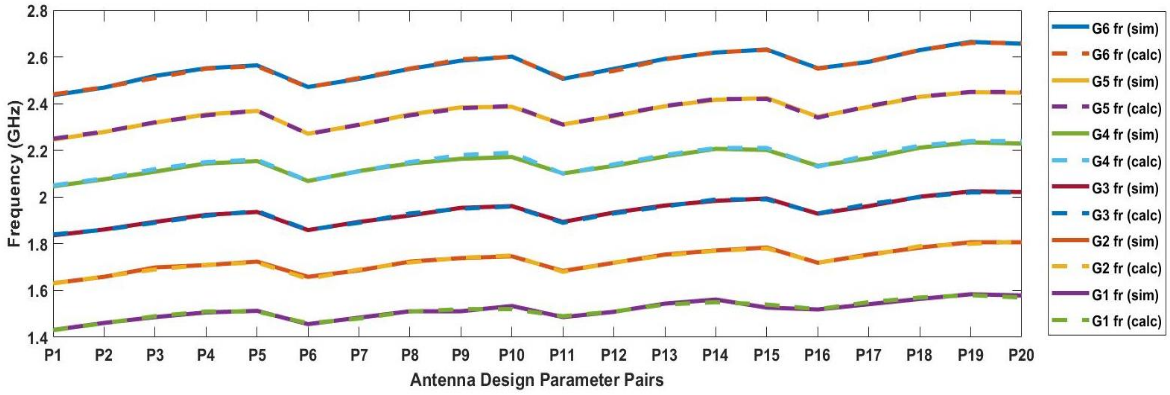

Figure 3. The comparison of simulated (solid) and calculated (dashed) frequencies for each group (Group 1 (bottom) to Group 6 (top)).

PSO and FOA is used to optimize the SMPA in the frequency range between 1.43 GHz and 2.65 GHz. The aim is to obtain an antenna design that operates at the required frequency. The optimization methods are used to minimize the fitness function which is the difference between the target frequency (f_0) and the calculated one (f_c) Equation (23). The calculated frequency is obtained via Equation (22).

$$\Delta f = min\{|f_0 - f_c|\} \qquad (23)$$

Certain constraints are applied to guarantee the functionality of the antenna design. All the constraints for the design variables are defined as follows:

$$0.1L \le r \le 0.5L \qquad (24)$$

$$0.6h_{max} \le h \le h_{max} \qquad (25)$$

4. Results

In the optimization methods the initial population size is defined as 20. The variables to be optimized according to the required operational frequency are the height of the substrate (h) and the radius of the slot (r). The optimization is run for 200 iterations and it is repeated 50 times for each frequency group. The obtained design variable values and the corresponding frequency values are compared Table 3. The Best, Worst and Mean values of the required frequency for each group is obtained via PSO and FOA, and they are listed in Table 4.

Table 3. The design parameters *(r,h)* obtained via PSO and FOA methods.

Group No (Frequency)	Variables	Optimization Methods PSO	FOA
	r (mm)	21.53	10.85
1	*h (mm)*	6.66	6.55
(1.575 GHz)	f_r *(GHz)*	1.575	1.557
	r (mm)	17.59	9.67
2	*h (mm)*	5.93	6.43
(1.800 GHz)	f_r *(GHz)*	1.800	1.740
	r (mm)	9.06	8.61
3	*h (mm)*	6.93	6.54
(1.900 GHz)	f_r *(GHz)*	1.899	1.918
	r (mm)	14.65	9.11
4	*h (mm)*	5.52	4.79
(2.200 GHz)	f_r *(GHz)*	2.200	2.197
	r (mm)	10.77	7.32
5	*h (mm)*	4.82	4.39
(2.400 GHz)	f_r *(GHz)*	2.399	2.396
	r (mm)	6.46	7.52
6	*h (mm)*	5.44	4.85
(2.500 GHz)	f_r *(GHz)*	2.499	2.536

Table 4. The comparison of operation frequency obtained via PSO and FOA.

Frequency (GHz)		Optimisation Methods PSO	FOA
1.575	***Best***	1.575	1.575
	Mean	1.575	1.557
	Worst	1.574	1.521
	Std. Dev.	9.84×10^{-5}	0.0168
1.800	***Best***	1.800	1.771
	Mean	1.800	1.740
	Worst	1.799	1.718
	Std. Dev.	1.38×10^{-4}	0.0147
1.900	***Best***	1.900	1.898
	Mean	1.8999	1.918
	Worst	1.8999	1.934
	Std. Dev.	1.46×10^{-4}	0.0178
2.200	***Best***	2.200	2.200
	Mean	2.200	2.197
	Worst	2.199	2.222
	Std. Dev.	8.39×10^{-5}	0.0113
2.400	***Best***	2.400	2.399
	Mean	2.399	2.396
	Worst	2.399	2.381
	Std. Dev.	1.16×10^{-4}	0.0061
2.500	***Best***	2.500	2.503
	Mean	2.499	2.536
	Worst	2.499	2.553
	Std. Dev.	1.49×10^{-4}	0.0219

The FOA and PSO are also repeated for different population sizes which are 50, 100, 200, 500. It is observed that the results are closer to the required values when the population is higher for FOA. The values of the design parameters and the operating frequency which are obtained with different population sizes are listed in Table 5. The results obtained via PSO for different population sizes show that the population size has no significance impact on the PSO results Table 6.

Table 5. The comparison of FOA results for population size 20, 50, 100, 200 and 500.

Required Frequency (GHz)	Design Parameters	Population size N=20	N=50	N=100	N=200	N=500
	r (mm)	10.85	11.29	12.84	14.26	13.60
1.575	***h (mm)***	6.55	6.49	6.38	7.23	6.43
	f_r (GHz)	**1.557**	**1.561**	**1.572**	**1.572**	**1.575**
	r (mm)	9.68	12.26	12.51	12.72	12.67
1.800	***h (mm)***	6.43	6.21	6.28	6.14	5.98
	f_r (GHz)	**1.740**	**1.763**	**1.764**	**1.772**	**1.779**
	r (mm)	8.62	6.71	5.91	7.05	11.54
1.900	***h (mm)***	6.54	6.21	5.85	6.32	7.38
	f_r (GHz)	**1.918**	**1.917**	**1.925**	**1.919**	**1.909**
	r (mm)	9.11	8.80	8.99	9.26	9.29
2.200	***h (mm)***	4.79	4.79	4.79	4.79	4.79
	f_r (GHz)	**2.197**	**2.194**	**2.196**	**2.199**	**2.200**
	r (mm)	7.32	7.54	7.54	7.60	7.59
2.400	***h (mm)***	4.39	4.38	4.38	4.39	4.39
	f_r (GHz)	**2.397**	**2.399**	**2.399**	**2.400**	**2.400**
	r (mm)	7.52	7.00	13.28	11.66	8.89
2.500	***h (mm)***	4.85	5.85	6.03	6.65	8.10
	f_r (GHz)	**2.536**	**2.529**	**2.510**	**2.515**	**2.511**

Table 6. The comparison of PSO results for population size 20, 50, 100, 200 and 500.

Required Frequency (GHz)	Design Parameters	Population size N=20	N=50	N=100	N=200	N=500
	r (mm)	21.53	17.93	16.86	17.199	20.83
1.575	***h (mm)***	6.66	6.63	6.65	6.66	6.99
	f_r (GHz)	**1.575**	**1.575**	**1.575**	**1.575**	**1.575**
	r (mm)	17.59	17.43	14.40	19.79	14.79
1.800	***h (mm)***	5.93	5.89	5.67	6.14	5.69
	f_r (GHz)	**1.800**	**1.800**	**1.800**	**1.800**	**1.800**
	r (mm)	9.06	8.68	9.40	9.15	10.02
1.900	***h (mm)***	6.93	6.86	6.98	6.94	7.09
	f_r (GHz)	**1.899**	**1.899**	**1.900**	**1.900**	**1.899**
	r (mm)	14.65	13.01	13.64	15.25	12.86
2.200	***h (mm)***	5.52	5.33	5.39	5.62	5.28
	f_r (GHz)	**2.200**	**2.200**	**2.200**	**2.199**	**2.200**
	r (mm)	10.77	10.76	11.19	11.62	11.60
2.400	***h (mm)***	4.82	4.87	4.89	4.92	4.93
	f_r (GHz)	**2.399**	**2.399**	**2.400**	**2.400**	**2.400**
	r (mm)	6.46	6.29	6.23	5.88	7.13
2.500	***h (mm)***	5.44	5.40	5.39	5.84	5.57
	f_r (GHz)	**2.499**	**2.500**	**2.499**	**2.499**	**2.500**

5. Conclusions

In this paper a modified rectangular patch antenna is designed. The effect of the radii of the slots and substrate thickness on operating frequency (f_r) are observed. The simulations for each radius are also repeated for five different substrate thicknesses (h) between $(0.6h_{max})$ and (h_{max}) where $h_{max}=0.05\lambda_0$.

The results showed that the f_r can be adjusted by varying the radius of the quarter-circular slots without changing the outer dimensions of the patch (*W and L*). It is observed that, the same f_r value can be obtained with different *(r, h)* pairs. Therefore, the slotting approach may be used to compensate for the influence of h on f_r.

Different than most of the researches, instead of parallel computation an operating frequency is obtained as a function of design parameters *(r,h)*. The design parameters *(r,h)* are optimized to design an antenna operating at the required frequency. The original algorithms (FOA and PSO) have been adapted for its application to a modified rectangular patch antenna design problem: resonance frequency and design of antenna. The usefulness of the implemented algorithm is illustrated via different numerical examples. From the test results, it is found that the PSO and FOA can find the dimensions correctly.

Both PSO and FOA are performed for different population sizes. It is observed that the population size has no significance effect on optimization performance of PSO whereas the sensitivity of the FOA is related to fruit fly quantity. Although the convergence of the algorithm is faster with a larger number of fruit files, the disadvantage is the slower execution speed of the program. Therefore, the number of fruit flies must be selected considering the complexity of the optimization problem. The results show that PSO and FOA algorithms are useful optimization algorithms for antenna designs. However, PSO is better than FOA for equal particles and fruit flies, when the proposed antenna design is considered.

The study shows that, curve fitting approach can be applied to obtain a design function for irregular MPAs. In the future work, bandwidth can also be included in the optimization process which will transform the problem into a multi-objective optimization.

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