Evaluation of the performance of a novel Fitness Function improving Genetic Algorithm optimization of Micro Strip Patch Antennas

Original Scientific Paper

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Abstract *– Standard formulas may not produce the expected outcomes when designing Micro Strip Patch Antennas (MSPA). Finding the proper proportions can be accomplished through optimization. Over a quarter of a century has passed since the genetic algorithm (GA) was first applied to MSPA optimization. The fitness function (FF) is what drives the optimization algorithm. Here, multiple performance parameters of an MSPA are improved by optimizing its dimensions, the length* L_y *and width* W_x*, using a novel fitness function applying graded fitness and graded penalty. Three performance criteria are targeted by the antenna optimization: a 5 GHz operating frequency, a bandwidth BW exceeding 250 MHz spanning on each side of the center frequency, and a return loss* S_{11} *value of less than -20 dB. The performance of the proposed FF, when compared against the performance of the most popular five FFs, outperformed the other five FFs by achieving all three targeted performance criteria by returning an MSPA resonating at 5 GHz, with a return loss of -24.18 dB and a bandwidth of 270 MHz. HFSS and MATLAB were used for optimization along with RT Duroid as the material for the antenna.*

Keywords*:* *Micro Strip Patch Antenna, Genetic Algorithm, Optimization, Fitness function*

Received: Received: July 23, 2023; Received in revised form: July 2, 2025; Accepted: July 7, 2025

1. INTRODUCTION

The Micro Strip Patch Antennas (MSPAs) have become increasingly popular since they are simple and inexpensive to make, planar in nature, lightweight, and simple to integrate into integrated circuits at microwave frequencies. Low in efficiency, smaller gain, limited bandwidth, and less return loss are the drawbacks. The departure of the actual output from the anticipated output, when theoretically estimated dimensions are applied in the simulation is still another significant issue that the researchers must overcome. The experimental outputs based on theoretically calculated design parameters will also show a discrepancy between the actual outcomes and what was anticipated. To accomplish the intended design aim, theoretical values of the design variables must be modified. The process of optimizing micro strip patch antenna design parameters to meet desired objectives has traditionally relied on a trial-and-error approach. However, when faced with the challenge of achieving multiple design objectives by varying multiple parameters, this method often proves inefficient or even infeasible. This is where employing Genetic algorithm makes sense [6,9].

Since John Holland's 1975 genetic algorithm (GA) proposal, MSPA design and optimization have benefited from the use of GA. When it comes to MSPA design optimization, GA often requires developing a fitness function containing one or more desired design out comes. Every individual (chromosome) inside a population (generation) represents the dimension of the MSPA to be optimized and is continually compared to a predetermined value to determine its fitness or cost. In the procedure, the best chromosome is chosen based on its capacity to produce a generation, or collection, of entirely new individuals (chromosomes). The evaluation goes on until either the target fitness level is attained or the stated number of generations have reached, whichever comes first [1-5, 12-14, 16, 17].

Central to the success of Genetic Algorithm optimization is the formulation of a well-defined fitness function. Despite efforts in crafting such functions, optimizing multiple parameters for multiple objectives often leads to trade-offs between design goals, as in sections [1-5]. In this manuscript, a novel fitness function is proposed leveraging Genetic Algorithm optimization to address this issue. The proposed fitness function achieves all desired patch antenna parameters simultaneously, without sacrificing one objective for another. By optimizing patch dimensions and slot positions using the proposed fitness function, the attainment of desired levels for return loss, bandwidth, and operating frequency is ensured. This manuscript presents a comprehensive exploration of a novel fitness function, in [6], demonstrating its efficacy, when used in Genetic algorithm optimization, in achieving superior antenna performance while eliminating the need for trade-offs between design objectives as compared to existing fitness functions.

An extensive survey was conducted on the fitness functions formulated over the last 25 years for use with GA for MSPA optimization. Accordingly, five of the most popularly used fitness functions were selected for comparison with the proposed fitness function. The first FF discussed in section 4.1 sums up the return loss over a range of frequencies [6, 9, 18-23]. The second fitness function given in section 4.2 sums up return loss over a range of frequencies and averages it with the number of frequencies [15, 24-30, 34]. The third fitness function, as per section 4.3, sums up the square of the return loss, averaged with the number of sampling frequencies and scaled up by a factor of 100 [31]. FF discussed in section 4.4 is the fourth FF selected for comparison with the proposed FF. The fitness value for each antenna is determined by taking the difference between the average values of the desired and undesirable bands of frequencies after they have been scaled down separately by the two variables Na and Nb [32]. The fifth FF selected for comparison with the proposed FF is discussed in section 4.6. Here, the logarithm of the average fitness value is taken if the frequency is the desired one and is scaled down by a factor if the frequency deviates from the desired frequency f_r [33].

This article initially presents the design of MSPA design in section 2, followed by a brief insight into the GA in section 3. This is followed by the discussion on the five selected FFs selected for comparison in section 4 and subsequently the presentation of the proposed FF. The results are then summarized in a table and discussed in section 5 before concluding the article in section 6.

2. MSPA DESIGN

When simulating MSPA, the "Transmission Line model" is employed. This model compares MSPA to a conductor with dimensions of "W" for width, "h" for height of substrate, and "L" for length as in Fig. 1 [35].

Here, h is constrained by $0.333\lambda_0 \leq h \leq 0.5\lambda_0$ and λ_0 being the wavelength in empty space. The following is a summary of the equations regulating the design of MSPAs.

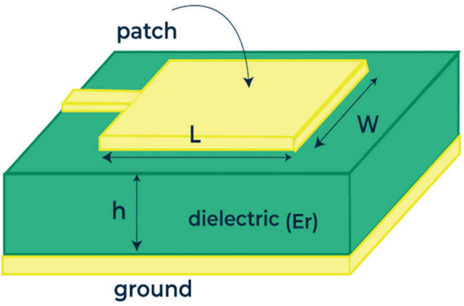

Fig 1. Microstrip patch antenna

Selection of substrate

The loss tangent affects the power loss caused by the dielectric (24). The dielectric constant typically ranges from $2.2 \leq \mathcal{E}_r \leq 12$. This substrate, RT-Duroid, has an $\mathcal{E}_r$ value of 2.2. Dielectric losses are decreased by its low-value loss tangent [6].

Designing patch dimensions

MSPA's performance is heavily dependent on the MSPA dimensions, which are calculated using conventional formulas. According to the specifications, the theoretical values of the patch's dimensions are given in the design equations below from (1) to (14) [7,8,9].

(i) Patch width (W)

$$\mathrm{W} = \frac{1}{fr\sqrt{\mu_0\varepsilon_0}}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{C}{2fr}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

c is the speed of light in empty space, ε_r is the substrate's dielectric constant, and fr is its resonance frequency.

(ii) ε_{eff}

Effective value of dielectric constant is

$$\varepsilon_{\mathrm{eff}} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(\frac{1}{\sqrt{1+\frac{12h}{W}}}\right) \tag{2}$$

Frequency affects the effective dielectric constant as well.

$$f_r = \frac{v_0}{2\sqrt{\varepsilon_{reff}}(L+2\Delta L_{eff})} \tag{3}$$

(iii) Length of the Patch (L)

$$L \text{ is given by } L_{eff}\text{-}2\Delta L \tag{4}$$

L_{eff} is effective length given by

$$\frac{c}{2fr\sqrt{\varepsilon_{eff}}} \tag{5}$$

(iv) Extended length of patch, ΔL

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)} \tag{6}$$

(v) Dimensions calculated for Ground

$$\text{Length of ground, } L_g = 6h+L \tag{7}$$

$$\text{Width of ground, } W_g = 6h+W \tag{8}$$

(vi) Dimensions calculated for Strip line

The strip length is calculated from

$$R_{in(x=0)} = cos^2\left(\frac{\pi}{L}x_0\right) \tag{9}$$

Micro strip line width can be found as

$$W = \frac{1}{2f_{r\sqrt{\mu_0\varepsilon_0}}}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{v_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{10}$$

Here $\lambda_0 = v_0/f_r$, where λ_0 and v_0 are the wavelength and velocity of light in free space. Also, $\lambda_{eff} = (v_0)/f_r\ \sqrt{(\varepsilon_{reff})}$, where λ_{eff} and ε_{reff} are the effective wavelength and dielectric constant respectively.

(vii) Calculating dimensions of transition - line

A quarter wave long is the transition line

$$l = \frac{\lambda}{4} = \frac{\lambda_0}{\sqrt[4]{\varepsilon_{reff}}} \tag{11}$$

Transition line's width W_T is given by

$$Z_T = \frac{60}{\sqrt{\varepsilon_r}}\,ln\left(\frac{8d}{W_T} + \frac{W_T}{4d}\right) \tag{12}$$

where Z_T stands for the transition section's characteristic impedance.

The return loss is calculated as

$$R_L = 10\ log_{10}\ \frac{P_{in}}{P_{ref}}(dB) \tag{13}$$

Here, P_{in} stands for the incident power and P_{ref} for the reflected power [10]. The better the power transmission, the higher the P_{in}/P_{ref}, ratio. The following is the return loss equation RL utilising voltage, voltage-standing-wave-ratio $VSWR$, and impedance.

$$\begin{aligned} R_L &= 10\ log_{10}\left|\frac{1}{\rho}\right|\ (dB) = -20\ log_{10}|\rho|\ (dB) \\ R_L &= 20\ log_{10}\left|\frac{VSWR+1}{VSWR-1}\right|\ (dB) \\ &= (40\ log_{10}\ e)artanh\left|\frac{1}{VSWR}\right|\ (dB) \\ R_L &= 20\ log_{10}\left|\frac{Z_1+Z_2}{Z_1-Z_2}\right|\ (dB) \end{aligned} \tag{14}$$

where ρ is the complex reflection coefficient, $VSWR$ is the voltage standing wave ratio, and Z_1 and Z_2 are the load and characteristic impedances respectively.

3. GENETIC ALGORITHM

John Holland was inspired by Darwin's idea of natural selection and evolution when he created the genetic algorithm in 1975. The antenna design parameter values are encoded by a string of bits called chromosomes, which make up a generation. Randomness is used to generate one generation. This is the first generation. Every chromosome's fitness in a generation is evaluated separately. The targeted fitness level of the cost function is then contrasted with the fitness value of the chromosome. For the next generation, the strongest chromosomes from the previous generation were selected. Chromosomes that perform well are subject to selection, crossover, and mutation.

This generation assessment goes on up until the cost function reaches its fitness level, as seen in Fig. (2) below [11]. As has been mentioned, for over three decades, MSPA parameters were optimized using the genetic algorithm to achieve desired or almost desired performance. Prior to deciding on the necessary performance as the optimization outcome, a FF's fitness value is determined. The necessary performance parameters for optimization are included in the formulation of the FF. The FF's fitness value, which links antenna performance to its design variables, is assessed for fitness while optimizing to achieve the required output, thus making the formation of the FF a significant stage in the optimization process. The range of the design variables are specified for the optimization and they are suitably coded. A chromosome serves as the fundamental building block for optimization; it is a code word that combines unique binary codes for each parameter that needs to be optimized.

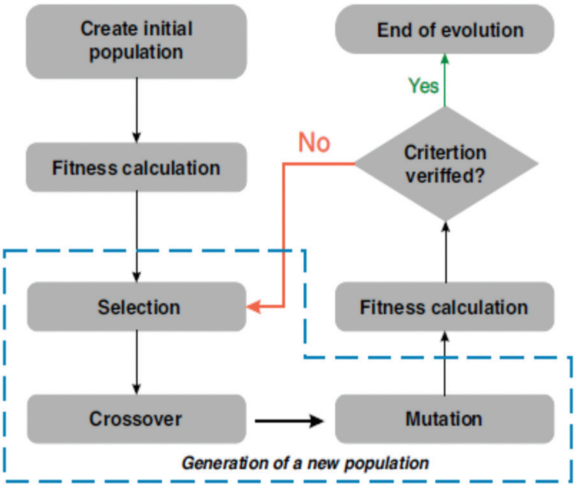

Fig. 2. Genetic Algorithm evolution

A generation is made up of a number of chromosomes, the exact number depends on the need. At first, a predetermined number of chromosomes are generated at random. Then, each chromosome in that generation is measured against a specified value to establish its fitness. A portion of the chromosomes is then subjected to crossover and mutation to create new chromosomes for the following generation after selection, depending on the fitness value of each individual chromosome. The chromosomes with high fitness levels are selected to continue in the generation that follows. This cycle continues until the cycle's fixed number of generations is completed or the required fitness value is reached, whichever occurs first [11].

4. PROPOSED WORK

Initially, the MSPA's dimensions for 5 GHz are computed using conventional design equations. The substrate is RT Duroid 5880, with a height equal to 1.6 mm. One-fifth of the patch length is taken as the feed length and 2 mm is the width. Half the wavelength is assigned as dimensions for the length and width of substrate. The MSPA with dimensions as per Table 1 below came up with the output shown in Fig. (3) when emulated using HFSS. The resonance frequency is 4.8650 GHz with a bandwidth of 210 MHz. The minimum return loss achieved is -14.17 dB.

Table 1. MSPA length and width obtained using standard equations

W_y is the width (mm)	L_x is the length (mm)
23.71	19.30

The outcomes differ significantly from what was desired. Therefore, the theoretically estimated MSPA dimensions, such as W_y and L_x, are optimized using both existing and proposed fitness function and their performance compared. For 50 generations with 40 chromosomes each, optimization is iterated using all fitness functions, including the proposed fitness function. The range of W_y and L_x values for optimization is listed in Table 2.

W_y is the width (mm)	L_x is the length (mm)
Min =22.70	Min = 18.70
Max = 25.30	Max = 20.30

This range is the same for all fitness-functions, including the proposed one, making it a fair comparison.

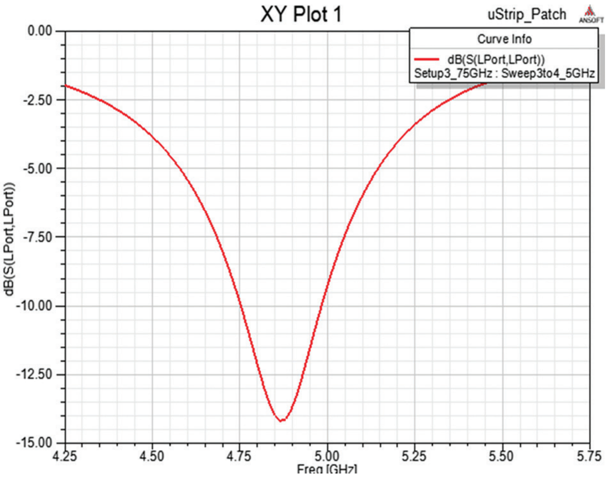

Fig 3. Performance of MSPA with dimensions derived from standard equations

4.1. FITNESS FUNCTION AS SUMMATION OF RETURN LOSS/REFLECTION CO-EFFICIENT

One of the most frequently used fitness functions over the past 25 years in the articles [6,9, 20] is the one displayed below.

$$\text{Cost} = \sum_1^N Q_{fi}, \text{ where } Q_{fi} = \begin{cases} 10, & for\ S_{11} \le -10\ dB \\ 0, & for\ S_{11} > -10\ dB \end{cases} \quad (15)$$

Here N represents the total frequencies sampled for measuring the fitness value for a certain chromosome representing MSPA dimension.

The fitness function in the same form or in slightly modified form is used in [18-23]. It entails adding up return loss over a particular range of operating frequencies. Based on a few conditions, fitness is ascribed to the return loss S_{11}. In this instance, fitness is given a value of 10 for $S_{11} \le 10\ dB$ and 0 for S_{11} values $>10\ dB$. Individual chromosome's fitness is calculated by adding the fitness values over a range of sampling frequencies. Every chromosome is a different MSPA dimension. The MSPA dimension's suitability for selection to the next generation is determined by comparing the fitness of each individual antenna with the desired fitness level.

The optimized MSPA dimension using fitness function given by the equation (15) is shown in Table 3.

Table 3. MSPA dimensions obtained on optimization using FF in (15)

W_y is the width (mm)	L_x is the length (mm)
24.62	19.02

Below in Fig. (4) is a display of the performance result for those dimensions.

The antenna produced a bandwidth of 245 MHz at an f_r of 5.015 GHz and a minimal S_{11} of -19.41dB for the optimized MSPA dimensions. This is against the desired output, which calls for a precise resonance frequency of 5 GHz, a bandwidth of more than 250 MHz spanning on either side of the center frequency, and an S_{11} value that is less than - 20 dB.

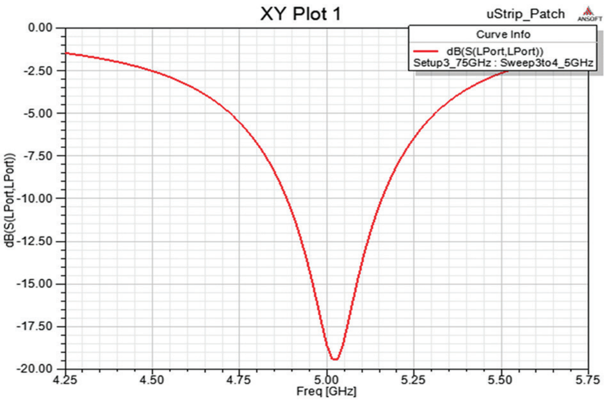

Fig 4. Performance of MSPA with dimensions derived from fitness function in section 4.1

4.2. FITNESS FUNCTION AVERAGING RETURN LOSS OVER A BAND OF FREQUENCIES

The sum of the return loss over N frequencies for each antenna dimension represented by a chromosome is averaged using the fitness function employed in equation

(16) and referred in [20, 34-35]. Based on a set of criteria, values are assigned to the return loss at each frequency. The average return loss value is used to determine the overall fitness of each individual antenna dimension after the return loss data have been added up.

$$Fitness \;=\; \frac{1}{N}\sum_{i=1}^{N} Q(f_i) \qquad (16)$$

where $Q(f_i) = \begin{cases} 10 & S_{11} < -10 \\ |S_{11}\,(f_i)| & S_{11} \;\geq\; -10 \end{cases}$

The patch dimensions returned by the above fitness function after optimization is shown in Table 4.

Table 4. MSPA dimensions obtained on optimization using FF in (16)

W_y **is the width (mm)**	L_x **is the length (mm)**
24.95	19.22

These dimensions when used for simulation using HFSS resulted in the performance as shown in Fig. 5. Here optimized dimensions as per Table 4 returned a $\boldsymbol{BW}$ of 255 MHz at an $\boldsymbol{f}_r$ 4.94 GHz with a minimal $\boldsymbol{S}_{11}$ of -20.54 dB.

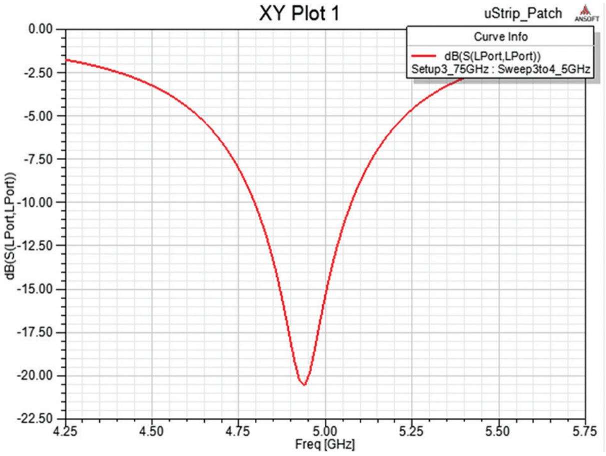

Fig. 5. Performance of MSPA with dimensions derived from fitness function in section 4.2.

4.3. FITNESS FUNCTION AVERAGING RETURN LOSS OVER A BAND OF FREQUENCIES WITH A SCALING UP FACTOR

For the fitness function used in equation (17) and referred in [31] to determine the fitness value, the sum of the squares of the return loss over N frequencies for each antenna dimension represented by a chromosome is averaged and scaled up by a factor of 100. Here the optimization is performed for maximizing the fitness value.

$$Fitness \;=\; \frac{100}{N}\sum_{n=1}^{N} (S_{11n})^{\,2} \qquad (17)$$

Table 5 displays the patch dimensions that the aforementioned fitness function, after optimization, returned. When these dimensions were used in HFSS simulation, the performance is shown in Fig. 6.

Table 5. MSPA dimensions obtained on optimization using FF in (17)

W_y **is the width (mm)**	L_x **is the length (mm)**
24.86	19.14

Dimensions mentioned in Table 5, when used for simulation, returned a patch antenna with a bandwidth of 255 MHz at an $\boldsymbol{f}_r$ of 4.94 GHz with a minimal $\boldsymbol{S}_{11}$ of -18.79 dB.

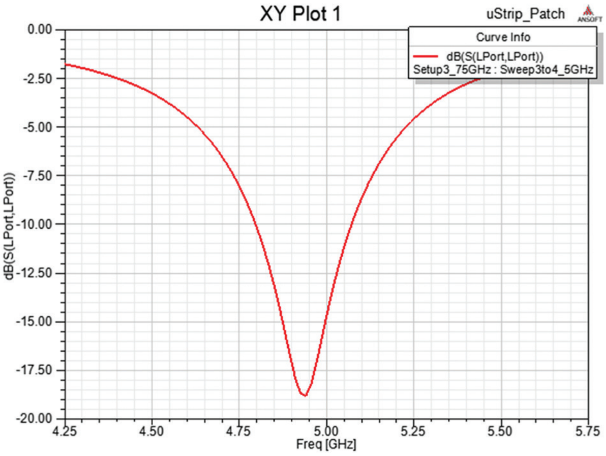

Fig 6. Performance of MSPA with dimensions derived from fitness function in section 4.3.

4.4. FITNESS FUNCTION AVERAGING RETURN LOSS OVER A BAND OF DESIRED AND UNDESIRED BAND OF FREQUENCIES

In the fitness function referred in [32] and used in (18), for each antenna dimension represented by a chromosome in the desirable, N_i, and undesired, N_j, band of frequencies, the average of the return loss over N frequencies is calculated. The fitness value for each antenna is determined by taking the difference between the average values of the desired and undesirable band of frequencies after they have been scaled down separately by the two variables N_a and N_b.

$$Cost = \frac{1}{N_b}\sum_{nb=1}^{N_b}\left(\frac{\sum_{n_i}^{N_i} L_{Nb}(f_{ni})}{N_i}\right) - \frac{1}{N_a}\sum_{na=1}^{N_a}\left(\frac{\sum_{n_j}^{N_j} L_{Na}(f_{ni})}{N_j}\right) \qquad (18)$$

$$L(f) = \begin{cases} |S11(f)|dB, & -5\;dB > |S11(f)|dB \geq -10\;dB \\ -10, & |S11(f)|dB < -10\;dB \\ 0, & |S11(f)|dB \geq -5\;dB \end{cases}$$

The patch dimensions that the aforementioned fitness function, after optimization, produced are shown in Table 6.

Table 6. MSPA dimensions obtained on optimization using FF in (18)

W_y **is the width (mm)**	L_x **is the length (mm)**
24.6	19

The antenna's performance when simulated with HFSS using the dimensions as per Table 6 is given in Fig. 7.

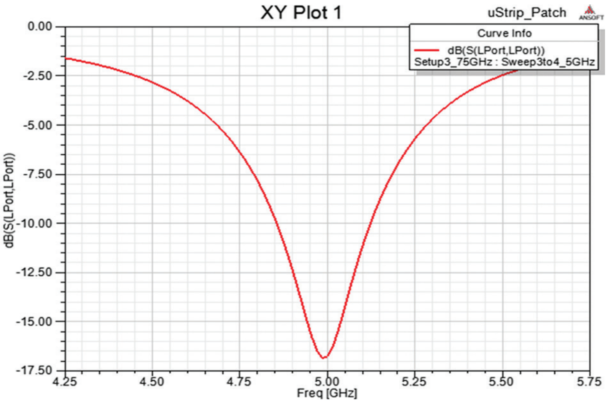

Fig 7. Performance of MSPA with dimensions derived from fitness function in section 4.4.

BW is 255 MHz, f_r is 4.9850 GHz and the minimal S_{11} is -16.82 dB.

4.5. FITNESS FUNCTION AVERAGING RETURN LOSS OVER A BAND OF FREQUENCIES WITH A SCALING DOWN FACTOR FOR DEVIATIONS

Depending on the value of the S_{11}, the fitness function applied here can take either of the two values. The fitness value is the logarithm of the average S_{11} within a range of N sampling frequencies if S_{11} is greater than -9.5 dB over the range of frequencies. Otherwise, the average fitness value is scaled down before taking the logarithm by a factor equal to the variance of difference frequency f_d from the resonance frequency f_r [33].

$$Fitness = \begin{cases} log\left(\frac{\sum_N L(f_i)}{N}\right), & S_{11\,min} > -9.5\ dB \\ log\left(\frac{\sum_N L(f_i)}{N(f_r - f_d)}\right), & otherwise \end{cases} \tag{19}$$

Table 7 displays the patch dimensions that the previously discussed fitness function generated following optimization.

Table 7 MSPA dimensions optimized using FF in (19)

W_y is the width (mm)	L_x is the length (mm)
24.79	18.95

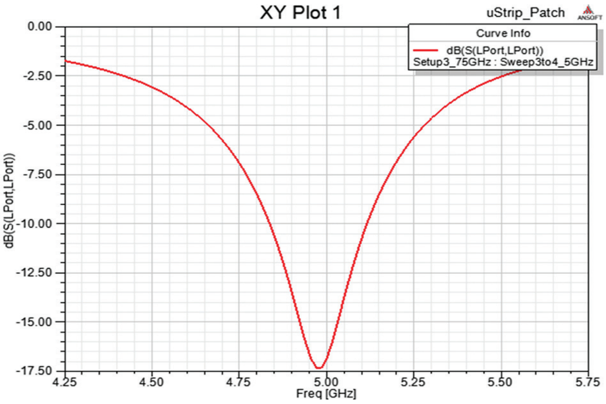

Fig. 8. Performance of MSPA with dimensions derived from fitness function in section 4.5.

The performance of the antenna as calculated by HFSS using the dimensions from Table 7 is shown in Fig (8). The optimized dimensions as per Table 7 when used for simulation of MSPA yielded a BW of 255 GHz at an f_r of 4.97 GHz. The minimum return loss was -17.30 dB.

4.6. PROPOSED FITNESS FUNCTION

To accomplish the appropriate level of optimization in this work, a novel fitness function formulation using carrot and stick policy is introduced. Here, graded fitness and graded penalties for deviations between real and intended antenna performance criteria are introduced. The penalty will be stiffer the greater the discrepancy. The level of fitness will also increase the more comparable the two things are.

In addition to the graded penalty, the fitness function components' dependence on one another in determining the ultimate fitness of a chromosome is where the uniqueness lies. The operating frequency fitness f_p, bandwidth fitness b_p, and return loss fitness s_p values were used to create the proposed fitness function. Both b_p and s_p in this fitness function are dependent on f_p. This ensures that the optimized antenna meets all of the desired antenna performance characteristics, as opposed to convergent on a chromosome producing high value for one parameter and low value for another, resulting in their total fitness value F returning high fitness value. The fitness function provides different penalties for deviating from the desired maximum bandwidth of 250 MHz, the desired f_r of operation of 5 GHz, and the lowest return loss of -20 dB. The penalty will increase in proportion to the deviation. As a result, the fitness function directs the optimization algorithm to MSPA dimensions that produce better results than earlier fitness functions employed in comparable circumstances. The proposed fitness function prevents chromosomes from being picked for the following generation if they deviate from the necessary resonance frequency, bandwidth, and return loss. While keeping all other dimensions constant, the suggested fitness function greatly increased bandwidth and improved S_{11} while precisely retaining the operating frequency at 5 GHz.

Fitness function is $F = f_p + bp + sp$ (20)

After penalizing for an erroneous operating frequency by a factor of $Diff_p$, the fitness value for the resonant frequency is obtained as f_p. The fitness value for bandwidth attained is b_p. An encouraging factor of f_p encourages the success in bandwidth. This guarantees that the chromosomes chosen for the next generation represents the antenna dimensions having the greatest bandwidth and operates closer to the resonant frequency. The chromosomes with the lowest return loss are chosen by s_p, the third fitness factor in the fitness function. The relationship between s_p and f_p ensures that the chromosomes receiving the least return loss and being closest to the 5 GHz resonance frequency receive the most fitness.

$$\boldsymbol{f_p} = \begin{cases} 125, & Diff_p = 0 \\ 0, & Diff_p \geq 125, \\ 125 - Diff_p, & Diff_p < 125 \end{cases} \qquad (21)$$

Here $Diff_p$=(abs(f_r- 5 GHz)/15)×1000 and f_r - actual resonant frequency.

The term "$Diff_p$" refers to the expense of departing from the desired $\boldsymbol{f_r}$ of 5 GHz. The value of $Diff_p$ was set to 1 unit for a 1 MHz departure from the ideal resonance frequency. The measured frequency for lowest return loss serves as the actual resonance frequency $\boldsymbol{f_r}$. With the required 250 MHz BW covering two sides of the centre frequency at 125 MHz each, a variance of 125 MHz from the ideal $\boldsymbol{f_r}$ on either side is penalized by a value of 125. The selection of such chromosomes for the subsequent generation was discouraged since the largest penalty for a deviation from the measured centre frequency above 125 MHz on any one side is 125. The antenna whose frequency is 5 GHz was given the highest fitness rating. All other operating frequencies received a graduated penalty based on how far off the $\boldsymbol{f_r}$ was from the target frequency of 5 GHz. The penalty increases with the deviance.

$$\boldsymbol{b_p} = \begin{cases} 0, \quad BW < 100\,MHz \;\; or \; f_p = 0 \\ BW + f_p/4, \;\; 100 \leq BW < 150 \\ BW + f_p/2, \;\; 150 \leq BW < 200 \\ BW + 3f_p/4, 200 \leq BW < 250 \\ BW + f_{p,} \qquad BW \geq 250 \end{cases} \qquad (22)$$

The BW spanning either side of the center frequency is given by

$$\mathrm{BW} = \textstyle\sum_{i=1}^{20} K, \;\; K = \begin{cases} 10, & S_{11} \leq -10\,dB \\ 0, & S_{11} > -10\,dB \end{cases} \qquad (23$$

The required bandwidth was fixed at 250 MHz or higher. The fitness value was then determined by measuring $\boldsymbol{S_{11}}$ at intervals of 15 MHz for frequencies on the two sides of the mid-frequency. Sampling was carried out on the two sides for a distance of up to 125 MHz. The real BW and the penalized value of $\boldsymbol{f_p}$ are added up to determine the fitness award based on the obtained bandwidth. When BW is larger than 250 MHz, the fitness value is equal to the sum of BW and the entire value of $\boldsymbol{f_p}$, and zero if $\boldsymbol{f_p}$ is equal to zero or BW is less than 100 MHz. $\boldsymbol{b_p}$ also equals zero when $\boldsymbol{f_p}$ is zero. For any other BW, the real BW is decreased by the penalized value of $\boldsymbol{f_p}$. As a result of this, it is certain that the fitness earned from the bandwidth obtained in the undesirable frequency range will not have an effect on total fitness. Because of this, the fitness function only chooses antennas that have the optimal bandwidth for the coming generation and operate close to the specified operating frequency.

$$\boldsymbol{s_p} = \begin{cases} 0, & 0 < \boldsymbol{S_{11}} < 10 \\ 10 + \boldsymbol{f_p}, & 10 \leq \boldsymbol{S_{11}} < 20 \\ 20 + \boldsymbol{f_p}, & 20 \leq \boldsymbol{S_{11}} < 30 \\ 30 + \boldsymbol{f_p}, & 30 \leq \boldsymbol{S_{11}} < 40 \\ 40 + \boldsymbol{f_p}, & 40 \leq \boldsymbol{S_{11}} < 50 \\ 50 + \boldsymbol{f_p}, & 50 \leq \boldsymbol{S_{11}} \end{cases} \qquad (24)$$

The fitness function's addition of another term $\boldsymbol{s_p}$, as the fitness component for $\boldsymbol{S_{11}}$ ensures optimization of $\boldsymbol{S_{11}}$ along with BW and center frequency $\boldsymbol{f_r}$. The optimization will converge on the least value for $\boldsymbol{S_{11}}$, thanks to the grading of $\boldsymbol{s_p}$.

The patch dimensions provided by the proposed fitness function after optimization are shown in Table 8. Fig. 9 displays the antenna's performance as determined by HFSS using the dimensions from Table 8.

Table 8. MSPA dimensions optimized using FF in (20)

W_y **is the width (mm)**	L_x **is the length (mm)**
25	19.1

The proposed fitness function returned patch dimensions, which when applied in simulation resulted in a patch antenna with a bandwidth of 270 GHz at an $\boldsymbol{f_r}$ of exactly 5 GHz and a minimal $\boldsymbol{S_{11}}$ of -24.18 dB.

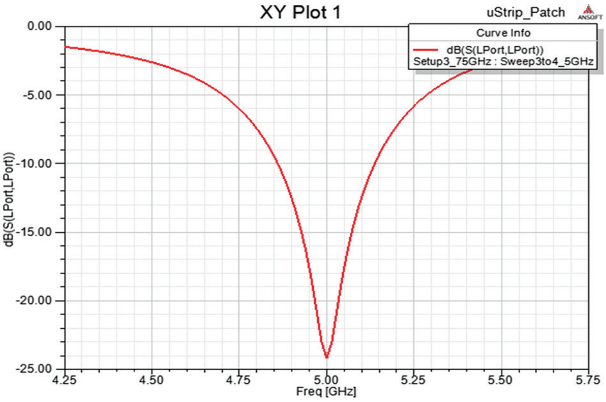

Fig. 9. Performance of MSPA with dimensions derived from proposed fitness function in section 4.6.

5. RESULTS AND DISCUSSION

A BW of at least 250 MHz, an accurate $\boldsymbol{f_r}$ of 5 GHz, and a $\boldsymbol{S_{11}}$ value of at least -20 dB are the objectives that are set for optimization using the proposed fitness function. The performance of the proposed fitness function under similar circumstances is compared with five popular fitness functions that are commonly used for MSPA optimization using GA. The findings are compiled in Table 9.

The first fitness function in the Table 9 returned an $\boldsymbol{f_r}$ of 5.015 GHz with a BW of 245 MHz and an $\boldsymbol{S_{11}}$ value of -19.41 dB. None of the three-optimization targets was achieved with this fitness function. The second fitness function, as per the order in Table 9, was able to achieve the optimization targets for BW and $\boldsymbol{S_{11}}$, but deviated from the desired resonance frequency of 5 GHz. The third fitness function succeeded in achieving the optimization target for BW alone and deviated from the other two optimization parameters, such as $\boldsymbol{f_r}$ and $\boldsymbol{S_{11}}$. The same is the case with the fourth and fifth fitness functions as per their order in Table 9. Only BW could be optimized, while other optimization parameters deviated from the target set for optimization.

It is evident from looking at the five fitness functions' formulations—that were compared to the proposed fitness function—that none of them were able to lead GA optimization to the necessary level of optimization for each of the three target outputs simultaneously. The proposed fitness function alone achieved the desired values for all three design parameters, including the BW, f_r, and S_{11}, after optimization. The novel fitness function presented here made sure that there was no trade-off in the fitness value of individual fitness components even when taking into account the combined fitness of all three parameters. To achieve this, the fitness-related factors are fairly weighted among one another utilizing a weighted penalty system based on a "carrot and stick" approach. There was no provision to guarantee that the fittest antenna dimensions had the best values for all three design requirements, even if the initial fitness function in (15) summed up the return loss based on some criteria. This also applies to the fitness function in (16). Instead of using the sum in this case, the average return loss over a range of frequencies is used as the fitness value. To achieve greater isolation from stronger and weaker chromosomes, the fitness function in (17) employed a scale-up value of the average of the square of return loss. The desired optimization for each of the three design requirements is still not achieved. To ensure that the fittest chromosome operates at the correct resonance frequency, the fitness function added a penalty component in (18). The other two performance outputs, however, were not guaranteed. The fitness function in (19) takes into account the difference between the actual and desired operating frequencies, but it was unable to handle the other two optimization goals. The proposed fitness function in (20) offered a minimum return loss of -20 dB, a minimum bandwidth of at least 250 MHz, and an exact resonance frequency of 5 GHz.

HFSS and MATLAB were used for optimization. Each chromosome is a binary string of 32 bits, which is used to encode the width and length of the antenna, with 16 MSBs denoting the antenna's width (W_y) and the remaining 16 bits denoting its length (L_x).All fitness functions were optimized over 50 generations with 40 chromosomes each. The performance comparison is summarized in Table 9. The comparison of the data shows that, in contrast to existing fitness functions, the proposed fitness function successfully drove GA towards optimizing MSPA dimensions to meet all three performance objectives.

Table 9. Performance comparison of optimization using various fitness functions

Reference	Fitness function returning fitness f	Dimension after optimization in mm		f_r in GHz	BW in MHz	S_{11} in dB
		W_y	L_x			
[6, 9]	$f = \sum_{1}^{N} Q_{fi}$	24.62	19.02	5.015	245	-19.41
[30, 34-35]	$f = \frac{1}{N}\sum_{i=1}^{N} Q(f_i)$	24.95	19.22	4.94	255	-20.54
[31]	$f = \frac{100}{N}\sum_{n=1}^{N} (S_{11n})^2$	24.86	19.14	4.94	255	-18.79
[32]	$f = \frac{1}{N_b}\sum_{nb=1}^{N_b}\left(\frac{\sum_{n_i}^{N_i} L_{Nb}(f_{ni})}{N_i}\right) - \frac{1}{N_a}\sum_{na=1}^{N_a}\left(\frac{\sum_{n_j}^{N_j} L_{Na}(f_{ni})}{N_j}\right)$	24.6	19	4.985	255	-16.82
[33]	$f = \begin{cases} log\left(\frac{\sum_N L(f_i)}{N}\right), & S_{11\,min} > -9.5\,dB \\ log\left(\frac{\sum_N L(f_i)}{N(f_r - f_d)}\right), & otherwise \end{cases}$	24.79	18.95	4.97	255	-17.30
Proposed	$f = f_p + b_p + s_p$	**25**	**19.1**	**5**	**270**	**-24.18**

6. CONCLUSIONS

This article proposes a novel fitness function that uses fitness and penalty gradation to enhance the performance of MSPA. The antenna has been optimized using six fitness functions, including the proposed fitness function, for three performance criteria: an S11 value below -20 dB, a BW over 250 MHz, and an accurate f_r of 5 GHz. The proposed fitness function greatly directs the optimization process toward the desired results, such as a minimum BW of 250 MHZ at a f_r of 5 GHZ with an S11 of at least -20 dB. The proposed fitness function yielded an S11 of -24.18 dB, a BW of 270 MHz, and a f_r of 5 GHZ. For all three of the intended optimization parameters, none of the five fitness functions produced optimal results. This underlines the fact that a properly formed fitness function is the key to the successful optimization using GA. The proposed fitness function's optimization performance is compared to the performance of five different fitness functions that have been in use for the past 25 years under comparable settings and is summarized in Table 9. The result when compared shows the proposed fitness function achieved all the three desired optimization targets thereby outperforming other fitness functions when it comes to optimizing MSPA using GA. This once again reiterates the role of smartly formulated fitness functions in the GA optimization of patch antennas.

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