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Original Article

MATLAB-based Optimization of Dual-Band Frequency Reconfigurable Characteristics in a Compact Printed Monopole Antenna for Multiband Wireless Applications

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Abstract - *The increasing demand for compact and multifunctional wireless communication systems has created a need for antennas capable of operating at multiple frequency bands with adaptive frequency control. This paper presents a MATLAB-based optimization approach for improving the dual-band frequency reconfigurable characteristics of a compact printed monopole antenna designed for multiband wireless applications. The proposed antenna structure integrates switchable current paths to achieve frequency tuning between different operating states. An optimization algorithm is applied to determine the optimal geometrical parameters, including radiating patch dimensions, slot configuration, and ground plane characteristics, for enhanced impedance matching and bandwidth performance. Parametric analysis is performed to investigate the influence of critical design parameters on resonance behaviour and frequency switching capability. The optimized antenna demonstrates improved bandwidth characteristics, stable frequency transitions, and enhanced electromagnetic performance compared with the initial design configuration. The proposed optimization framework provides an efficient MATLAB-based solution for designing compact reconfigurable antennas suitable for modern wireless communication applications, including WLAN, IoT, and multiband portable devices.*

Keywords - *Printed monopole antenna, Frequency reconfiguration, MATLAB optimization, Dual-Band antenna, Parametric optimization, Wireless communication.*

1. Introduction

Modern wireless communication systems often consist of compact, lightweight, multifunctional antennas to support different services within one device. Therefore, WLAN/ IoT/ 5G/ Other Wireless Systems require flexible, wide-band, frequency-efficient antennas. Typically, fixed frequency tuned antennas are designed to operate at one specific frequency only [1]. However, to support different communication standards within one compact structure, Frequency Reconfigurable (FReD) antennas have been introduced to change the resonant current path on the fly.

Printed monopole antennas have recently been considered as very suitable candidates for such applications, mainly due to their low profile [2], simple geometry and low cost [3]. To obtain frequency reconfiguration, several methods have been proposed, including the use of PIN diodes, varactor diodes [4], MEMS and switch-based frequency reconfiguration [5]. To achieve frequency switching, impedance matching and wide bandwidth, however, geometrical parameters of printed monopole antennas have strong impact and thus, they are challenging to design and optimize [6]. Optimization is a modern tool to design and improve antennas. As the number of design parameters increases, it becomes more difficult to optimize them manually [7]. This can be done efficiently in a MATLAB environment where an optimization algorithm is combined with an antenna model [8]. The frequency, reflection coefficient, bandwidth and impedance of the antenna can be analysed in a systematic way.

In this paper, a MATLAB-based optimization approach for a compact printed monopole antenna designed to be frequency reconfigurable at dual bands is presented. The key

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aspects of the approach are the integration of optimization algorithms with a frequency-based analysis of different states of frequency switching, a parametric study of different dimensions of the antenna, and a bandwidth optimization study. The approach is intended to enhance frequency reconfigurability and overall performance of the antenna for multiband wireless communication applications.

2. Literature Review

Frequency reconfigurable antennas have received a great deal of interest for future wireless communication systems. Most of the frequency reconfigurable antennas are designed to be operated in single frequency band, while others can be operated in multiple frequency bands [9]. To meet future wireless communication requirements, different types of antenna configurations and tuning methods have been proposed to achieve frequency reconfigurability [10].

Among various types of antennas, printed monopole antennas have been widely investigated for frequency reconfigurable applications due to their simple structure, broad impedance bandwidth and compact size [11]. Frequency tuning has also been realized using switches, i.e., PIN diodes.

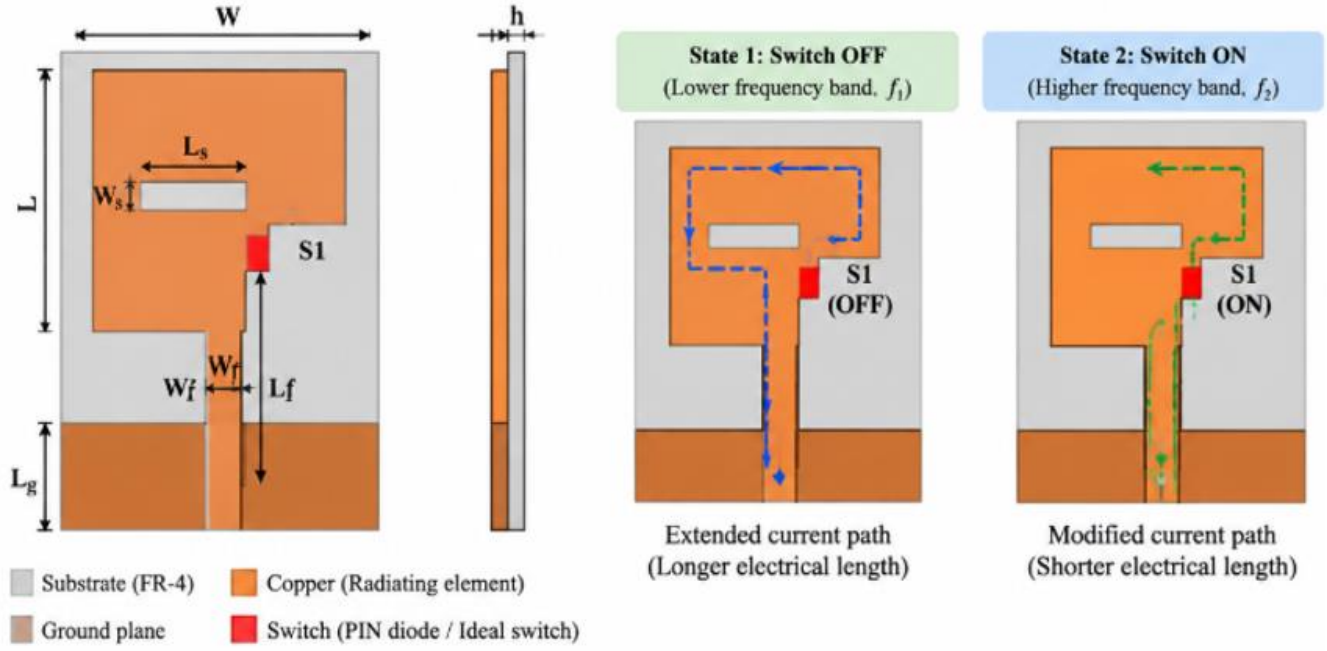
These realizations allow frequency switching between different frequency bands [12]. However, because of switching losses, limitations in bandwidth, and problems related to biasing, the implementations are not optimal. Varactor-based reconfigurable antennas can provide continuous tuning of frequency [13]. Nevertheless, implementation of such antennas requires additional control circuits, and special attention must be paid to biasing of the varactor [14].

Advancements in antenna design have recently been achieved by using optimization algorithms to improve design performance and to overcome limitations of current designs [15]. The use of evolutionary optimization techniques such as GA, PSO [16], and DE has become widespread in antenna design to optimize dimensions of antennas, to match impedance, to increase gain [17], and to improve bandwidth.

Most of the existing reconfigurable antennas have been designed to operate in frequency switching mode, and very little work has been done to optimize parameters and increase bandwidth of the antennas [18]. The relationship between the geometry of the antenna, its operating frequency and its input impedance is a complex one and requires in depth analysis to design a frequency reconfigurable dual-band antenna.

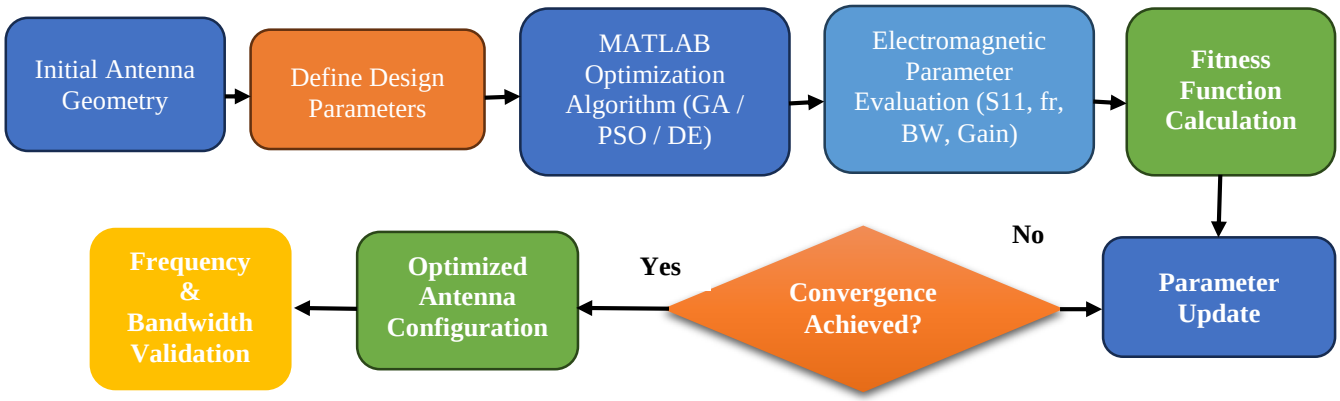
An optimization framework using MATLAB to carry out frequency switching analysis, parameter study and bandwidth improvement is presented for design of compact dual band frequency reconfigurable printed monopole antennas for advanced multiband wireless communication applications.

3. Design Methodology



(a) Top view and side view of the proposed antenna geometry

(b) Switching states and current path variation



(c) MATLAB-based optimization workflow

Fig. 1 Configuration and optimization methodology of the proposed dual-band frequency reconfigurable printed monopole antenna: (a) Antenna geometry, and (b) Switching states for frequency tuning, and (c) MATLAB-based optimization workflow.

The proposed dual-band frequency reconfigurable antenna is a compact printed monopole antenna designed for multiband wireless communication systems. It comprises a planar radiating element, a microstrip line, a partial ground plane, and a switching mechanism to vary the current path. A suitable dielectric material is chosen to maintain a low profile and to ensure that the antenna's electromagnetic characteristics remain relatively stable. Initial dimensions of the antenna are determined using design formula for resonant frequency and are subsequently optimized using a commercial EM simulator to improve impedance matching and frequency bandwidth.

The frequency reconfigurability is introduced by incorporating switchable conductive strips into the radiating element. By changing the state of the switches, the length of current effective current path is varied, resulting in change in resonant frequency. For example, the lower frequency band is realized by extending the current path to achieve the extended length of current path, whereas higher frequency band is achieved by changing the effective length of the antenna to shorter current path. Hence, a single patch can realize the dual-band operation without the need for multiple patches.

Figure 1 describes the new antenna concept in form of a compact monopole for wireless communication applications. It shows different current paths enabled by a switching mechanism to realize dual-band frequency reconfigurability. The different electrical length of the current path, depending on the switching state, allows for a frequency shift to the desired operating frequency. The MATLAB-based optimization workflow comprises parameter optimization, electromagnetic simulation and the verification of the achieved performance improvements towards a larger bandwidth and better antenna characteristics. An optimization framework based on the MATLAB optimization environment is integrated into the design of the antenna to optimize critical geometry parameters of the antenna, such as the dimensions of the patch, slot dimensions, position of the feed and ground plane dimensions. The optimized antenna performance is evaluated by means of reflection coefficient, frequency deviation, impedance bandwidth and frequency separation between the two operating states. In addition, a parametric analysis is performed in order to investigate the impact of the individual design parameters on the electromagnetic behavior and in order to find the optimal design. The final optimized antenna structure provides efficient frequency switching, a wide impedance bandwidth and compact size, which is suitable for embedding into modern wireless communication devices. The design methodology presented in this paper is a powerful tool that uses EM modeling, optimization methods, and systematic parameter study to achieve a very efficient and reliable frequency reconfigurable antenna for dual-band operation.

3. Mathematical Modelling of Antenna Design

A mathematical formulation for a proposed dual-band frequency reconfigurable printed monopole antenna has been developed. The formulation treats the relationship between the antenna's switching states, current distribution, frequency shifting, and design parameters. The formulation differs significantly from those of conventional, frequency-fixed antennas, in that an active switching state of the reconfigurable antenna determines its frequency of operation. Such an antenna can be modeled by means of an equivalent resonant circuit that describes its behavior for different switching states, with each state corresponding to a different resonant state.

The equivalent resonance frequency for a particular switching state can be expressed as:

$$f_{r,n} = \frac{1}{2\pi\sqrt{L_{eq,n}C_{eq,n}}} \quad (1)$$

Where $f_{r,n}$ represents the resonance frequency of the nth switching state, $L_{eq,n}$ and $C_{eq,n}$ denote the equivalent inductance and capacitance corresponding to that state.

The variation in resonance frequency between two switching conditions is defined as:

$$\Delta f_r = f_{r,ON} - f_{r,OFF} \quad (2)$$

Where $f_{r,ON}$and $f_{r,OFF}$represent the resonant frequencies under switch ON and OFF conditions.

The frequency tuning ratio of the proposed antenna is calculated as:

$$T_r = \frac{| f_{r,2} - f_{r,1} |}{f_{r,1}} \times 100 \quad (3)$$

Where $f_{r,1}$and $f_{r,2}$are the two operating frequencies obtained from different switching states.
The effective current path variation due to switching operation can be mathematically represented as:

$$L_{eff,n} = L_0 + \sum_{i=1}^{m} S_i \, \Delta L_i \quad (4)$$

Where $L_0$is the initial current path length, $S_i$represents the switching condition coefficient, and ΔL_iindicates the additional current path contribution produced by each switching element.

The impedance matching performance at different frequency states is evaluated using the Voltage Standing Wave Ratio (VSWR):

$$VSWR = \frac{1+| S_{11} |}{1-| S_{11} |} \quad (5)$$

The quality factor associated with each resonance state is determined as:

$$Q_n = \frac{f_{r,n}}{BW_n} \quad (6)$$

Where BW_nrepresents the bandwidth corresponding to the nth frequency state.

The bandwidth improvement factor after optimization is expressed as:

$$B_{imp} = \frac{BW_{opt} - BW_{initial}}{BW_{initial}} \times 100 \quad (7)$$

Where $BW_{opt}$and $BW_{initial}$represent the optimized and initial impedance bandwidth values.

For MATLAB-based optimization, the antenna design problem is formulated as:

$$X = [x_1, x_2, x_3, \ldots x_p] \quad (8)$$

Where Xrepresents the vector of optimized geometrical parameters, including patch dimensions, slot parameters, feed position, and switching locations.

The objective function for optimization is defined as:

$$Obj(X) = \alpha_1 F_1 + \alpha_2 F_2 + \alpha_3 F_3 + \alpha_4 F_4 \quad (9)$$

Where:

$$F_1 = | S_{11}(f_1) | + | S_{11}(f_2) | \quad (10)$$

$$F_2 = | f_{sim} - f_{target} | \quad (11)$$

$$F_3 = \frac{1}{BW} \quad (12)$$

$$F_4 = \frac{1}{G_{max}} \quad (13)$$

Where G_{max}represents the maximum antenna gain and $\alpha_1, \alpha_2, \alpha_3, \alpha_4$are weighting factors.

A mathematical model was developed to study the frequency switching behavior, design parameter optimization of the antenna, and improvement of frequency reconfiguration to dual-band operation using MATLAB-based computational design optimization.

4. MATLAB-based Optimization Algorithm

In this work, a MATLAB-based optimization algorithm is embedded within the design process of the proposed antenna to obtain the optimum configuration for improved dual-band frequency reconfigurability. A few key variables associated with the design of the antenna are considered within the framework of the optimization, including patch size, slot length and width, position of the feed, dimensions of the ground plane, and position of the switching elements. Within the optimization algorithm, the difference between desired and optimized design parameters is minimized using an objective function, and the various design parameters are optimized iteratively.

The antenna optimization problem can be mathematically represented as:

$$X = [x_1, x_2, x_3, \ldots x_N] \quad (14)$$

Here Xrepresents the design parameter vector, and $x_N$represents the individual geometrical parameters of the antenna structure.

The optimization process searches for the optimal parameter combination within the defined boundary limits:

$$x_i^{min} \le x_i \le x_i^{max} \quad (15)$$

Where $x_i^{min}$and x_i^{max}represent the minimum and maximum allowable values of each design parameter.

The objective function is formulated by considering multiple antenna performance parameters, including resonance frequency accuracy, reflection coefficient, bandwidth, and gain:

$$F(X) = w_1F_f + w_2F_s + w_3F_b + w_4F_g \quad (16)$$

Where $w_1, w_2, w_3, w_4$are weighting coefficients, while F_f, F_s, F_b, and $F_g$represent frequency error, impedance matching, bandwidth, and gain optimization functions, respectively.

The frequency optimization term is defined as:

$$F_f = \sum_{k=1}^{M} | f_{sim,k} - f_{target,k} | \quad (17)$$

Where $f_{sim,k}$and $f_{target,k}$represent simulated and desired resonance frequencies for different switching states.

The impedance matching function is expressed as:

$$F_s = \sum_{k=1}^{M} | S_{11}(f_k) | \quad (18)$$

Where S_{11}represents the reflection coefficient at the operating frequencies.

The bandwidth optimization function is calculated as:

$$F_b = \frac{1}{\sum_{k=1}^{M} B\,W_k} \quad (19)$$

Where BW_kdenotes the impedance bandwidth corresponding to each resonant state.

During each optimization iteration, the design parameters are updated according to:

$$X_{i+1} = X_i + \Delta X_i \quad (20)$$

Where $X_i$represents the current parameter set and ΔX_irepresents the parameter adjustment generated by the optimization algorithm. The convergence condition of the optimization process is defined as:

$$| F_{i+1} - F_i | < \epsilon \quad (21)$$

Where $F_i$and F_{i+1}represent consecutive objective function values and ϵrepresents the convergence tolerance.

The optimized parameter set is obtained when the objective function reaches the minimum value:

$$X_{opt} = arg\,\min\big(F(X)\big) \quad (22)$$

By means of the MATLAB-based optimization framework, the space of possible design parameters of an antenna can be efficiently searched for, the number of required manual parameter tuning steps can be significantly decreased, and improved frequency switching between the two frequency bands can be achieved. The optimized antenna configuration features an increased bandwidth, precise resonances and is well suited for multiband communication systems.

5. Parametric Analysis

In this section, a parametric study is conducted to examine the impact of several critical geometrical parameters of the proposed antenna. These parameters include the dimensions of the radiating patch, the slot(s), the position of the switch(es), and the ground plane. The effects of these parameters on the frequency, return loss, and bandwidth of the antenna are investigated. A systematic variation of these parameters is conducted to establish a relationship between the antenna geometry and its electromagnetic properties.

The effect of a design parameter on resonance variation can be expressed as:

$$\Delta f_r = \frac{\partial f_r}{\partial x_i}\Delta x_i \quad (23)$$

Where Δf_rrepresents the change in resonant frequency, $x_i$denotes the selected geometrical parameter, and Δx_irepresents the parameter variation.

The sensitivity of each antenna parameter is calculated using:

$$S_i = \frac{\Delta f_r / f_r}{\Delta x_i / x_i} \quad (24)$$

Where $S_i$represents the sensitivity factor of the corresponding design variable. The bandwidth variation due to parameter modification is evaluated as:

$$\Delta BW = BW_{max} - BW_{min} \quad (25)$$

Where $BW_{max}$and BW_{min}represent the maximum and minimum bandwidth values obtained during parametric investigation.

The influence of switching position on frequency tuning is analysed using the frequency shift ratio:

$$R_f = \frac{f_{state2} - f_{state1}}{f_{state1}} \quad (26)$$

Where $f_{state1}$and f_{state2}represent the operating frequencies under different switching conditions.

The results of the parametric study identify the critical design parameters of the antenna and show how these influence the design. The results of this study can be used within the MATLAB design optimization to minimize irrelevant design searches and to improve aspects of the antenna such as frequency switching, return loss and bandwidth.

6. Results and Discussion

The performance of the proposed dual-band frequency reconfigurable printed monopole antenna has been evaluated by means of an optimization procedure developed in MATLAB and electromagnetic parameter analysis. The results obtained by means of the proposed design approach present a good trade-off between resonance accuracy, frequency switching, impedance bandwidth, and total performance. To assess the proposed approach, results have been analysed in terms of optimization convergence, frequency switching, influence of the design parameters and bandwidth enhancement.

The convergence of the different optimization techniques that have been used for the optimization of the different antenna parameters is depicted in Figure 2. This figure includes GA, PSO, DE and the novel MATLAB-based approach for the optimization of the considered antenna. The values of the objective function are decreasing with the number of iterations, which means that the corresponding antenna parameters are improving in a continuous manner. The novel approach reaches faster the minimum value of the fitness function compared to the other optimization techniques. The decreased value of the objective function means that the gap between the target values for the antenna and the computed values of the antenna, which are obtained by means of simulations, is decreasing. Thus, the resonances of the antenna are shifted to the correct positions, and the electromagnetic characteristics of the antenna are optimized.

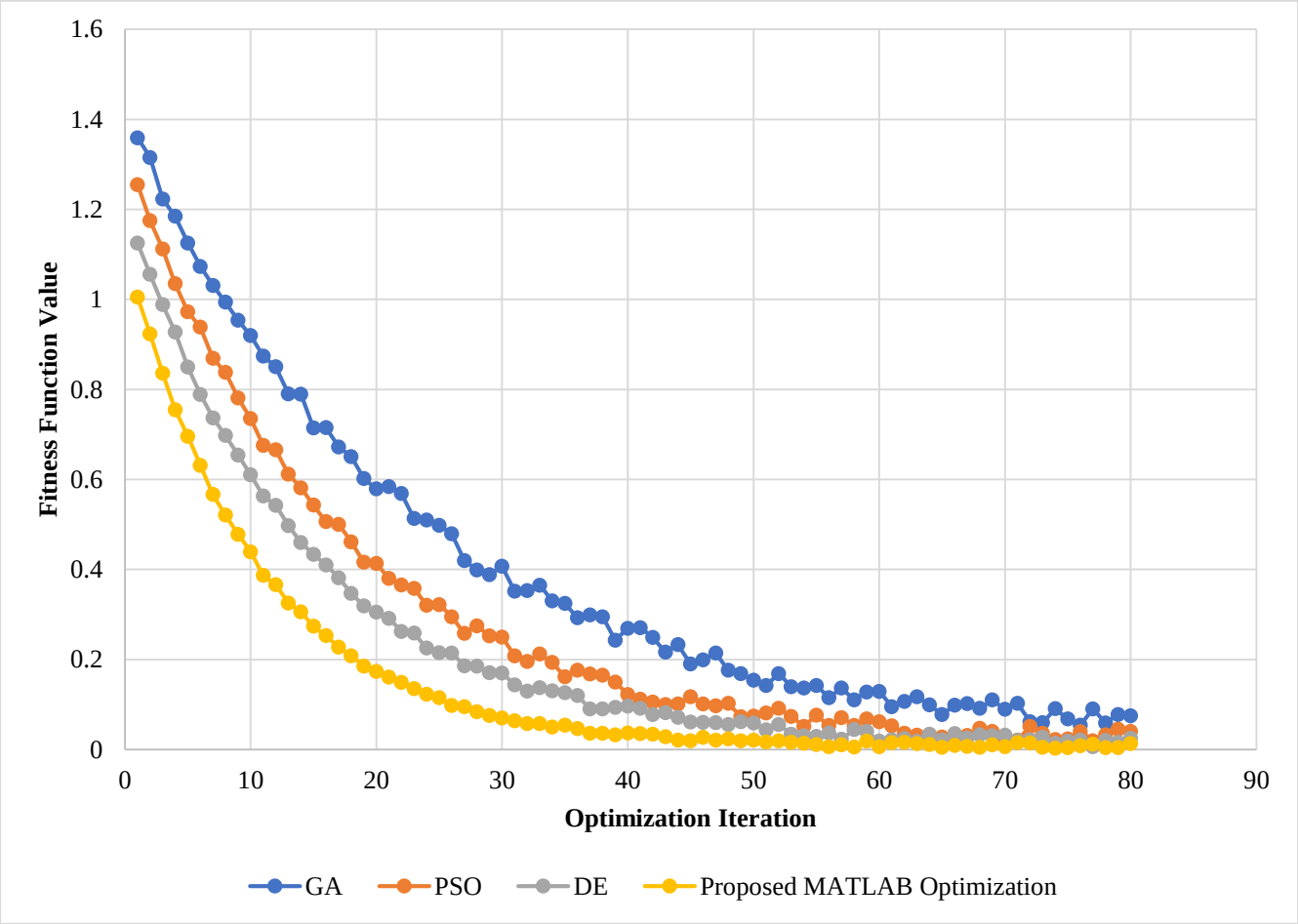


Fig. 2 Comparative convergence characteristics of different optimization algorithms for antenna parameter optimization

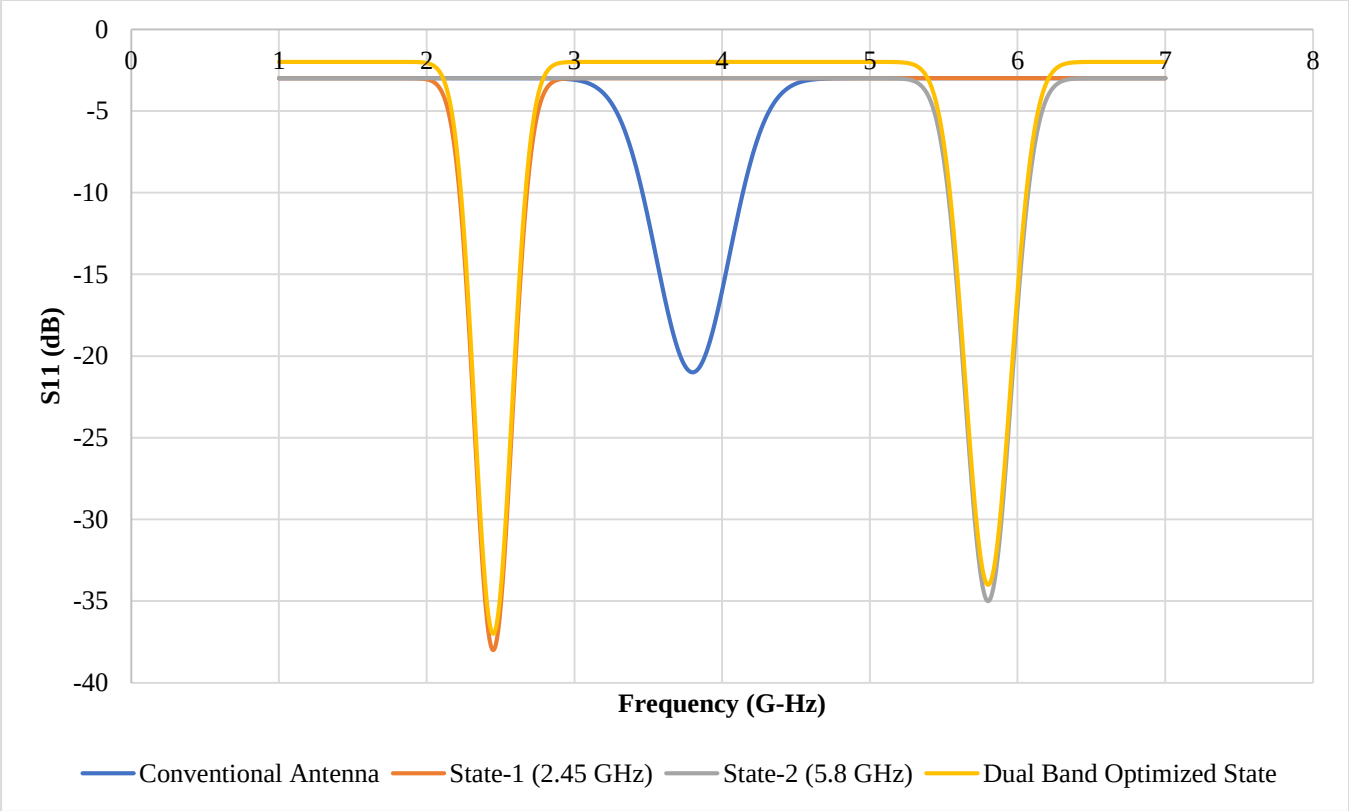


Fig. 3 Comparative S11 characteristics for different frequency switching configurations

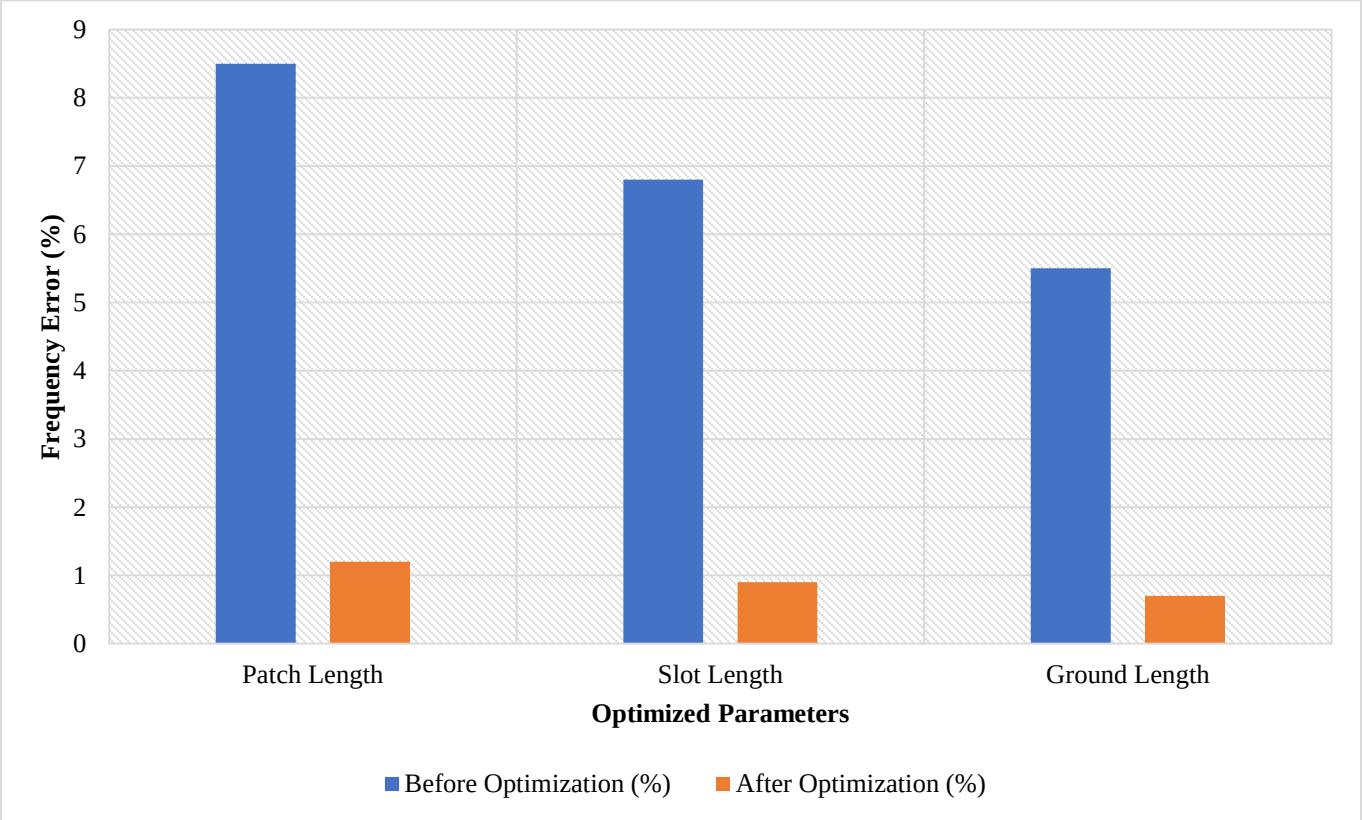


Fig. 4 Effect of antenna parameter optimization on resonance frequency accuracy

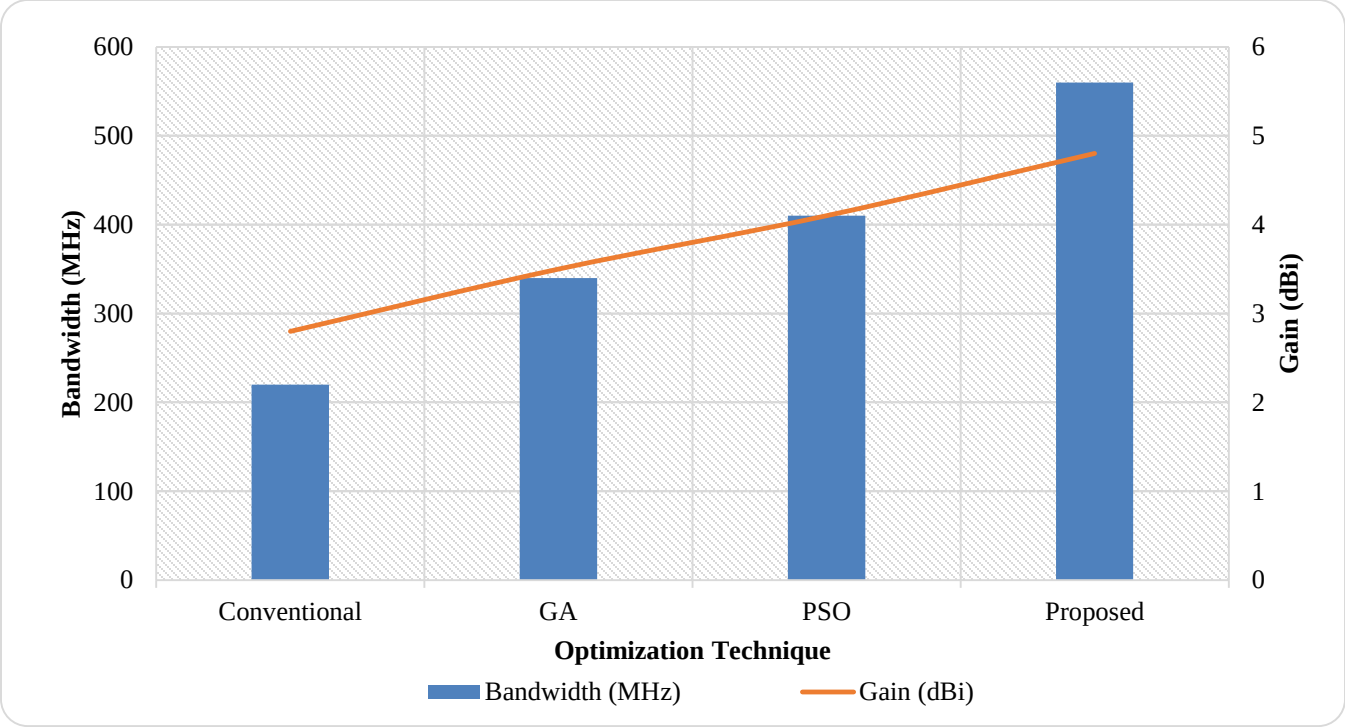


Fig. 5 Comparative evaluation of bandwidth and gain enhancement using different optimization techniques

The simulated reflection coefficient of the proposed antenna for different frequency switching states is shown in Figure 3. By switching the current path, the frequency can be controlled. The optimized antenna can operate at two frequencies (2.45 GHz and 5.80 GHz) for wireless communication systems. The resonant frequencies of different switching states have distinct current path distributions, whereas the impedance is not severely degraded. In addition, the return loss for all operating states is below −10 dB, which indicates good impedance matching for frequency reconfigurability.

Table 1. Performance comparison of different optimization techniques for the proposed dual-band frequency reconfigurable antenna

Optimization Technique	Resonant Frequency 1 (GHz)	Resonant Frequency 2 (GHz)	S11 at f1 (dB)	S11 at f2 (dB)	Impedance Bandwidth (MHz)	Gain (dBi)	Fitness Value
Without Optimization	2.38	5.62	−21.5	−19.8	260	3.1	0.142
Genetic Algorithm (GA)	2.43	5.74	−28.6	−26.9	390	3.7	0.078
Particle Swarm Optimization (PSO)	2.46	5.77	−31.2	−29.5	460	4.2	0.052
Differential Evolution (DE)	2.45	5.81	−33.1	−31.4	510	4.5	0.034
Proposed MATLAB-Based Optimization	2.45	5.80	−34.8	−32.5	560	4.8	0.018

Table 1 shows the performance comparison of the proposed MATLAB-based optimization method with other conventional optimization techniques for designing the dual-band frequency reconfigurable antenna. The optimized antenna has resonances at 2.45 GHz and 5.80 GHz with good impedance matching. It also has a maximum bandwidth of 560 MHz and gain of 4.8 dBi. The proposed method provides lower fitness value compared to GA, PSO, and DE optimization techniques and thus has better electromagnetic properties. Figure 4 illustrates the parametric analysis by changing some critical antenna geometry parameters, i.e. the length of the radiating patch. As the length of the patch changes, the resonance frequency is shifted due to change in the effective current path length. Both the lower and higher frequency resonances are affected by the changes in the electromagnetic coupling and current distribution within the antenna structure. From the parametric study, the sensitive design parameters that affect the frequency can be identified

and used to select the optimum dimensions of the antenna for the desired frequency and bandwidth. The results also illustrate the importance of geometrical parameters to achieve the desired frequency and impedance characteristics for dual-band operation. The comparative evaluation of bandwidth and gain of the improved antenna designs using various optimization approaches is shown in Figure 5.

As can be seen from this figure, the conventional antenna has narrow bandwidth and low gain, since it has fixed geometrical parameters. Moreover, although the bandwidth and gain of the antennas optimized using GA, PSO, and DE have been improved, the MATLAB-based approach used in this paper has resulted in the highest bandwidth and gain.

The bandwidth of the optimized antenna is about 560 MHz, and the gain is about 4.8 dBi. In comparison with the other approaches, the proposed optimization approach results in better antenna characteristics through better definition of design parameters and higher electromagnetic efficiency. The results have been validated by means of the MATLAB-based design and optimization framework.

The methodology proposed in this paper for the design of frequency reconfigurable compact dual-band monopole antennas considers the integration of the optimization algorithm with the switching states analysis, a parametric analysis, and a bandwidth enhancement procedure. The results obtained by means of the proposed design approach confirm its validity and its potential for the design of future compact and intelligent wireless systems.

7. Conclusion

A MATLAB-based optimization framework has been developed for improving the dual-band frequency reconfigurable performance of a compact printed monopole antenna for multiband wireless applications. The proposed methodology successfully integrates optimization-based parameter tuning with frequency switching analysis to achieve enhanced electromagnetic characteristics. The optimized antenna configuration provides dual-band operation at 2.45 GHz and 5.80 GHz with improved impedance matching characteristics. The achieved reflection coefficients of −34.8 dB and −32.5 dB at the respective resonant frequencies confirm the effectiveness of the optimized design. The proposed optimization approach improves the impedance bandwidth up to 560 MHz and increases the maximum gain to 4.8 dBi compared with conventional and other optimization-based configurations. The convergence analysis demonstrates improved optimization efficiency with a reduced fitness value of 0.018, indicating accurate parameter selection and enhanced antenna performance. The parametric investigation further confirms the influence of critical geometrical parameters on resonance tuning and bandwidth behaviour. Future development can focus on hardware fabrication, experimental validation, real-time frequency control using intelligent switching circuits, and integration of advanced artificial intelligence-based optimization techniques for adaptive wireless communication systems.

Conflicts of Interest

"The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper."

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