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Application Level Optimization of Sierpinski Carpet Fractal Antenna Using Artificial Intelligence and High Frequency Structure Simulator

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Abstract: Recently, intensive research have been going on in the wireless communication systems thus creating a demand for multifunctional antennas with high efficiency and flawless performance due to their application like military communications, UAV tracking systems and healthcare IoT devices. It is required to optimize the bandwidth to enhance the performance. Hence, fragment antennas are a futuristic option due to their vital characteristics, like miniaturization with broadband/multiband systems. Such miniaturization leads to the system development for more compact device facilities. The naval systems and remote military locations are highly dependent on wireless communication systems. Hence, this paper presents the design process for the Sierpinski Carpet fractal structure generation. The proposed model uses an artificial neural network and a high-frequency structure simulator (HFSS). These methods provide accurate simulations of the antenna radiation patterns, impedance characteristics, and resonant frequencies across multi-frequency bands. The results of the proposed system show the potential of combining intricate fractal geometries with computational techniques. Consequently, as per the study's outcome, it is depicted that the Artificial Neural Networks are the optimal choice for antenna design and optimization. The designed Fractal antenna resonates at different frequency there by making it suitable for C Band (5.5GHz to 6.3GHz &7.1GHz to 8GHz),WiFi(5.15GHz-5.35GHz, 5.17GHz-5.72GHz & 5.725GHz-5.875GHz),WLAN (3.65GHz,4.9-5.0GHz,5.9GHz & 6.0GHz) applications

Keywords: Fractal, ANN, HFSS, Sierpinski-carpet, Performance parameters, Return loss,, VSWR

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1. Introduction

Current telecommunication systems, including radio services, radars, and portable devices, necessitate antennas capable of operatingin distinct, intricate conditions. Specifically, new mobile devices, such as smart phones, tablets, IoT's, and wireless sensor networks, provide numerous complicated services that need significant gain beam forming as well as driving features regardless of the modest dimensions of the gadgets [1].Fractal antennas exhibit a unique quality, maintaining their shape through recursive transformations, a self-similarity inherent in various fractals [2]. Despite being a singular antenna, the fractal antenna offers multiband capabilities, supporting multiple frequencies while enhancing bandwidth and reducing size. Its standout feature lies in sustaining optimal performance even after undergoing miniaturization. In essence, the fractal antenna fulfills the criteria of diverse wireless communication systems, providing attributes like wideband, multiband, low profile, and compact size. Notably, the response of fractal antennas diverges significantly from conventional designs.

Integrating fractal shapes into antenna geometry facilitates the attainment of wideband and multiband capabilities. Fractal antennas can be categorized into classes, such as Deterministic and Random. Examples of deterministic fractal antennas include classic wideband antennas, Koch curves, Koch snowflakes, Sierpinski gaskets, and Sierpinski carpets.The Sierpinski carpet, a form of fractal antenna, adopts the structure of a square patch antenna, applying fractal concepts to the micro strip patch antenna and generating numerous elements. The recursive generation of the Sierpinski carpet yields an efficient radiation pattern, surpassing other fractal antennas in adaptive beam forming. The efficiency of resonant frequencies increases with higher iterative geometries. The number of antenna iterations not only aids in reducing metal usage but also contributes to achieving a favorable reflection coefficient, resulting in cost savings [3].Multiband antennas and low-profile antennas are in superior popularity. Due to its self-similarity and self-affinity characteristics, the fractal antenna is applied to accomplish this demand [4].

The Sierpinski carpet fractal antenna structure comprises basic Micro strip Patch Antennas printed on a substrate with a feed line (transmission line). One side of the substrate features a radiating patch. In contrast, the other side has a ground plane, as illustrated in Figure 1. Here, ‘h’ represents the substrate thickness, and ‘t’ signifies the conductor thickness. Table 1 provides detailed specifications of the proposed antenna.

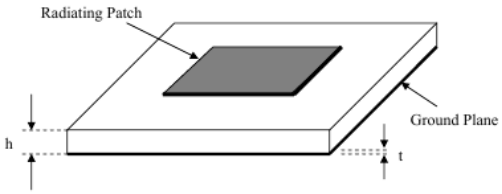


Figure 1: Structure of Sierpinski Carpet Antenna.

Table 1: Antenna Design Specifications

Sl. No	**. Parameters**	**Value**
1	Dielectric constant	4.4
2	Substrate height	1.58mm
3	Loss tangent	0.0013
4	Square patch length	35.4mm
5	Square patch width	35.4mm
6	Ground plane length	70mm
7	Ground plane length	70mm

This work uses the microstrip line as a transmission line to create a Sierpinski Fractal antenna. The Microstrip, a prevalent stripline form, comprises thin metal strips printed on a Printed Circuit Board (PCB). Essentially, it is a type of transmission line smaller and lighter than coaxial cables and waveguides. The proposed antenna design is simulated using the High-Frequency Structure Simulator (HFSS) 15.0, a high-computing, full-wave electromagnetic (EM) field simulator for 3-D modeling of volumetric passive devices. HFSS provides:

- Insights into various 3-D electromagnetic problems.
- Calculating matrix scattering parameters (S, Y, Z-Parameters).
- EM fields (near and far fields).
- Resonant frequency.

The Microstrip Feeding Technique is employed, and a lumped port is used for excitation [5].An artificial neural network (ANN) is a system modeled after the human brain [6, 7]. It comprises various types of simple, nonlinear functional blocks known as neurons, organized into layers interconnected by parallel synaptic weights. The ANN exhibits learning ability, where synaptic weights can be adjusted to store information in the neural network during the learning process. In the ANN model, a formula is unnecessary for designing the microstrip antenna due to its empirical nature, relying on observing physical phenomena. In this work, an artificial neural network is developed to design a Sierpinski carpet fractal antenna. The obtained results are compared with simulation and experimental results, demonstrating that the ANN model is fast, accurate, efficient, and cost-effective for antenna modeling, simulation, and optimization.

2. HFSS 15.0 Modeling

In the proposed design of the Sierpinski Fractal antenna, the chosen transmission line is the Microstrip line, a prevalent strip line characterized by thin metal strips printed on a Printed Circuit Board (PCB). This transmission line is notably smaller and lighter compared to coaxial cables and waveguides. The fundamental structure of the Microstrip patch antenna feed line reveals that the microstrip patch antenna is imprinted on the substrate.

This substrate includes a dielectric layer separating the transmission line, a patch on one side, and a ground plane on the other. The effective dielectric constant of the microstrip configuration typically ranges between 1 (air) and about 4 (substrate G-10 or FR-4), with the signal conductor exposed to air. The feeding system employs a microstrip transmission line where a microstrip patch directly connects with the strip line. The dimensions, specifically the length (L_{TX}) and width (W_{TX}), are meticulously calculated to ensure the impedance of the strip line matches that of the patch.

While various formulas describe the impact of altering the transmission line width or length, the ultimate priority lies in achieving optimal performance. Therefore, in the design process, the emphasis is on constructing a transmission line that yields favorable results within the desired frequency range. The width (Wi), length (Li), and effective constant (€e) of the microstrip line are determined by applying specific equations tailored to ensure the desired performance characteristics.

The width W_i of the radiating edge

$$W = \frac{c[(\varepsilon_r + 1)/2]^{-1/2}}{2f_r}$$

The length $L_i$is slightly smaller than ½ of wavelength in the dielectric. To calculate aninitial value of L_i, the equation used is:

$$L = \frac{c}{2f_r\sqrt{\varepsilon_e}} - 2\Delta L$$

Where

$$\Delta L = 0.412h\frac{\varepsilon_e + 0.300W/h + 0.264}{\varepsilon_e - 0.258W/h + 0.813}$$

The effective constant of microstrip line is approximated by

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\frac{1}{\sqrt{1 + 12h/W}}$$

The proposed sierpinski carpet patch antenna is designed to enhance the performance parameters and to reduce the size of the antenna .The Simulation of designed antenna is carried out using HFSS 15.0 software through the subsequent steps:

- Primarily the substrate with dimensions of 70mm x 70mm is chosen, and then design of carpet antenna begin with square patch starting with base size of 35.4mm x 35.4 mm..The squarepatch of size 11.68mm x 11.68mm from the centre of base shape is removed to get the next iteration which results in dividing the base fractal antenna into a 3-by-3 grid. Since the size of the removed square is one third of base square further subdivide the remaining eight solid squares into nine equal squares and remove the center square of size 3.85mm x 3.85mm from each one to attain the next iteration. With the application of above process, the designed antenna is iterated for iteration zero, iteration one and iteration two illustrated in figure 2below
- Consequently the size of the antenna is reduced by due to fractal antennas by 10.22% in the first iteration and
- In the second iteration the antenna size is further reduced by approximately 20.11% resulting in further reduction of antenna size.
- Simulation results pertaining to Return loss(S_{11})&VSWRfor iterations zero, one & two are plotted as shown in figure 3 & 4

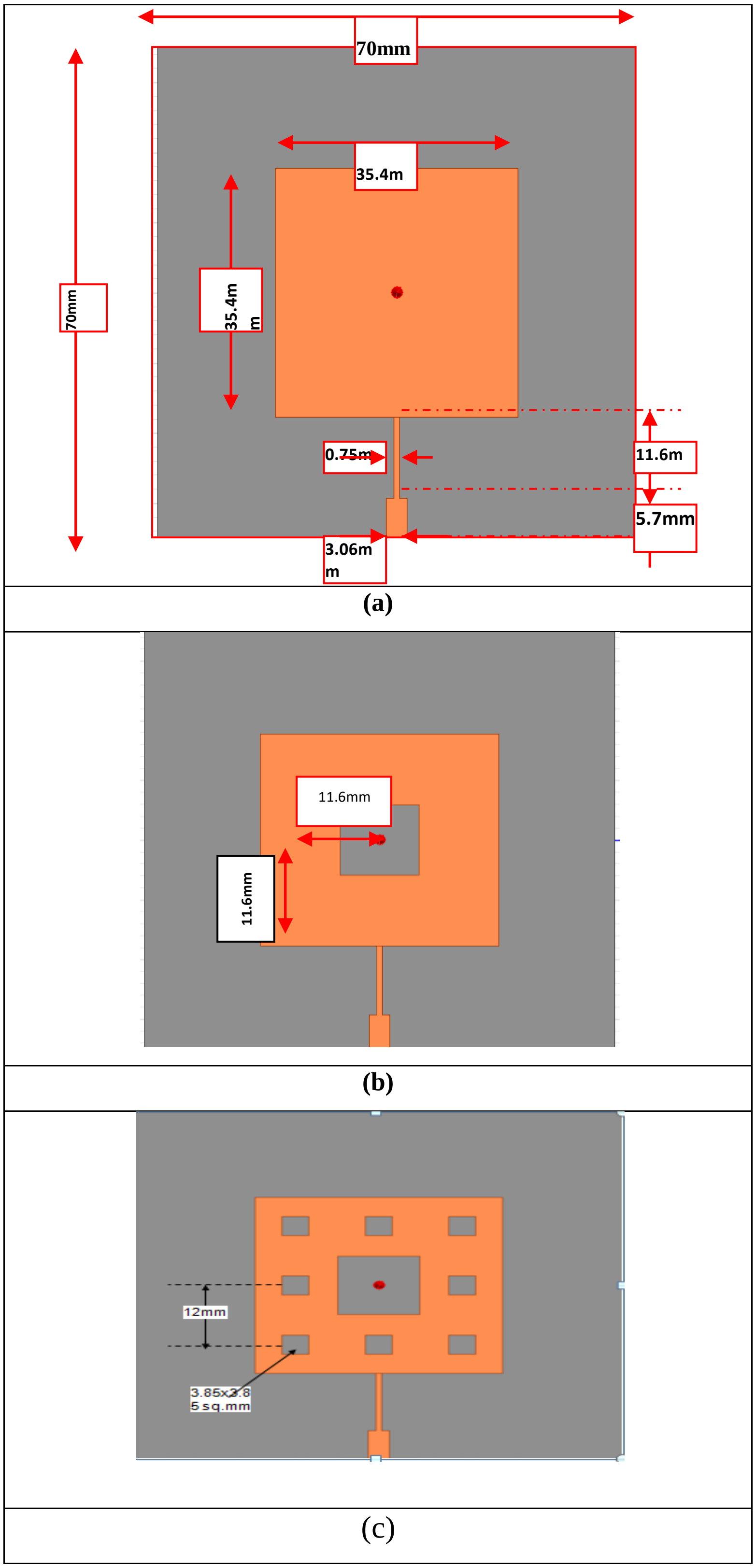
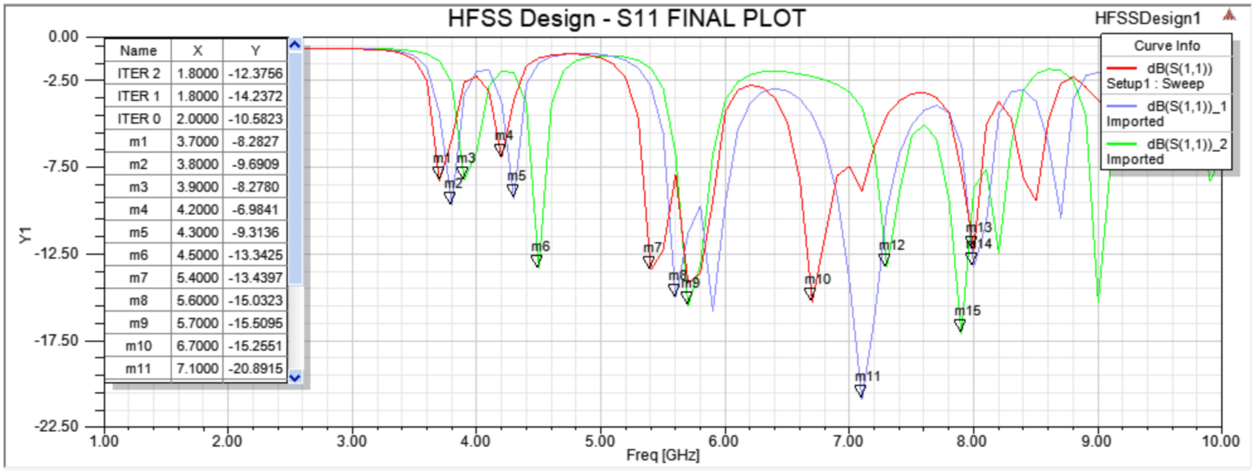
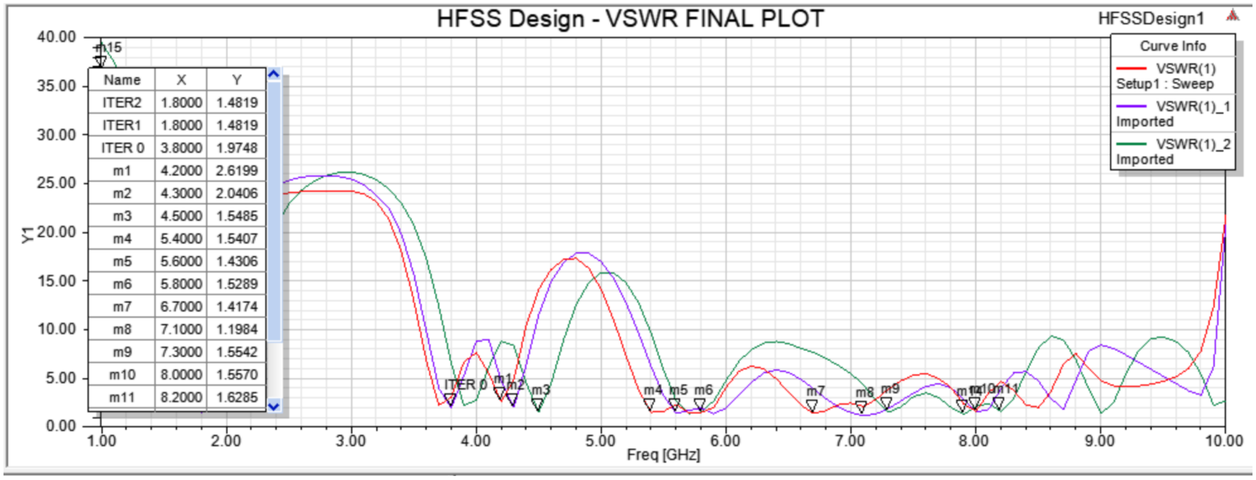


Figure. 2 Sierpinski Carpet Fractal antenna dimension for Various Iterations (a) Sierpinski Carpet Fractal antenna dimension for Iteration Zero (b) Sierpinski Carpet Fractal antenna dimension for Iteration Two(c) Sierpinski Carpet Fractal antenna dimension for Iteration Two



Name	X	Y
ITER 2	1.8000	-12.3756
ITER 1	1.8000	-14.2372
ITER 0	2.0000	-10.5823
m1	3.7000	-8.2827
m2	3.8000	-9.6909
m3	3.9000	-8.2780
m4	4.2000	-6.9841
m5	4.3000	-9.3136
m6	4.5000	-13.3425
m7	5.4000	-13.4397
m8	5.6000	-15.0323
m9	5.7000	-15.5095
m10	6.7000	-15.2551
m11	7.1000	-20.8915

Figure 3 : Consolidated Graph of S11Vs Frequency up to 8 GHz for Iteration, Zero, One & Two of Sierpinski Carpet Fractal Antennausing HFSS 15.0



Name	X	Y
ITER2	1.8000	1.4819
ITER1	1.8000	1.4819
ITER 0	3.8000	1.9748
m1	4.2000	2.6199
m2	4.3000	2.0406
m3	4.5000	1.5485
m4	5.4000	1.5407
m5	5.6000	1.4306
m6	5.8000	1.5289
m7	6.7000	1.4174
m8	7.1000	1.1984
m9	7.3000	1.5542
m10	8.0000	1.5570
m11	8.2000	1.6285

Figure 4: Consolidated Graph of VSWR up to 8 GHz for Iteration, Zero, One & Two of Sierpinski Carpet Fractal Antennausing HFSS 15.0

3. ANN Modeling

The neural network has become a widely recognized mathematical structure, forming the foundation of data-driven models [8-10]. These networks, inspired by the human brain, are a category of machine learning models characterized by interconnected nodes called neurons, organized into layers. Each neuron receives input, processes it through an activation function, and produces an output passed to the next layer.Artificial Neural Networks (ANNs) can be trained from specific inputs to targets, adjusting parameters like the number of hidden layers, neurons in each layer, and the training algorithm. Weights and biases are automatically adjusted during training to minimize the error between the desired and network outputs. The initial step in the ANN technique involves generating a database of samples, a crucial aspect of Artificial Intelligence for effectively handling nonlinear data [11-14].

ANN architectures typically feature three logic layers: the input, hidden layer(s), and output layers. Hidden layers containing one or more neurons lie between the input and output layers. While different applications dictate specific configurations, most models include two or three hidden layers for estimating various mathematical functions. The model's performance relies on data collection, learning algorithm, weight initialization, and activation function. In antenna design, data is collected through simulations or experimental measurements, extending slightly beyond the model's operational range [15-17].

In the initial step, data samples are categorized into training (approximately 80%) & testing (20%) sets. The percentage allocation may vary based on specific application requirements. Subsequently, the network size is determined, specifying the number of hidden layers and neurons in each layer. In the proposed ANN model, training occurs over 300 epochs with a batch size 32. During training, weights and biases are updated using backpropagation and gradient descent to achieve minimum mean squared error. Data for this work is collected by simulating a Sierpinski carpet antenna using HFSS software, leading to the selection of the best combination for the proposed model.

The model comprises a feed-forward neural network with four layers: the first layer is a dense layer with 128 neurons, two dense layers with 256 neurons each, and a final dense layer with one neuron. A Rectified Linear Unit (ReLU) activation function is applied to the first, second, and third layers. In contrast, no activation functions are used for the fourth and final layer. Activation functions are crucial in stimulating hidden nodes to produce a desirable output.

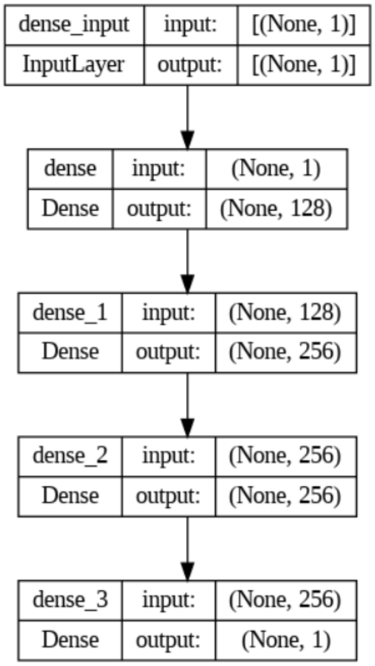


Figure 5: Neural Network Model Flow

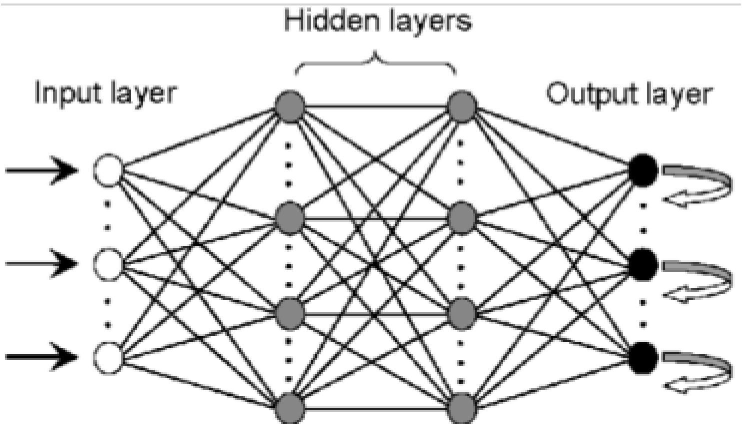
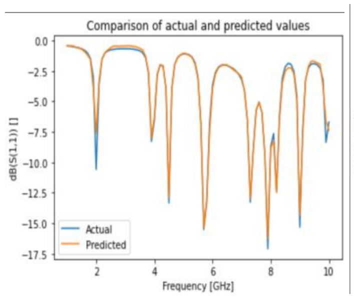


Figure 6: Neural Network Model

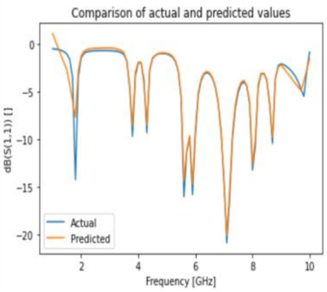
In this implementation, the neural network predicts significant parameters, such as S_{11} dB and VSWR values, based on frequency (Freq [GHz]). The flow and structure of the neural network model are depicted in Figures 3a and 3b.The design steps encompass loading the dataset, splitting it into input and output variables, normalizing the input data, splitting the dataset into training and test sets, defining the neural network model, compiling the model, training it on the training set, and evaluating the model on the test set.

4. Results & Discussion

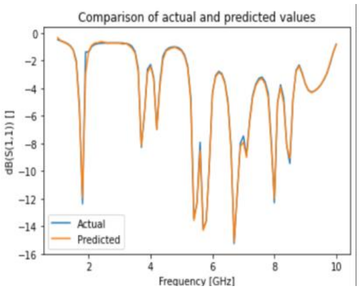
The S11 and VSWR values obtained through HFSS15.0 software align closely with those from the Neural Network model, indicating effective optimization of the antenna dimensions using NN. The proposed technique employs a multilayer feed- forward artificial neural network as an fairly accurate model for determining various antenna parameters. The outcome thus obtained are highly convincing, demonstrating the suitability of the ANN model to predict accurate performance parameters under specific conditions.



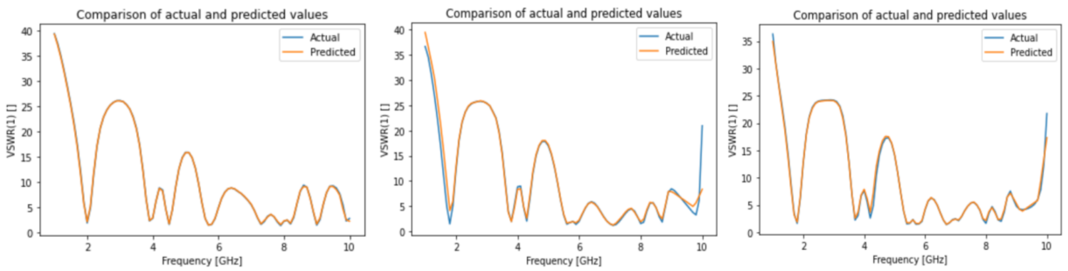
(a)



(b)



(c)



(d) (e) (f)

Figure.7 (a) Graph of S_{11}VsFrequencyforIteration-0,(b)Graph of S_{11}Vs Frequency for Iteration-1,(c).Graph of S_{11} Vs Frequency for Iteration-2, (d) Graph of VSWR Vs Frequency for Iteration-0, (e) Graph of VSWR Vs Frequency for Iteration-1, (f) Graph of VSWR Vs Frequency for Iteration-2

Simulated results for three iterations from the Plot for S_{11}(dB)andVSWRareshowninFigs.7(a)to(f). The S_{11} (Return Loss) and VSWR values of the fractal antenna attained through ANNs exhibit excellent agreement with the simulated values, as presented in Table 2 and 3. This close correspondence between simulated and ANN results reinforces the strength of the proposed model.

Table2.Simulated results for three iterations from the Plot for S_{11}(dB)

Sl.No.	Iteration-0S_{11}(dB)			Iteration-1S_{11}(dB)			Iteration-2S_{11}(dB)		
	Freq (GHz)	HFSS Result (Actual)	NN Result (Predicted)	Freq (GHz)	HFSS Result (Actual)	NN Result (Predicted)	Freq (GHz)	HFSS Result (Actual)	NN Result (Predicted)
1.	2.0	-10.58	-9.63	1.8	-14.23	-9.70	1.8	-12.37	-11.92
2.	3.9	-9.27	-9.99	3.8	-9.69	-9.56	3.8	-9.28	-9.16
3.	4.5	-13.34	-12.86	4.3	-9.31	-9.52	4.3	-8.98	-8.98
4.	5.7	-15.50	-15.38	5.6	-11.32	-11.16	5.4	-14.19	-14.29
5.	7.3	-13.27	-12.98	7.1	-16.22	-15.37	7.1	-11.67	-11.53
6.	7.9	-17.09	-16.24	8.0	-13.23	-12.73	8.0	-12.29	-11.98

Table3.Simulated results for three iterations from the Plot for VSWR

Sl.No.	Iteration-0VSWR			Iteration-1VSWR			Iteration-2VSWR		
	Freq (GHz)	HFSS Result (Actual)	NN Result (Predicted)	Freq (GHz)	HFFS Result (Actual)	NN Result (Predicted)	Freq (GHz)	HFSS Result (Actual)	NN Result (Predicted)
1.	2.0	1.83	2.02	1.8	1.48	2.11	1.8	1.63	1.89
2.	3.9	2.05	2.07	3.8	1.97	1.95	3.8	2.05	2.08
3.	4.5	1.54	1.66	4.3	2.04	2.08	4.3	2.21	2.23
4.	5.7	1.40	1.41	5.6	1.74	1.77	5.4	1.48	1.64
5.	7.3	1.55	1.66	7.1	1.36	1.61	7.1	1.71	1.77
6.	7.9	1.32	1.50	8.0	1.55	1.92	8.0	1.64	2.06

5. Conclusion

The proposed research results provide optimum outcomes according to the demand for compact wireless communication systems. Based on the literature, new design processes have been introduced for efficient gain. The ANN modeling lowers the cost of physical device testing and provides simulated results. A compact multiband Sierpinski carpet fractal antenna, designed for operation between1 GHz and 8 GHz using FR4 epoxy (dielectric constant=4.4 loss tangent=0.02, substrate height=1.58mm) and excited with a 50Ω microstrip line, were modeled and simulated to enhance performance parameters. The results indicate that as iterations increase, the antenna size is reduced by 10.22% in the first iteration and 20.11%in the second iteration, making it the smallest for the chosen frequency bands. After the second iteration, the antenna size is approximately 33% smaller than the basic patch, with S_{11} parameter/return losses below- 10 dB for all iterations and also VSWR equal to or less than 2, thus exhibiting multiband properties at resonant frequencies of 2, 3.9, 4.5, 5.7, 7.3 & 7.9 GHz

In summary, Artificial Neural Networks emerge as one of the best choices for antenna design and optimization. The computational efficiency of Neural Network models surpasses traditional techniques such as the Finite Element Method, Method of Moments, HFSS, CST Microwave Studio, etc. The neural model enables accurate and efficient optimization once learning data is available through electromagnetic simulation or measurement. Additionally, the design can be obtained within the training region. Thus, Artificial Neural Networks can be considered as a fast, accurate, cost-effective solution for antenna modeling, simulation, and optimization. As a future scope, the ANN modeling can be tested for remote patient monitoring and naval and military applications in collaboration with satellite communication.

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