FRACTAL ANTENNA DESIGN USING BIO-INSPIRED COMPUTING ALGORITHMS

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ISBN (Online): 978-981-5136-35-7

ISBN (Print): 978-981-5136-36-4

ISBN (Paperback): 978-981-5136-37-1

First published in 2023.

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FOREWORD

The book “FRACTAL ANTENNA DESIGN USING BIO-INSPIRED COMPUTING ALGORITHMS” is a Ph.D. research work based on low-cost optimized fractal antennas in order to meet the challenging requirement of compact antennas in wireless and medical applications. The objectives of this research work are mainly based on these three folds: development, optimization and experimentation of fractal antennas for low-power applications.

The book has been written in a logical and comprehensive manner with a detailed explanation of the design and methodology adopted. I am confident that this book will be of immense use to the researchers pursuing research in the domain of antenna design and optimization.

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PREFACE

The demand of the compact antennas is increasing continuously due to the requirement for reduced-size wireless communication devices. The use of fractal geometry for the design of small-size antennas is a modern trend. As closed-form expressions do not exist for fractal antennas, alternative methods of designing fractal antennas are needed. The use of bio-inspired computing techniques like Artificial Neural Network (ANN), Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Bacterial Foraging Optimization (BFO) is very appropriate in such cases. In the presented research work, these techniques have been used for parameter estimation and design optimization of fractal patch antennas. Therefore, the presented research works confines the fractal antennas & bio-inspired computing techniques to provide cost-effective & efficient solutions. An extensive literature survey is carried out to understand the concept of fractal antennas, their features and design approaches. Also, a number of research papers are reviewed on the applications of bio-inspired computing techniques for antenna design, especially fractal antenna design. The extracts of the literature survey presented in the book highlight these important issues.

Many fractal antenna geometries suitable for medical and communication applications have been proposed in the presented research work. The IE3D software has been used to simulate various fractal antennas, and the simulation results are obtained to analyze the performance of the selected antennas. The desired features are assessed from the S_{11} plots, gain plots and radiation patterns which are validated with experimental and analytical findings. The multilayer perceptron neural network, radial basis function neural network, and generalized regression neural network models are developed to estimate various parameters of the proposed fractal antennas. The performance of various ANN models has also been compared in order to find optimally suitable models. The use of ANN ensemble models for the design of fractal antennas is also explored, and it has been found that the ANN ensemble approach is better than the traditional ANN model approach. The different methods of developing ANN ensemble models are also presented. The bio-inspired computing techniques based on GA, PSO and BFO are developed to find the optimal design of the proposed fractal antennas for the desired applications. The performance comparison of the various bio-inspired computing techniques is also carried out to select the best algorithm. The use of ANN models as an objective function of optimization algorithms is also enumerated to design the presented fractal antennas. It has been observed that the developed bio-inspired computing techniques provide accurate solutions with a very small computational cost. The performance of the designed antennas is validated by fabricating prototypes and then performing experimental testing. The simulated results are compared with the experimental results, and good matching of simulated and experimental results is observed in almost all cases. The obtained results are also compared with the previously published results to validate the presented designs. The research work has resulted in the design of the fractal antennas having many desirable features like size reduction characteristics, enhanced gain, and improved bandwidths

This book contains six chapters which present the outcomes of the above-described research work.

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ACKNOWLEDGEMENT

The authors would like to thank IKG Punjab Technical University, Jalandhar, for providing the opportunity to publish this work.

CHAPTER 1

Recent Advances in The Design and Analysis of Fractal Antennas

Abstract: Microstrip patch antennas mainly draw attention to low-power transmitting and receiving applications. These antennas consist of a metal patch (rectangular, square, or some other shape) on a thin layer of dielectric/ferrite (called a substrate) on a ground plane. Microstrip antennas have matured considerably during the past three decades, and many of their limitations have been overcome. As the size of communication devices is decreasing day by day, the demand for miniaturized patch antennas is growing. Many methods of reducing the size of antennas have been developed in the past two decades. The recent trend in this direction is to use fractal geometry. The design of an antenna for a specific resonant frequency requires the calculation of the optimal value of various dimensions. This is a hard task for fractal antennas because the accurate mathematical formulas leading to exact solutions do not exist for the analysis and design of these antennas. The use of bio-inspired computing techniques is gaining momentum in antenna design and analysis due to rapid growth in the computational processing power, and the main techniques are Artificial Neural Network (ANN), Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Bacterial Foraging Optimization (BFO), and Swine Influenza Model-based Optimization (SIMBO), *etc*. In the area of antenna design, the ANNs are employed to model the relationship between the physical and electromagnetic parameters. The trained ANNs are effectively used for the analysis and design of various types of antennas. Bio-inspired optimization techniques have been used by researchers to calculate the optimal parameters of various patch antennas and for the size optimization of antennas. Also, the hybrids of ANN and optimization techniques are proposed as effective algorithms for many applications, especially when the expressions for relating the input and output variables are not available. The presented research has addressed these recent topics by designing miniaturized fractal antennas using bio-inspired computing techniques for various low-power applications, thus, providing cost-effective and efficient solutions.

Keywords: Fractal antenna, Miniaturized antennas, Multiband antennas, Sierpinski gasket, Ultra wide band antenna.

INTRODUCTION

Antennas are used in almost all electronic devices used for wireless communication. These communications include direct person-to-person communications, communication through base station/Satellite, wireless networks

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like Wireless Local Area Networks (WLAN), *etc*., and entertainment communications. The quality and efficiency of these communications largely depend on the efficient antenna design. Also, the size of communication devices is decreasing day-by-day, which dictates a very small space for fitting antennas. Therefore, miniaturized antennas are a need of the day [1, 2]. Another requirement is the design of wide-band antennas because most of the communications transfer data with complex signals composed of voice, data, images and video. The fractal antennas have the capability of miniaturized, multiband and wideband performance [3 - 6]. Also, bio-inspired optimization algorithms have the potential to provide better-quality results with reduced computation costs [7]. So, the motivation of the presented research work is to use the fractal geometry concept to provide solutions to the requirement of multiband, miniaturized and enhanced gain antennas for medical and communication applications and to use bio-inspired computing techniques to obtain the optimized fractal antennas to address the issues of antenna requirements.

ANTENNAS FOR COMMUNICATION APPLICATIONS

The antennas are the most important part of wireless communication systems. The resonant behavior of the antenna has a large effect on the communication system's performance. Most of the wireless communication applications, like Bluetooth, Wireless-Fidelity (Wi-Fi), *etc*., work in Industrial, Scientific, and Medical (ISM) bands. The ISM bands cover frequency ranges 902-928 MHz, 2400-2484 MHz and 5725-5850 MHz, which can be used without end-user licenses. The advantage of being in the category of unlicensed bands is that there is a great scope for the development of consumer and professional products which is considered to be an important step towards the development of wireless computing, mobile internetworking, or multimedia applications. These bands have various types of applications like Bluetooth, Radio Frequency Identification (RFID), Wi-Fi, WLAN and Worldwide Interoperability for Microwave Access (WiMAX) [1]. There are two types of approaches to designing a system operating at multiple frequencies: the conventional technique using multiple single-band antennas, each intended for only one of the multiple discrete frequency bands, or a single multi-band antenna designed to handle all discrete frequency bands, *e.g*., a fractal antenna. Another important aspect of antenna design for communication applications is to develop miniaturized antennas, *i.e*., antennas with reduced dimensions. The miniaturization of antennas helps in designing compact wireless communication devices [2]. The bandwidth of conventional microstrip antennas is very small, so bandwidth enhancement techniques are also very essential in antenna design. There are several methods of increasing bandwidth, and the use of fractal geometry is the latest trend to achieve this [3]. The design of antennas suitable for Multi Input Multi Output (MIMO) systems is also attracting the attention of antenna designers because this technology enhances the data transmission capacity and reduces multipath fading effects [4]. The design of wearable antennas, which are flexible enough that these can be bent, crumpled, and folded, is also another recent trend. These antennas are generally stitched as part of clothes and are used for many applications such as military, health monitoring activities, telemedicine, sports, tracking, *etc* [5]. The main challenge in designing wearable antennas is to find appropriate fabrics and polymers which can be employed as flexible substrate materials. The other important challenges are the design of antennas having high gain [6] and circular polarization [7].

ANTENNAS FOR MEDICAL APPLICATIONS

Antennas for medical applications have been widely investigated and reported in the recent past. The recent applications are typically in the field of information transmission, such as RFID / wearable or implantable antennas, in diagnoses such as Magnetic Resonance Imaging and microwave computed tomography/ radiometry, and also wireless telemedicine / mobile health systems. Applications are also reported in thermal therapy (hyperthermia, coagulation, *etc*.) and microwave knife [8]. Most modern Implantable Medical Devices (IMD) help in establishing a communication link between the implant and external devices behaving as a telemetry system. This communication link can be used to temporarily or permanently program the operating parameters of the IMD, to retrieve both real-time and stored physiological data, and to enquire about the IMD system status and therapy history. Several techniques aiming at creating a physical channel have been developed for IMD telemetry, namely static magnetic field coupling, reflected impedance coupling and Radio-Frequency (RF) propagation. Recently, RF transmissions have received increased attention because of their higher data rates and ability to communicate over long distances between the IMD and the external device [9]. For medical data telemetry, the Medical Implant Communication Service (MICS) band (402-405 MHz) was established by the Federal Communications Commission (FCC) in 1999, and the ISM frequency bands are also available. However, most of the transceivers make use of the MICS and 2400 MHz ISM bands [10]. Hence, by providing communication of the sensor with external equipment, antennas find a major role in medical systems. Small size and high radiation efficiency are the main challenges faced by antenna designers for medical applications. Other than these, some other issues like impedance matching, low-power requirements, and biocompatibility with the body's physiology, directivity, lobe control, *etc*., are also considered while designing antennas [11, 12].

LIMITATIONS OF EXISTING ANTENNA SYSTEMS

The limitations of existing antennas used in medical and communication applications are as follows:

CHAPTER 2

Bio-inspired Computing Techniques and their Applications in Antennas

Abstract: This chapter is dedicated to bio-inspired computing techniques and their applications in antennas. The working principles of ANN, ANN Ensemble, GA, PSO, and BFO are described, and some hybrid bio-inspired computing techniques are also discussed. The literature survey related to the applications of bio-inspired computing optimization techniques in antennas is given in this chapter. The limitations of the existing bio-inspired computing techniques are highlighted. The existing applications of bio-inspired computing techniques in fractal antennas are also reviewed in this chapter.

Keywords: Bacterial foraging optimization, Fractal antenna, Genetic algorithms, Particle swarm optimization, Sierpinski gasket.

INTRODUCTION

Many bio-inspired computing techniques have been proposed by researchers in the past two decades that imitate genetic evolution, the human brain or the behavior of biological individuals in the natural world. Bio-inspired computing can tolerate uncertainty, vagueness, partial truth, and approximation. The bio-inspired computing techniques make use of these tolerances to achieve tractability, robustness and low solution cost [1]. A precise analytical model is required in traditional computing; the computation time is generally very large. Also, in most of the cases, the analytical models are applicable to ideal situations, and real-world problems exist in non-ideal conditions. Bio-inspired computing techniques are a group of methods spanning several areas that come under different categories in artificial intelligence. Despite the fact that some of these algorithms are new, they have been used effectively in many optimization problems with several constraints [1]. The main constituents of bio-inspired computing techniques are ANN, GA, PSO, BFO, and SIMBO. At present, these techniques are fundamental to many antenna design solutions and have shown great promise in tackling the growing requirements of antenna engineering for improved performances, reduced size, and overall cost [2, 3]. The bio-inspired computing techniques have resulted in many useful and non-intuitive antenna

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design solutions and, in most of the cases, these techniques have outperformed the traditional methods. Another important reason for the suitability of bio-inspired computing techniques is that antenna synthesis and optimization problems frequently involve many parameters and a very large number of possibilities, thus making exhaustive searches impractical. The use of these techniques for fractal antennas' design is very suitable because of the non-availability of exact mathematical expressions for these antennas [3, 4].

BIO-INSPIRED COMPUTING TECHNIQUES

This section describes the working of the important constituents of the soft computing algorithm.

Artificial Neural Network (ANN)

ANNs have been employed for analysis and prediction in almost all disciplines of engineering as these can model non-linear systems very efficiently. The use of ANN models for the analysis and design of microstrip antennas is widely accepted. This is obvious from the growing count of research/academic journals' publications in this field. ANNs have been used for the analysis of antennas, synthesis of antennas, parameter estimation, *etc*., as discussed in the following sections.

The ANNs are computational models inspired by biological neural networks. The ANNs can process information like the human brain to attain, gather and exploit experimental knowledge. ANNs are used to find patterns in data or to model complex relationships between inputs and outputs [1]. The basic computational unit of the ANN is the neuron. The ANNs are massive parallel structures of neurons arranged in the form of layers having interconnections between them. The neurons are of three types: (i) input neurons which receive inputs from the outside world, (ii) hidden neurons which receive inputs from other neurons and whose outputs are inputs for other neurons in the network, and (iii) output neurons whose output is supplied to the outside world [2]. The connecting branches of the neurons have the associated connection strength parameters which are known as the weights. The design of the ANN involves the training of the network for the specific application. During training, an input-output data set is used to adjust the weights so that the ANN produces the correct output for the input applied [4]. Once the network is successfully trained, it can be used for predicting outputs for unknown inputs.

There exist different types of ANNs, which are constructed by using different kinds of interconnections and various types of neurons. The most common type of ANN is feed-forward neural networks in which the information flows in the forward direction only, *i.e*., there is no feedback connection. The three important forms of feed-forward ANNs are Multi-Layer Perceptron Neural Networks (MLPNN), Radial Basis Function Neural Networks (RBFNN), and General Regression Neural Networks (GRNN) [1]. These three forms are very popular in the field of antennas.

Multi-Layer Perceptron Neural Networks (MLPNN)

MLPNN is a widely used neural network structure in antenna applications. It consists of multiple layers of neurons that are connected in a feed-forward manner [4]. The base structure of an MLPNN is shown in Fig. (**2.1**), which depicts that the network has *K* layers. The first layer is the input layer, and the last layer (K^{th} layer) is the output layer. The other layers, *i.e*., layers from *2* to *K-1,* are hidden layers. Each layer has a number of neurons [5]. In the input and output layers, the numbers of neurons are equal to the number of inputs and outputs, respectively. The neurons in the hidden layers are selected using a trial-and-error process, so that accurate output is obtained. Each neuron processes the inputs to produce output using a function called the activation function.

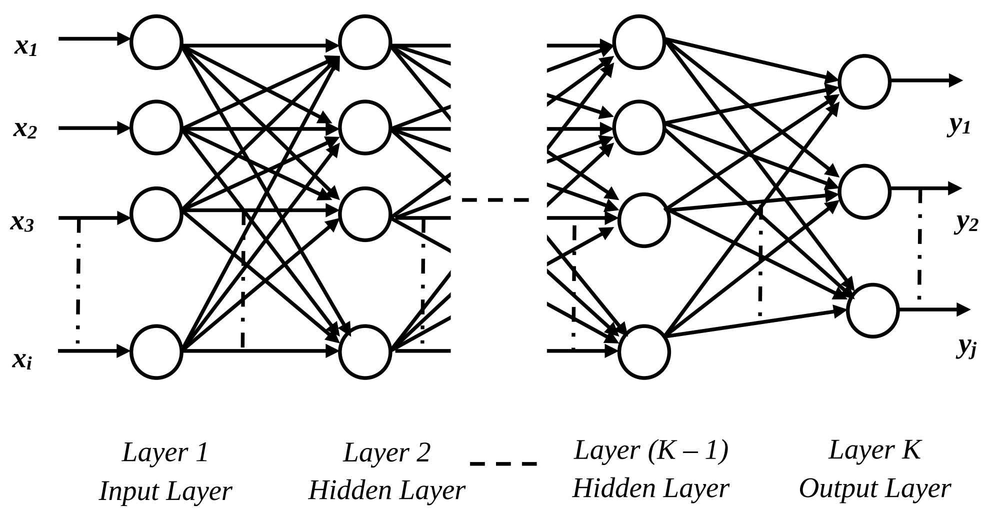

Fig. (2.1). Basic Structure of MLPNN [6].

The input neurons normally use a relay activation function and simply relay (pass) the external inputs to the hidden layer neurons. The most commonly used activation function for hidden layer neurons is the sigmoid function defined as in the equation given below [2]:

CHAPTER 3

Fractal Antennas

Abstract: This chapter discusses fractal geometry concepts and fractal antennas. Selected fractal antennas and their features are described, and all the designed fractal antennas are introduced in this chapter. The important features like miniaturization & multiband operation of the designed fractal antennas are highlighted, and their applications are also discussed.

Keywords: Crown fractal antenna, Fractal antenna, Miniaturized antenna, Sierpinski gasket.

INTRODUCTION

The term 'fractal' is used to represent a class of geometry with unique properties. This term was originally employed by Mandelbrot to describe recursively generated self-similar geometric shapes [1]. The shape of fractal structures is similar at different scales, *i.e.*, the subparts of the overall geometry are similar to the overall global shape. Due to this property, the fractal shapes are called self-similar shapes [2]. Another important property of fractal geometries is the space-filling property, which means the possibility to enclose an infinitely long curve in a finite area [3] *e.g.*, a surface with a very large perimeter can be enclosed in fractal loops.

Another important property of fractal shapes is the fractional dimensions, *i.e.*, the dimensions of the fractal geometry are not whole numbers but fractional numbers [1]. The self-similarity property of fractals states that the fractional dimension (*Dim*) of fractal geometry is calculated by the equation given below [4]:

$$Dim = \frac{\log(M)}{\log(s_d)} \tag{3.1}$$

where M represents the number of similar copies of fractal geometry and s_d is the inverse of the scaling down ratio of fractal geometry, which is calculated as $1/s_d$ [5, 6].

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Many fractal shapes are generated by applying repetitive procedures, such as multiple reduction copy machine algorithm [7] or by using an IFS [8]. In these repetitive algorithms, a starting base shape named 'Initiator' is selected, and another shape named 'Generator' is copied a number of times at various locations, scaling ratios and orientations, to achieve the end geometry [7]. Ideally, fractal geometries are designed by iterating an infinite number of times, however, practically, few starting geometries (also called pre-fractals) are considered [9]. The repetitive designing technique is shown in Figs. (**3.1** and **3.2**) for two different geometries. Fig. (**3.1**) shows the repetitive procedure for the implementation of the Sierpinski gasket geometry. The initiator triangle is replicated at different scales and shifted to form the various iterations. Each triangle is replaced with the three small triangles arranged as shown in Fig. (**3.1**). The repetitive-designing procedure for the Minkowski Island fractal shown in Fig. (**3.2**) involves the replacement of each straight line of the structure by the generator shape.

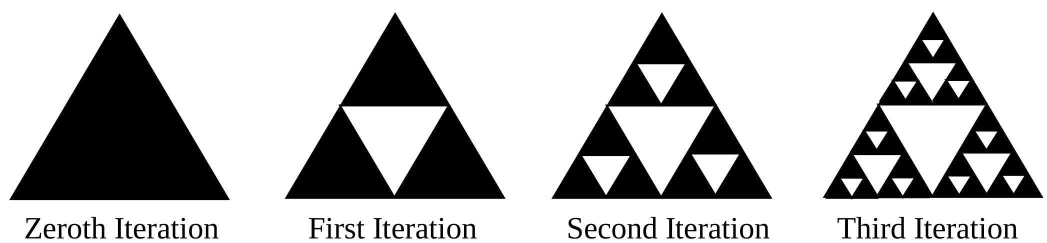

Fig. (3.1). Development of Sierpinski Gasket Geometry (Reprinted from the Springer Nature: Neural Computing and Applications, Performance Comparison of Bio-Inspired Optimization Algorithms for Sierpinski Gasket Fractal Antenna Design, Dhaliwal, B.S. and Pattnaik, S.S. © 2016).

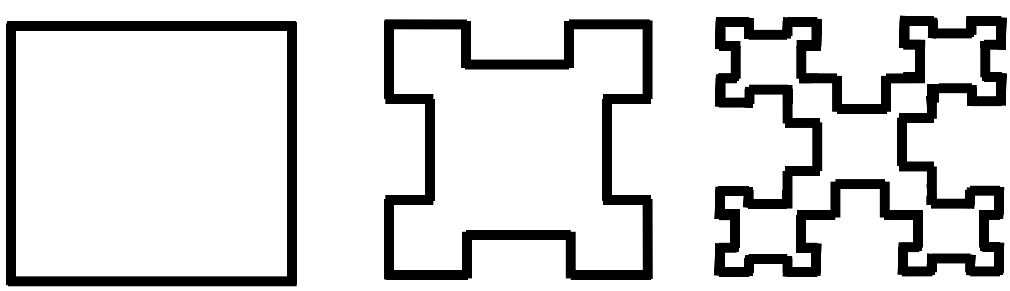

Fig. (3.2). Development of Minkowski Island Fractal Geometry [9].

Fractal geometries have been used in antenna structures to extend antenna design concepts beyond Euclidean geometry [6]. The fractal antennas are antennas in which the fractal geometry concepts are used to design the radiating shapes [10]. The properties of fractal geometries result in a number of advantages in antenna design. The space-filling property of fractal shapes leads to the fitting of very long electrical lengths into compact physical spaces. This results in the miniaturization of antennas [9]. The self-similar property of fractals means that various segments of the structure are like the other parts but at different scales. This leads to the multiband behaviour of antennas [11]. The fractional dimensions of the fractals are considered an important mathematical property [12]. In self-similar shapes, the variation of the scale ratio results in changed fractal dimensions of the geometry [5]. There exists a direct relationship between antenna characteristics and variation of dimensions [6]. This property is used for tuning fractal antennas for desired frequencies. The other advantages of fractal antennas include enhanced bandwidth, improved gain and directivity, and better efficiency [13, 14].

SELECTED TYPICAL FRACTAL ANTENNAS AND THEIR FEATURES

Some of the popular fractal antennas are introduced in this section. The electromagnetic behaviour and important features are also described to highlight the potential/advantages of the fractal antennas.

Sierpinski Gasket Monopole Fractal (SGMF) Antenna

The most popular fractal antenna is an antenna based on a fractal shape named as Sierpinski triangle. This fractal shape, also called the Sierpinski gasket, was proposed in 1915 by a Polish mathematician named Waclaw Sierpinski. This fractal shape is used to design a monopole antenna by Puente-Baliarda *et al*. [7], and the fractal antenna is named as the SGMF antenna. The first four iterations of the Sierpinski gasket are shown in Fig. (**3.1**). The starting shape, *i.e*., the zeroth iteration, is an equilateral triangle from which the first iteration gasket is constructed by subtracting the central inverted triangle. After the subtraction, three equal-sized triangles remain on the structure, each one being half of the size of the original. So, the first iteration shape is a self-similar structure and each one of its three main parts has exactly the same shape as the whole object but is reduced by a factor of two. Each triangle of the first iteration geometry is replaced by three small size rectangles to obtain the second iteration and similarly, this iterative procedure is carried out further to obtain the next iterations [7].

The SGMF monopole antenna is constructed by printing the Sierpinski gasket on a substrate and then mounted over a conducting surface perpendicular to the plane of the printed substrate, which acts as a ground plane. This arrangement is similar to a monopole feeding structure. The geometry is excited by a coaxial signal source from the reverse side of the ground plane.

The SGMF antenna is a self-similar structure and this property is also observed in its S_{11} results and the radiation patterns [7]. This antenna has a multiband performance, and the number of bands depends on the number of iterations *n*. The

CHAPTER 4

Development of ANN Models for the Design of Fractal Antennas

Abstract: In this chapter, the development of ANN models for the design of proposed fractal antennas is explained. The various parameters of the fractal antennas selected for ANN models are described. The ANN models are designed using feed-forward neural networks, namely MLPNN, RBFNN and GRNN. The performance comparison of different ANN models on the basis of different performance measures is also given. The design of ANN ensemble models for fractal antennas is introduced, and different techniques for developing ANN ensemble models are also discussed in this chapter.

Keywords: ANN, ANN ensemble, Crown fractal antenna, Fractal antenna, Miniaturized antenna.

INTRODUCTION

ANNs have been used for the design of microstrip patch antennas by a number of researchers. ANNs are applied by Mishra and Patnaik [1] and Turker *et al*. [2] to design rectangular patch antennas. ANN coupled with GA is used by Panda *et al*. [3] and Khuntia *et al*. [4] for designing rectangular microstrip antennas on thick substrates. Kumar *et al*. [5] presented the use of ANN for parameter estimation of a multislotted rectangular microstrip antenna. The use of a PSO-driven RBFNN to design an equilateral triangular microstrip antenna is presented by Chintakindi *et al*. [6]. A circularly-polarized square microstrip antenna is designed by Wang *et al*. [7]. ANN is used by Siakavara [8] to design a circular microstrip ring antenna for multi-frequency operation. The application of ANN for designing a rectangular microstrip ring antenna with proximity-coupled feed is proposed by Manh *et al*. [9]. An application of ANN for the design of an inset-fed rectangular microstrip antenna is discussed by Vilovic *et al*. [10]. The design of a circular microstrip antenna using ANN is presented by Gultekin *et al*. [11]. Bose and Gupta [12] have presented an ANN model based on RBF and a back-propagation algorithm to design aperture-coupled microstrip antennas.

ANNs are also used to estimate the resonant frequencies of microstrip antennas. Devi *et al*. [13] and Khuntia *et al*. [14] used ANNs to calculate the resonant freq-

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uency of different rectangular microstrip patch antennas. Pattnaik *et al*. [15] presented an ANN model to compute the resonant frequency of a single-shorting post-tunable rectangular microstrip-patch antenna. The resonant frequency of a rectangular microstrip antenna with and without an air gap is calculated using ANN by Tighilt *et al*. [16]. ANN models are used by Can *et al*. [17] for estimating the resonant frequencies of a dual-band equilateral triangular microstrip antenna. Yu-Bo *et al*. [18] presented the use of an ANN ensemble for modeling the resonant frequency of a rectangular microstrip antenna. The ANN models have also found a number of applications in estimating parameters other than the resonant frequencies. Hettak and Delisle [19] used ANN to calculate the radiation efficiency of a rectangular microstrip patch antenna. Neog *et al*. [20] designed a tunnel-based ANN model for the parameter calculation of a wideband microstrip antenna. The input impedance of a loop antenna is predicted by Kim *et al*. [21] by using the ANN models. Panda *et al*. [22] used ANN to speed up FDTD calculations to evaluate the input impedance of a stacked microstrip patch antenna. The feed point of a circular microstrip antenna is estimated with the help of the RBFNN model by Vilovic and Burum [23]. An application of the RBFNN model to analyze the bandwidth of a slot-loaded triple-band patch antenna is proposed by Aneesh *et al*. [24]. The use of ANNs for the analysis and design of antenna arrays has been reported by various researchers. Patnaik *et al*. [25] proposed an ANN-based approach to locate the faulty elements in antenna arrays. The optimization of energy parameters of antenna arrays using the ANN is proposed by Bashly and Popovskii [26]. The side-lobe reduction of an antenna array is achieved by Lee *et al*. [27] using an ANN-based automatic converging scheme. Vakula and Sarma [28] proposed the use of the RBFNN model for the diagnosis of planar antenna arrays from far-field radiation patterns. Zaharis *et al*. [29] presented ANN models for adaptive beamforming of antenna arrays. The use of RBFNN for directivity estimations of arrays of short dipoles is presented by Mishra *et al*. [30].

The above applications of ANNs in microstrip antennas' analysis and design show that the ANNs are very suitable in this field. The applications of ANNs for the parameter estimation of fractal antennas are developed in the presented research work and are described in this chapter.

DEVELOPMENT OF ANN MODELS FOR FRACTAL ANTENNAS

As compared to the traditional patch antennas, the fractal antenna patch shapes are complex, and the mathematical formulas for the analysis and design of these antennas do not exist. ANNs are suitable choices for fractal antennas because development of analytical methods is challenging for new structures, numerical modeling methods are computationally expensive, and empirical models have limited range and accuracy [31]. The following sections describe the ANN models developed for the analysis and design of fractal antennas designed in this research work. The input and output parameters of the ANN model depend on the fractal shape as well as on the relationships to be modeled. Three feed-forward ANN types, namely MLPNNs, RBFNNs, and GRNNs, are considered in the presented work.

ANN Model for Analysis of SGMF Antenna

The SGMF antenna has been explored most widely than any other fractal antenna since its presentation in 1998 by Puente-Baliarda *et al*. [32]. The development of the first four iterations is shown in Fig. (**4.1**). This antenna is a multiband antenna, and the number of bands depends on the number of iterations n [32]. The zeroth iteration (base triangular shape) has only one resonance frequency. The first iteration antenna has two resonant frequencies and so on. The side length s of the antenna, ε_r, and h of the substrate also affect the resonant frequencies. So, the resonant frequencies f_r, depend upon the values of ε_r, h, s and number of iterations n.

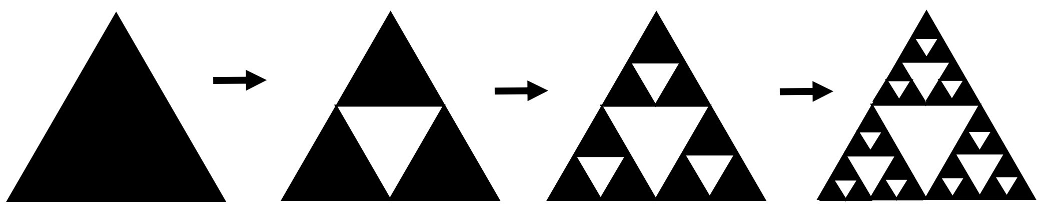

Fig. (4.1). First Four Iterations of SGMF Antenna (Reprinted from the Springer Nature: Neural Computing and Applications, Performance Comparison of Bio-Inspired Optimization Algorithms for Sierpinski Gasket Fractal Antenna Design, Dhaliwal, B.S. and Pattnaik, S.S. © 2016).

A closed-form expression for estimating the resonant frequency f_r of this antenna is also proposed by Puente-Baliarda *et al*. [32], which is first modified by Song *et al*. [33] and then by Mishra *et al*. [34]. The latest expression is given below in equation (4.1):

$$f_r = \begin{cases} (0.15345 + 0.34\rho x)\frac{c}{H_e}\,(\xi^{-1})^n & for\; n = 0 \\ 0.26\frac{c}{H_e}\delta^n & for\; n > 0 \end{cases} \quad \textbf{(4.1)}$$

where H_e is effective height of the largest Sierpinski gasket defined by $H_e = \frac{\sqrt{3}s_e}{2}$,

CHAPTER 5

Development of Hybrid Bio-inspired Computing Algorithms for Design of Fractal Antennas

Abstract: One of the novel contributions of this book is the development of hybrid bio-inspired computing algorithms for the design of fractal antennas. This work is presented in this chapter. The hybrid algorithms are developed to design the proposed fractal antennas for desired frequencies. The performance comparison of bio-inspired computing algorithms for the design of a multiband Sierpinski Gasket fractal antenna is also explained. The development of various hybrid algorithms like the GA-ANN hybrid Algorithm, BFO-ANN ensemble hybrid Algorithm, and PSO-ANN Ensemble hybrid Algorithm is explained. The use of ANN models as objective functions of optimization algorithms is discussed in this chapter. This chapter also deals with the experimental testing and validation of the developed fractal antennas. The photographs of the fabricated antennas and the experimental results are included. The comparison of the simulated results and experimental results is discussed. The suitability of the designed antennas for different applications is also highlighted in this chapter.

Keywords: Bacterial foraging optimization, Crown fractal antenna, Fractal antenna, Genetic algorithms, Miniaturized antenna, Particle swarm optimization, Sierpinski gasket.

INTRODUCTION

One of the challenging points in designing an antenna for a given frequency is to determine the required accurate dimensions of the antenna [1]. In fractal antennas, the radiating patches use complex geometries with many parameters, so the method used to determine the dimensions must consider all the geometry parameters. Also, the closed-form expressions do not exist, and the development of analytical methods is extremely difficult for complex fractal geometries of antennas. The numerical modeling methods are computationally expensive, and empirical modeling solutions have limited range and accuracy. In such cases, the use of bio-inspired optimization algorithms is very suitable [2, 3]. In the last decade, there has been exponential growth in the use of artificial intelligence techniques like ANN, fuzzy logic systems and bio-inspired optimization echniques in the designing of antennas [4 - 8]. The two most popular bio-inspired optimization algorithms: GA and PSO have been applied by a few researchers for

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the optimization of fractal antennas in recent years [9 - 13]. But, the application of another popular bio-inspired optimization algorithm, the BFO algorithm, in the field of fractal antennas is not investigated yet.

Literature shows that the initial work in the domain of optimization of fractal wire antennas is proposed by Werner *et al*. [11]. Pantoja *et al*. [14] proposed the optimization of fractal shapes such as the Delta, Koch, and Sierpinski-types using a multi-objective GA. A procedure for designing Sierpinski gasket and Koch monopole fractal antennas for user-defined frequencies using ANN and the PSO technique is presented by Anuradha *et al*. [10]. Pantoja *et al*. [12] applied a multi-objective GA algorithm to the design of wire fractal antennas optimizing their bandwidth and efficiency while reducing their resonant frequencies. Azaro *et al*. [15] described the design of a Koch-like fractal miniaturized monopole antenna for ISM-band application by optimizing the fractal geometry and the segment widths through a PSO algorithm. A PSO-based approach for the design and optimization of a triple-band fractal-eroded antenna has been described [16]. The synthesis of a miniaturized three-band planar antenna working in GSM and Wi-Fi frequency bands is described [17]. Lizzi and Massa [18] proposed a dual-band fractal monopole antenna based on a perturbed planar Sierpinski fractal shape suitable for LTE standards by means of PSO. An H-shaped fractal antenna is optimized by Weng and Hung [19] using the PSO algorithm for 2.45 GHz and 5.5 GHz WLAN applications. In bio-inspired optimization algorithms, a suitable objective function relating the variables to be optimized with the design variables is required. As the mathematical expressions are not available for fractal antennas, the use of the ANN model as an objective function is very appropriate in such cases [10, 20]. The use of ANN as an objective function of a GA for designing a rectangular microstrip antenna is described by Khuntia *et al*. [20]. The design of multiband fractal antennas using the PSO algorithm employing the ANN as an objective function is presented by Anuradha *et al*. [10].

The comparative analysis of different approaches available to solve a specific problem is important to find the best suitable algorithm for that application, and in the past, many researchers have compared the performance of different analytical and optimization algorithms for a variety of antennas. A comparison of different models to find the resonant frequencies of a rectangular microstrip antenna is proposed by Dearnley and Barel [1]. An analytical antenna model for chiral scatterers is compared with numerical and experimental data by Tretyakov *et al*. [21]. The application of GA and PSO for the phased array synthesis is compared by Boeringer and Werner [22]. The performance of optimized signal processing algorithms is analyzed for smart antenna systems by Gondal and Anees [23]. Pérez and Basterrechea [24] presented the performance of different heuristic optimization methods for radiation pattern estimation. The performance of BFO and PSO algorithms for adaptive antenna array processing is compared by Datta and Misra [25]. Panduro *et al*. [26] compared the performance of three different evolution methods for the design of scannable circular antenna arrays. However, the comparative analysis of optimization algorithms for fractal antennas has not been explored yet.

In this chapter, the applications of bio-inspired computing techniques to design fractal antennas are described. The performance comparison of different methods on the basis of different metrics is also discussed. The development of hybrids of optimization algorithms and ANN is also presented. The standard method of validation of the performance of antennas designed using simulation software is by fabricating the prototypes of antennas and then experimentally measuring the various parameters. This chapter also presents the measured results of the prototypes of proposed antennas and compares them with the simulation results. The potential applications of the fabricated antennas are also discussed.

DESIGN OF SGMF ANTENNA USING BIO-INSPIRED COMPUTING TECHNIQUES

As discussed in Chapter 4, the latest updated expression to determine the frequency of SGMF antenna for a particular side-length s is proposed by Mishra *et al*. [27]. This formula, as shown in equation (5.1), predicts the value of f_r of the SGMF antenna for the given values of s, ε_r, h and n.

$$f_r = \begin{cases} (0.15345 + 0.34\rho x)\frac{c}{H_e}(\xi^{-1})^n & for\ n = 0 \\ 0.26\frac{c}{H_e}\delta^n & for\ n > 0 \end{cases} \quad \textbf{(5.1)}$$

In equation (5.1), H_e denotes the effective height of the SGMF antenna, and it is calculated as $H_e = \frac{\sqrt{3}s_e}{2}$, s_e is the effective side-length of the SGMF antenna, and it is given by $s_e = s + \frac{h}{\sqrt{\varepsilon_r}}$, c is speed of light, δ is scale ratio, and its value is *2* for antenna under consideration, ξ is defined as equal to $1/\delta$, ρ is equal to ξ - *0.230735*, and x is defined as *0* for $n = 0$.

By putting the above values of H_e, s_e, c, δ, ξ, ρ, and x in equation (5.1), the simplified expression for calculating f_r of SGMF antenna is proposed in this thesis as equation (5.2):

$$f_r = \begin{cases} 53.157\frac{\sqrt{\varepsilon_r}}{h+s\sqrt{\varepsilon_r}}10^9 & for\ n = 0 \\ 90.067\frac{2^n\sqrt{\varepsilon_r}}{h+s\sqrt{\varepsilon_r}}10^9 & for\ n > 0 \end{cases} \quad \textbf{(5.2)}$$

CHAPTER 6

Conclusion and Future Scope

Abstract: The conclusion drawn from the research work presented in the book, with some recommendations for future work, is presented in this chapter.

Keywords: ANN ensemble, Crown fractal antenna, Hybrid soft computing algorithm, Miniaturized antenna.

CONCLUSION

The presented research describes the development of fractal antennas suitable for low-power communication. The size reduction of the antennas is considered the main design parameter for selecting various geometries.

The fractal antennas developed to are: CRF antenna having size-reduction capabilities, tapered corner CRF antenna having enhanced bandwidth features in addition to size-reduction characteristics and CCF antenna having size-reduction characteristics. All the presented antennas have been analyzed on the basis of various antenna performance parameters like S_{11}, gain, radiation pattern plots, *etc*., and acceptable performances are observed for desired applications.

The MLPNN, RBFNN and GRNN models have been developed for the estimation of various parameters of fractal antennas. The ANN model results are compared on the basis of different performance measures, and it is observed that the ANNs are very effective for fractal antenna analysis and design. The ANN ensemble models have resulted in further improved performances. The use of ANNs for fractal antennas has been found as an accurate and low-cost alternative to experimentation and lengthy simulation process. The ANN models have been developed to predict the required optimal dimensions of the fractal antenna for user-defined resonant frequencies, and to estimate other antenna parameters like S_{11}, gain, *etc*.

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The GA, PSO and BFO-based algorithms are successfully employed for optimizing the fractal antennas to achieve desired specifications. The PSO algorithm has been found to be a better choice as compared to GA and BFO for designing an SGMF antenna. However, the GA-MLPNN hybrid model has further better performance than PSO for this design. A BFO-ANN ensemble hybrid model is designed to optimize tapered CRF antenna for ISM band applications. ANN ensemble models are employed as the objective function of GA and PSO algorithms to optimize the CCF antenna geometries for desired frequencies. It has been observed that the developed bio-inspired optimizing techniques are flexible, accurate and simple methods of designing fractal antennas for user-defined objectives.

The designed antennas are fabricated and tested with the calibrated measurement set-ups. The S_{11} results are obtained using the site-analyzer and the vector network analyzers. The gain measurements are also done for two fabricated antennas. The simulated results are compared with the experimental results, and a good matching of simulated and experimental results is seen. The proposed design approach based on ANN models, ANN ensemble models, bio-inspired optimization techniques and a hybrid of ANN and optimization techniques is validated by matching measured and simulated results.

So the presented research findings have contributed to the antenna design field by (i) new fractal antenna geometries having miniaturization and multiband features, (ii) ANN models to estimate fractal antennas parameters, (iii) ANN ensemble models for fractal antennas having improved performances as compared to single ANN models (iv) bio-inspired optimization algorithm based design approaches (v) hybrid approaches to design fractal antennas for desired applications and (vi) compact flexible fractal antenna geometry to meet the growing demand of wearable antennas.

Overall, this book has contributed to the development of new antennas for wireless applications and also a new method of antenna design and analysis for enhancing accuracy and efficiency.

FUTURE SCOPE

In the presented work, the antennas are optimized for a single optimization goal. In the future, the multi-objective optimization of the fractal antennas may be explored to optimize various antenna parameters simultaneously. The multi-objective optimization is useful, especially for designing multiband antennas. The design of the array of fractal antennas may be investigated in the future as the array results in enhanced performances compared to single antennas. Recently, the MIMO technology has attracted increased interest as it can improve the data transmission capacity and decrease multipath fading. So, the design of fractal antennas suitable for MIMO systems is another potential area for future work. The new fractal geometries, especially hybrid fractal geometries, *i.e.*, the fractal geometries designed by combining two or more fractal geometries, may be explored for fractal antenna design. The fractal geometries are expected to have better performance than the conventional fractal shapes but are relatively complex. So, the benefit of these geometries may be explored if high-end computing facilities are available. The latest optimization techniques, *e.g.*, SIMBO, having improved performances, may be explored for the design and analysis of fractal antennas. It is expected that these latest optimization techniques will use less computational resources and generate better results. Also, the design of new optimization techniques more suitable for fractal antenna design can be undertaken.

GLOSSARY

ANFIS	Adaptive Network-based Fuzzy Inference System
ANN	Artificial Neural Network
APE	Absolute Percentage Error
BFO	Bacterial Foraging Optimization
CCF	Crown Circular Fractal
CPW	Co-Planar Waveguide
CR	Coefficient of Correlation
CRF	Crown Rectangular Fractal
FCC	Federal Communications Commission
FDTD	Finite-Difference Time-Domain
GA	Genetic Algorithm
GPS	Global Positioning System
GRNN	General Regression Neural Networks
IFS	Iterated Function System
IMD	Implantable Medical Devices
ISM	Industrial, Scientific, and Medical
LTE	Long-Term Evolution
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MEMS	Micro-Electro Mechanical System
MICS	Medical Implant Communication Service
MIMO	Multi Input Multi Output
MLPNN	Multi-Layer Perceptron Neural Networks
MoM	Method of Moments
PSO	Particle Swarm Optimization
RBF	Radial Basis Function
RBFNN	Radial Basis Function Neural Networks
RF	Radio-Frequency
RFID	Radio Frequency Identification
SGMF	Sierpinski Gasket Monopole Fractal
SIMBO	Swine Influenza Model-based Optimization
UWB	Ultra-Wide Band

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VHF	Very High Frequency
VSWR	Voltage Standing Wave Ratio
Wi-Fi	Wireless-Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WWAN	Wireless Wide Area Network

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