Design and Optimization of Microstrip Patch Antennas using Adaptive Neuro-Fuzzy Inference System (ANFIS)

Major Project Report

Submitted in partial fulfillment of the requirements

For the degree of

Master of Technology

in

Electronics and Communication Engineering

(Communication Engineering)

By

Ghadiya Jignesh Raghavbhai

(11MECC04)

Electronics and Communication Engineering Branch

Department of Electrical Engineering

Institute of Technology

Nirma University

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Under the Guidance of

Dr. Dhaval Pujara & **Dr. Dipak Adhyaru**

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Declaration

This is to certify that

(i) The thesis comprises my original work towards the degree of Master of Technology in Communication Engineering at Nirma University and has not been submitted elsewhere for a degree.

(ii) Due acknowledgement has been made in the text to all other material used.

Ghadiya Jignesh Raghavbhai

Certificate

This is to certify that the Project entitled **"Design and Optimization of Microstrip Patch Antennas using Adaptive Neuro-Fuzzy Inference System (ANFIS)"** submitted by **Ghadiya Jignesh Raghavbhai (11MECC04)**, towards the submission of the Project for requirements for the degree of Master of Technology in Communication of Nirma University, Ahmedabad is the record of work carried out by him under our supervision and guidance. In our opinion, the submitted work has reached a level required for being accepted for examination.

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Abstract

Over the past one decade, there is a rapid growth in the development of various applications involving wireless communication. The performance of all such wireless systems depends on the design and proper functioning of the antenna. Microstrip antennas are preferred for majority of these applications. This is because of their inherent advantages, such as small size, planner structure and ease of fabrication. However, for all modern wireless applications, the design of microstrip antenna has become challenging, as several performance parameters, such as return-loss, gain, cross-polarization, side-lobes, etc. are to be optimized simultaneously.

Conventionally, for design and analysis of microstrip antennas, methods such as, Finite Element Method (FEM), Full-wave Method of Moment (MoM), Finite Difference Time Domain (FDTD), etc. are in use. However, these techniques suffer from a serious drawback of high computation time and high computational resources. As alternative to these conventional methods, recently, the use of soft computing techniques for design and analysis of Microstrip antennas has increased. The most recognized soft computing techniques are : (i)Artificial Neural Networks (ANNs), (ii)Genetic Algorithm (GA), (iii)Fuzzy Logic Models (FLM), (iv)Partial Swarm Techniques (PST), (v) Adaptive Neuro-fuzzy Inference System (ANFIS). Out of all these techniques, ANFIS are most preferred technique for design and optimization of microstrip patch antennas. It is an integration of both neural networks and fuzzy logic.

In the present dissertation report, the analysis and synthesis of rectangular, circular, equilateral triangular and elliptical microstrip patch antennas using ANFIS

is presented. ANFIS based various CAD models have been developed are presented in the report. The genfis1 and genfis2 functions have been used to form network architectures of ANFIS based CAD models. The analysis model consists of antenna geometrical parameters as inputs and resonant frequency and return loss as outputs. In order to train these ANFIS models, the training data are obtained through microstrip antenna full-wave solver. For all CAD models, the results of testing data are compared with the theoretical / simulated results and are thoroughly summarized in the report.

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Chapter 1

Introduction

1.1 Background

The microstrip antennas have special characteristics such as low profile, small size and weight, low cost, printed directly on circuit board and easy to analysis and fabricate. Due to these characteristics in high performance spacecrafts, aircrafts, missile and satellite applications, microstrip antennas are the most preferred option. For the desired performance of microstrip antennas, it becomes important to calculate all design parameters such as height of substrate, dielectric constant of the substrate, patch dimensions and the frequency on which it is to be designed. The microstrip patch antennas are one of the most useful antennas working at microwave frequencies (frequencies which are greater than 1 GHz). The microstrip antennas have found their increasing in use widely as it can be fabricated by lithographic techniques [1],[2].

Presently, hard computing techniques are available for the analysis and synthesis of microstrip patch antennas. These includes, Finite Element Method (FEM), Full-wave Method of Moment (MoM), Finite Difference Time Domain (FDTD), etc. These techniques require high computational resources and high computational time [1].

The use of various soft computing techniques has increased for design and optimization of various antennas as it requires low computational resources and low computational time. Soft computing technique differs from hard computing in that, unlike hard computing, it is tolerant of imprecision, uncertainty, approximation and on the basis of partial truth. This is the principle of soft computing techniques.

Some of Soft Computing (SC) techniques are [3]:

- Artificial Neural Networks (ANNs)
- Fuzzy System (FL)
- Adaptive Neuro-Fuzzy Inference System (ANFIS)
- Evolutionary Computation (EC)

- Machine Learning (ML)
- Probabilistic Reasoning (PR)
- Genetic Algorithm (GA)

The Hard computing techniques and Soft computing techniques are discussed below:

- **Hard computing**, i.e., conventional computing is based on analytical model and requires a lot of computation time. **Soft computing** differs from conventional (hard) computing in that, unlike hard computing, it is tolerant of imprecision, uncertainty, and approximation. In effect, the role model for soft computing is the human mind.
- **Hard computing** based on binary logic, crisp systems, numerical analysis and crisp software but **soft computing** based on fuzzy logic, neural nets and probabilistic reasoning.
- **Hard computing** has the characteristics of precision and categoricity and the soft computing, approximation and dispositionality. Although in hard computing, imprecision and uncertainty are undesirable properties, in **soft computing** the tolerance for imprecision and uncertainty is exploited to achieve tractability, lower cost, high Machine Intelligence Quotient (MIQ) and economy of communication
- **Hard computing** requires programs to be written; **soft computing** can evolve its own programs
- **Hard computing** uses two-valued logic; **soft computing** can use multivalued or fuzzy logic
- **Hard computing** is deterministic; **soft computing** incorporates stochasticity
- **Hard computing** requires exact input data; **soft computing** can deal with ambiguous and noisy data
- **Hard computing** is strictly sequential; **soft computing** allows parallel computations
- **Hard computing** produces precise answers; **soft computing** can yield approximate answers

In the last decade, the use of various soft computing techniques has increased for design and optimization of various antennas. One of the most recognized soft computing techniques is Adaptive Neuro-Fuzzy Inference Systems (ANFIS). This thesis includes ANFIS for design and optimization of microstrip patch antennas. Here, ANFIS has been successfully implemented for various antenna applications.

1.2 Literature Review

Soft computing techniques have been extensively used for design and optimization of microstrip patch antennas. Several researchers have worked on this very interesting topic and few noteworthy contributions are described as follows:

K. Guney, **N. Sarikaya** [4] have given a method based on concurrent Neuro-fuzzy system (CNFS) is presented to calculate simultaneously the resonant frequencies of the rectangular, circular, and triangular microstrip antennas (MSAs). The CNFS comprises an artificial neural network (ANN) and an adaptive-network-based fuzzy inference system (ANFIS). In a CNFS, neural network assists the fuzzy system continuously (or vice versa) to compute the resonant frequency. They have given the resonant frequency results of CNFS for the rectangular, circular, and triangular MSAs are in very good agreement with the experimental results.

Jyh-Shing, Roger, Jang [5] have given the architecture and learning procedure of the ANFIS. They have proposed that the ANFIS can construct an input-output mapping based on human knowledge by using a hybrid learning procedure. Comparisons with artificial neural networks and fuzzy modeling are listed and discussed. Here the ANFIS application to automatic control and signal processing are also suggested.

Clodoaldo Ap. M. Lima, Andre L. V. Coelho, Fernando J. Von Zuben [6] have discussed in detailed the Neuro-fuzzy networks, since they are capable of learning and providing IF-THEN fuzzy rules in linguistic or explicit form. Amongst such models, ANFIS has been recognized as a reference framework, mainly for its flexible and adaptive character. In this paper, they extend ANFIS theory by experimenting with a multi-net approach wherein two or more differently structured ANFIS instances are coupled to play together. Moreover, it promotes the automatic configuration of different ANFIS units and the a posteriori selective combination of their outputs. Experiments conducted to assess E-ANFIS generalization capability are also presented.

Abbas Ali Heidari1, Abolfaz Dadgarnia [7] have presented a method based on combining adaptive Neuro-fuzzy inference systems (ANFISs) and genetic algorithm (GA) for design and optimization of a circularly polarized microstrip antenna for L1 frequency band of GPS. In design process, trained ANFISs are used for estimating return loss and axial ratio. In optimization process, a proper objective function is defined and minimized with GA in order to obtain optimum physical parameters. They have concluded that the optimization method is much faster than conventional optimization methods. Both simulation and measurement results confirm the accuracy and efficiency of the method.

K. Guney, S. Sagiroglu and M. Erler [8] has developed a generalized method for calculating the resonant frequencies of microstrip antennas of regular geometries based on the multilayered perceptrons network. They have developed a single ANN for calculation of resonant frequency of rectangular, circular and triangular microstrip patch antennas (MSA).

To determine the resonant frequencies of all these three geometries by using a single neural model, the areas of the circular and triangular patches were equated to that of the rectangular MSA. Three learning algorithms such as backpropagation (BP), delta bar delta (DBD) and extended delta bar delta (EDBD) were used to train perceptrons.

C. A. Balanis [9] has discussed a brief introduction to neural networks and ANN model for different geometries of patch antennas. He has developed an ANN model for circular patch antenna which gives resonant frequency as a function of radius of patch, height of substrate and relative dielectric constant of substrate. He also has developed ANN model for triangular patch antenna

A. Patnaik, D. E. Anagnostou, R. K. Mishra, C. G. Christodoulou and J. C. Lyke [10] has given applications of Neural Network (NN) in wireless communication in recent years. Some of the applications listed out are microstrip antenna analysis, direction of arrival estimation, adaptive beam forming and wideband mobile antenna design. They also have given implementation of neural network whose purpose was to change from the lengthy analysis and design cycles required to develop high performance systems to very short product development times.

V. V. Thakare and P. Singhal [11] have adopted a new method of calculation of patch dimensions of a rectangular microstrip patch antennas using ANN. Error back propagation algorithm was used as a training of ANN. Training data set were generated using IE3D electromagnetic simulator. Total 245 sets of data were generated, from that 230 sets of data were used for training of ANN. Constructed ANN consist of one hidden layer with 40 neurons. The results obtained using ANNs were compared with the simulation findings.

R. Gopalakrishnan and Prof Dr. N. Gunasekaran [12] has used ANN computation for designing equilateral triangular microstrip patch antenna. For that Backpropagation multilayered-perceptron network was used. Developed ANN consists of two hidden layers with 5 and 3 neurons respectively. They have compared the results obtained using ANN with the experiment results which were in very good agreement.

1.3 Problem Statement

The prime objective of this thesis is to develop different ANFIS models for design and optimization of various microstrip patch antennas. Different microstrip patch antenna geometries have been studied in detailed and their design are carried out for L-band. For a given relative permittivity and height of substrate, patch antenna dimensions and feed location are calculated for L-band. On the basis of this data different resonant frequency and return loss are obtained by using full-wave solver antenna design software. The ANFIS models for different number of membership function are developed for each of patch geometries. All the obtained results from ANFIS models are compared with the simulation results of full-wave solver antenna design software.

For clarity, the problem undertaken is stated below:
Design and optimization of microstrip patch antennas using Adaptive Neuro-Fuzzy Inference Systems (ANFIS)

1.4 Organization of the Thesis

There are in all five chapters in this dissertation which are organized as follows:

- **Chapter 1: Introduction**
  This chapter includes the relevance of the present investigations and a brief literature surveys on the Design and optimization of microstrip patch antennas using ANFIS". The objectives of the thesis are also laid out in this chapter.

- **Chapter 2: Microstrip Patch Antennas**
  This chapter deals with the basic characteristic of microstrip patch antennas, their advantages and limitations. This chapter includes various feeding techniques for microstrip patch antenna. It also includes design methodology of different geometries of patch antenna such as rectangular, circular, equilateral triangular and elliptical.

- **Chapter 3: Soft-Computing Techniques**
  This chapter deals with the introduction to soft computing techniques. It also covers brief details of the ANNs, Fuzzy systems and ANFIS.

- **Chapter 4: Development of ANN based CAD Models**
  This chapter includes the comparison of basic microstrip patch antenna parameters such as resonant frequency and returns loss using mathematical formulas and trained ANFIS model. The ANFIS model is designed for different number of membership function. This chapter also includes simulation results of analysis and synthesis model of ANFIS for all four geometries of microstrip patch antennas. The results of testing data are in close agreement with that of the theoretical / simulation results.

- **Chapter 5: Conclusion and Future Work**
  This chapter comments on the results of the simulations and concludes with the further work on this project.

Chapter 2

Microstrip Patch Antennas

This chapter consists of brief introduction to the basic concepts of patch antenna. The chapter is separated into many sections starting with advantages and limitation, basic characteristic, and feeding techniques of microstrip patch antenna. It also includes design methodologies of different geometries of microstrip patch antenna such as rectangular, circular, equilateral triangular and elliptical.

2.1 Introduction

The microstrip antennas are also known as patch antennas or printed antennas. The microstrip antennas are mostly a broadside radiator. The patch is designed in so that its pattern is maximum normal to it. End-fire radiator can also be chosen by proper mode selection. The microstrip patch antennas is one of the most useful antennas working at microwave frequencies (f >1 GHz). It consists of a metallic “patch ”on top of the dielectric substrate and below the dielectric material it has ground plane. The position of the feed has to be changed as before to control the input impedance. The patch, microstrip transmission line (or input, output pin of coaxial probe), and ground plane are made of high conductive material (typically copper). The patch may be in a variety of shapes, but rectangular and circular are the most common because ease of analysis and fabrication, attractive radiation characteristics, especially low cross polarization [13].

2.2 Advantages and Disadvantages

The principal advantages of microstrip antennas are as follows [1], [2]:

- Low profile
- Conformal to host surface
- directly on circuit board
- Easy to fabricate and analyses

- Easy to feed (coaxial cable, microstrip line, etc.)
- Easy to use in an array or incorporate with other microstrip circuit elements
- They can be made compact for use in personal mobile communication

The principal limitations of microstrip antennas are as follows [1], [2]:

- Low bandwidth
- Low efficiency
- Poor polarization purity
- Poor scan performance
- Spurious feed radiation
- Extraneous radiation from feed
- Excitation of surface wave with increasing the height of the substrate

2.3 Basic Characteristics of Microstrip Antennnas

A few important characteristic of microstrip antennas are as follows:

2.3.1 Height of Substrate

By increasing the height of the substrate, microstrip patch antennas can be used to extend the bandwidth and efficiency. So we can conclude that the bandwidth is the function of MPAs. Surface wave are introduced with increasing the height of the substrate which are not desirable, because they extract the power from the total available power for direct radiation into space. Surface wave travel within the substrate and they are scattered at the bends and at surface discontinuities. This results in the degradation of antenna pattern and polarization characteristics. Surface can be eliminated, while maintaining large bandwidths, by using cavities and stacking. The range of the height of the substrate is $0.003\lambda0 \leqslant$ h $\leqslant 0.05\lambda0$. If the height of the substrate is greater than $0.05\lambda0$, then the probe inductance becomes large enough so that the matching is difficult [1].

2.3.2 Dielectric Constant

Thick substrate with the low value of dielectric constant are desirable for good antenna performance because they provide loosely bound fields for radiation into space, and this results in better efficiency and large bandwidth at the cost of large element size. Thin substrate with high dielectric constant is desirable for microwave circuitry because they require tightly bound fields to minimize undesirable radiation and coupling, and it leads to smaller element sizes. However it has to suffer from greater losses, less efficient and relatively smaller bandwidth. Since the microstrip antennas are integrated with other microwave circuit, a compromise has to be done between good antenna performance and circuit design. The range of dielectric constant for these substrates is $2.2 \leqslant \epsilon r \leqslant 12$ [1].

2.3.3 Fringing Effects

In microstrip antennas, the dimension of the patch is finite along width and length. So, the fields at the edges of the patch undergo fringing as shown in Figure 2.1. The amount of fringing depends upon the dimension of the patch and height of the substrate. Fringing is the function of L/h and the dielectric constant r of the substrate. Since for microstrip antenna (L/h $\geq$ 1), fringing reduces so the resonant frequency of the antenna gets effected. Because of fringing effect electric fields lines go in air and then get grounded to ground plane. As can be seen, most of the electric field lines reside in the substrate and part of some line exist in air. Because of fringing effect, microstrip line looks wider electronically compared to its physical dimensions. Some of the waves travel in air and some in substrate so; effective dielectric constant ϵreff is introduced to account for fringing and wave propagation in line. Range of effective dielectric constant is $1 < \epsilon reff < \epsilon$ [1].

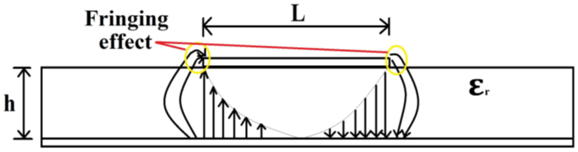


Figure 2.1: Patch Antenna having Fringing Effects[14]

2.4 Feed Techniques of Microstrip Antennas

Microstrip patch antenna has various methods of feeding techniques. As these antennas having dielectric substrate on one side and the radiating element on the other, the feed techniques or methods are being put as two different categories contacting and non-contacting.

Even though there are many new methods of feed techniques the most popular or commonly used techniques are:

- Coaxial cable or Probe feed
- Microstrip line feed
- Proximity-coupled feed
- Aperture-coupled feed

2.4.1 Coaxial Cable or Probe Feed

Microstrip antennas can be fed via a probe as shown in Figure 2.2. The outer conductor of the coaxial cable is connected to the ground plane, and the centre conductor is extended up to the patch antenna. The position of the feed can be changed as before to control the input impedance. If the height of the substrate increases, then coaxial feed introduces an inductance. Increasing the probe length makes the input impedance more inductive, leading to the matching problem. In addition, the probe will also radiate which can lead to radiation in undesirable directions [13].

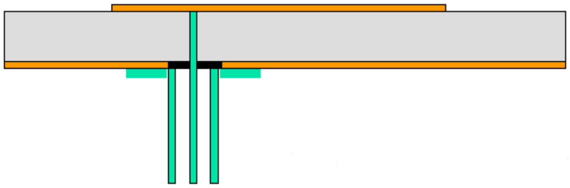


Figure 2.2: Coaxial Cable Feed of Patch Antenna[15]

The disadvantages are that the hole has to be drilled in the substrate and that the connector protrudes outside the bottom ground plane, so that it is not completely planar. Also, this feeding arrangement is not completely planar [15].

2.4.2 Transmission Line Feed

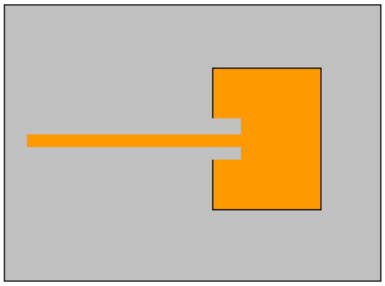


Figure 2.3: Patch Antenna with an Inset Feed[15]

It is also called as inset feed. This feed arrangement has the advantage that it can be etched on the same substrate, so it is completely planar. Moreover the construction is also simpler and easy to obtain input matching.

The drawback is significant radiation from the feed line, which leads to an increase in the cross-polar level. Also, in the millimeter-wave range, the size of the feed line is comparable to the patch size, leading to the increasing in undesired radiation [1].

2.4.3 Proximity Coupled Feed

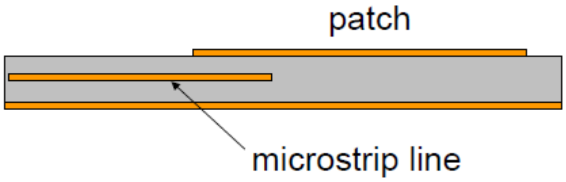


Figure 2.4: Patch Antenna with a Proximity-Coupled Feed[15]

The electromagnetic coupling is also known as proximity coupling. The feed line is placed between the patch and the ground plane, which is separated by two dielectric substrates. A high dielectric constant material is used for the bottom substrate, and thick low dielectric constant material for the top substrate. Microstrip line feed is placed in between two dielectric substrates. The feed above can be changed such that they do not directly touch the antenna. The length of feeding stub and the width-to-line ratio of the patch can be used to control the match. Width of feeding stub may drift frequencies of modes and it also defines amount of return loss [1], [13].

The advantages of this feed configuration result in the elimination of spurious feed-network radiation. Also, it includes the increase in the bandwidth due to the increase in the overall substrate thickness of the MSA. The disadvantages are that the two layers need to be aligned properly for the input matching. Also the overall thickness of the antenna increases [2].

2.4.4 Aperture Couple Feed

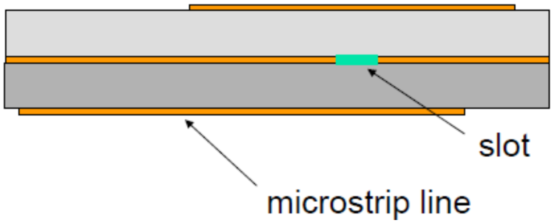


Figure 2.5: Patch Antenna with an Aperture-Coupled Feed[15]

The basic diagram of aperture coupled feed is shown in Figure 2.5. This feeding mechanism is the most difficult of all four to fabricate and it also has narrow bandwidth. It is somewhat easier to model and has moderate spurious radiation. The aperture coupled feeding method consists of two dielectric substrates separated by a ground plane. The upper substrate is made up of a lower permittivity to produce loosely bound fringing fields, yielding better radiation and the lower substrate can be independently made with a high value of permittivity for tightly coupled fields that don't produce spurious radiation. On the bottom side of the lower substrate there is microstrip feed line whose energy is coupled to the patch through a slot on the ground plane separating the two substrates [1].

The coupling aperture is usually centered under the patch, leading to lower cross-polarization due to symmetry of the configuration. The slot aperture can be either resonant or non-resonant. The resonant slot provides another resonance in addition to the patch resonance thereby increasing the BW at the expense of an increase in back radiation. As a result, a non-resonant aperture is normally used. Similar to the electromagnetic coupling method, the substrate parameters of the two layers can be chosen separately for optimum antenna performance [15].

The disadvantage of this method is increased difficulty in fabrication as it requires a multilayer fabrication.

2.5 Designing Methods of Microstrip Antennas

This section includes design procedure required for all for geometries of microstrip patch antennas such as rectangular, circular, equilateral triangular and elliptical.

2.5.1 Rectangular Patch Antennas

Rectangular microstrip patch antenna (RMA) is most widely used configuration. It is very easy to analyze using both the transmission-line and cavity models, which are very accurate for thin substrates. Rectangular patch with width (W) and length (L) is printed on a substrate with a thickness (h) and having dielectric constant (ϵr) as shown in Figure 2.6.

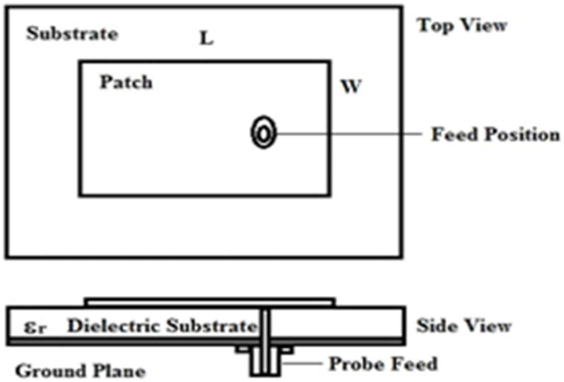


Figure 2.6: Rectangular Patch Antenna[14]

The design steps for RMA are as follows:

- **Step 1: Calculation of the Width (W):** The width of the rectangular microstrip patch is given by equation as:

$$W = \frac{1}{2f_r\sqrt{\mu_0\epsilon_0}}\sqrt{\frac{2}{\epsilon_r+1}} = \frac{\upsilon_0}{2f_r}\sqrt{\frac{2}{\epsilon_r+1}} \tag{2.1}$$

- **Step 2: Calculation of Effective dielectric constant (ϵreff):** For low frequencies the effective dielectric constant (ϵreff) is normally constant. Because of fringing effect, at high frequencies effective dielectric constant reduces as compare to dielectric constant (ϵr) of substrate. Equation gives the effective dielectric constant as:

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left[1 + 12\frac{h}{w}\right]^{-1/2} \tag{2.2}$$

- **Step 3: Calculation of the Effective length (Leff):** Equation gives the effective length as:

$$L_{eff} = \lambda/\left(2 * \sqrt{\epsilon_{reff}}\right) \tag{2.3}$$

- **Step 4: Calculation of the length extension ($\triangle$L):** Equation gives the length extension as:

$$\frac{\triangle L}{h} = 0.412\frac{(\epsilon_{reff} + 0.3)\left(\dfrac{w}{h} + 0.264\right)}{(\epsilon_{reff} - 0.258)\left(\dfrac{w}{h} + 0.8\right)} \tag{2.4}$$

- **Step 5: Calculation of actual length of patch (L):** The actual length is obtained by rewriting equation as:

$$L_{eff} = L + 2\triangle L \tag{2.5}$$

- **Step 6: Calculation of the ground plane dimensions (Lg and Wg):** The transmission line model is applicable to infinite ground planes only. However, for practical considerations, it is essential to have a finite ground plane. It has been shown that similar results for finite and infinite ground plane can be obtained if the size of the ground plane is greater than the patch dimensions by approximately six times the substrate thickness all around the periphery. Hence, for this design, the ground plane dimensions would be given as:

$$L_g = L + (6h) \tag{2.6}$$

$$W_g = W + (6h) \tag{2.7}$$

- **Step 7: Determination of feed point location**(f_X, f_Y)**:** A coaxial probe type feed is to be used in this design. As shown in Figure 4.1, the center of the patch is taken as the origin and the feed point location is given by the co-ordinates (f_X,f_Y) from the origin. The feed point must be located at that point on the patch, where the input impedance is 50 ohms for the resonant frequency. Hence, a trial and error method is used to locate the feed point. For different locations of the feed point, the return loss (R.L) is compared and that feed point is selected where the R.L is most negative. There exists a point along the length of the patch where the R.L is minimum. Hence in this design, f_Y will be zero and only f_X will be varied to locate the optimum feed point. For the determination of feed point location almost the same procedure is to be followed for different microstrip antennas.

2.5.2 Circular Patch Antenna

Circular patch antenna is the second most popular patch geometry after rectangular patch geometry. The circular patch has a radius (a) and printed on a substrate with a thickness (h) and relative dielectric constant (ϵr) as shown in Figure 2.7. For design of circular patch antenna, radius of patch is to be found out for the corresponding frequency.

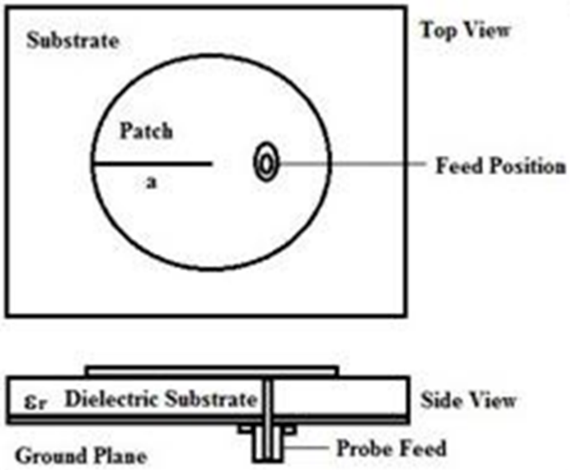


Figure 2.7: Circular Patch Antenna[14]

Because of fringing effect, electrically the patch of the microstrip antenna appears greater than its physical dimensions. So, here also in circular patch antenna radius is extended due to effect of fringing and hence correction is introduced by using an effective radius.

An actual radius is [1]:

$$a = \frac{F}{\left\{1 + \frac{2h}{\pi \epsilon r F}\left[\ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}^{\frac{1}{2}}} \tag{2.8}$$

$$F = \frac{8.791 \times 10^9}{f_r\sqrt{\epsilon_r}} \tag{2.9}$$

where, a is radius of patch, ϵr is relative permittivity of substrate and h is height of substrate and it is in cm.

An effective radius is[1]:

$$a_e = a\left[1 + \frac{2h}{\pi a \epsilon_r}\left[\ln\left(\frac{\pi a}{2h}\right) + 1.7726\right]\right]^{\frac{1}{2}} \tag{2.10}$$

The resonant frequency:

Resonant frequency (fr) of the microstrip antenna for the dominant TM110 mode, as a function of effective radius is [2]:

$$(f_r)_{110} = \frac{1.8412\upsilon_0}{2\pi a_e\sqrt{\epsilon_r}} \tag{2.11}$$

where υ_0 is the speed of the light in free space.

2.5.3 Equilateral Triangular Patch Antenna

Rectangular and circular geometries are most commonly used but other geometries having greater size reduction find wide applications in wireless communication systems, where the prime concern is compactness. The equilateral triangular patch antenna configuration is chosen here because it has the advantage of occupying less metalized area on substrate than other existing configurations. The equilateral triangular patch has a side length (S) and printed on a substrate with a thickness (h) and relative dielectric constant (ϵr) as shown in Figure 2.8.

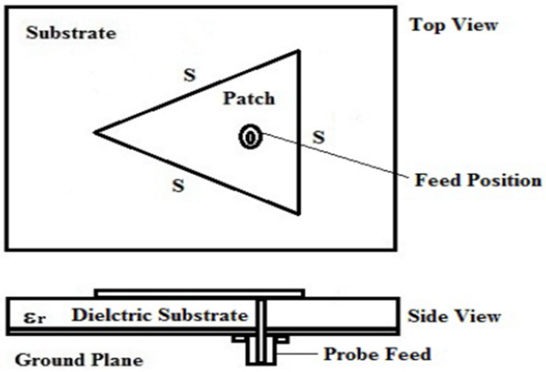


Figure 2.8: Equilateral Triangular Patch Antenna[14]

The resonant frequency is [16]:

$$f_r = \frac{cK_{mn}}{2\pi\sqrt{\epsilon_r}} = \frac{2c}{3s\sqrt{\epsilon_r}}\left(m^2 + mn + n^2\right)^{-1/2} \tag{2.12}$$

where c is the velocity of light in free space and Kmn is wave number and it is given by [12],

$$K_{mn} = \frac{4\pi}{3s}\left(m^2 + mn + n^2\right)^{-1/2} \tag{2.13}$$

The fundamental mode resonant frequency is [16]:

$$f_r = \frac{2c}{3s\sqrt{\epsilon_r}} \tag{2.14}$$

In the above relation, effects of fringing fields are not considered.

2.5.4 Elliptical Patch Antenna

Elliptical patch antenna consists of semi major axis (a) and semi minor axis (b) as antenna dimensions as shown in Figure 2.9. The feed position is located along the 45 degree line between the major and minor axis of the elliptical patch. The radiated fields cause two modes that are perpendicular to each other and have equal amplitude but are 90 degree out of phase. An elliptical patch antenna with optimum dimensions acts as a circular polarized wave radiator.

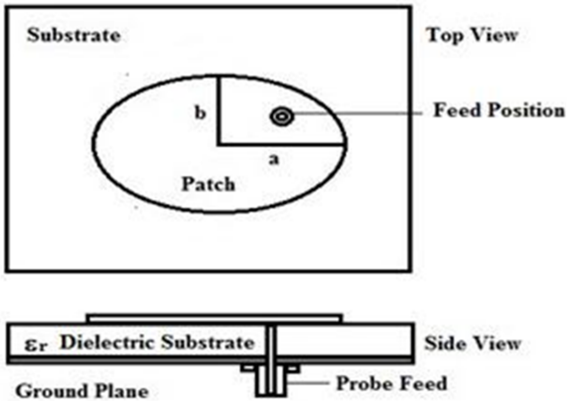


Figure 2.9: Elliptical Patch Antenna[14]

To solve elliptical geometries, elliptical coordinate system is used. The expressions of electric and magnetic field components in an elliptical patch can be obtained by solving the wave equation. The solution of the wave equation in an elliptical coordinate system includes even and odd Mathieu functions for both TE and TM type of modes. Thus, in an elliptical patch, four types of electromagnetic modes exist, namely, even (cos type) TE modes represented by TE_{cmn}, odd (sine type) TE modes represented by TE_{smn}, even (cos type) TM modes represented by TM_{cmn} and odd (sine type) TM modes represented by TM_{smn}. The empirical formulas for calculation of dual resonance frequency of elliptical patch antenna using approximated Mathieu function are listed below

$$a_{eff} = a + \left[1 + \frac{2h}{\pi a \epsilon_r}\left[\ln\left(\frac{a}{2h}\right) + (1.41\epsilon_r + 1.77) + \frac{h}{a}(0.268\epsilon_r + 1.65)\right]\right]^{-1/2} \tag{2.15}$$

Even mode resonance frequency is [17]:

$$f_{11}^{e} = \frac{15}{\pi e a_{eff}}\left(\frac{q_{11}^{e}}{\epsilon_r}\right)^{1/2} \tag{2.16}$$

Where, e is eccentricity and $q^0{}_{11}$ is approximated Mathieu function of the dominant mode $T^0{}_{11}$ mode and it is given by [16],

$$q_{11}^{e} = -0.0049_e + 3.7888e^2 - 0.7278e^3 + 2.314e^4 \tag{2.17}$$

Odd mode resonance frequency is [17]:

$$f_{11}^{0} = \frac{15}{\pi e a_{eff}} \left(\frac{q_{11}^{0}}{\epsilon_r} \right)^{1/2} \tag{2.18}$$

Where, $q^o{}_{11}$ is approximated Mathieu function of the dominant mode $TM^o{}_{11}$ mode and it is given by [16],

$$q_{11}^{0} = -0.0063e + 3.8316e^2 - 1.1351e^3 + 5.2229e^4 \tag{2.19}$$

2.6 Summary

Microstrip patch antennas are most preferred antenna due to its small size and so many advantages. Thus, basics of microstrip patch antenna have been discussed in this chapter. Moreover, feeding techniques for such antennas have also been discussed. Microstrip antenna consists of different patch geometries such as rectangular, circular, triangular and elliptical. For all these geometries, design methodologies also have been discussed.

Chapter 3

Soft Computing Techniques

This chapter covers introduction to Soft Computing techniques. Artificial Neural Networks, Fuzzy System and Adaptive Neuro-Fuzzy Inference Systems techniques are discussed at a length.

3.1 Introduction

The principal constituent methodologies in Soft Computing (SC) are complementary rather than competitive. Soft computing may be viewed as a foundation component of artificial intelligence. In many cases a problem can be solved most effectively by using FL, ANNs, GA and PR in combination rather than competitive. A good example of a particular effective combination is Adaptive Neuro Fuzzy Inference Systems. Such a system is widely used in consumer products such as air conditioners, washing machine, photocopiers etc. [3].

Goal of Soft Computing:

Soft Computing is a new field to develop new generation of Artificial Intelligence, known as Computational Intelligence. The main goal of Soft Computing is to develop intelligent machines that provide solutions to real world problems, which are not modeled or too difficult to model mathematically. Soft Computing (SC) is a field that includes following Soft Computing Techniques [3]:

- Neural Networks (NNs): NN is the term used to refer to a network or circuit of biological neurons. The modern usage of the term often refers to artificial neural networks, which are composed of artificial neurons or nodes.

- Fuzzy Logic System (FLS): FLS logic is widely used in machine control. FLS has the advantage that the solution to the problem can be cast in terms that human operators can understand, so that their experience can be used in the design of the controller.

- Evolutionary Computation (EC): EC is a subfield of artificial intelligence that involves combinatorial optimization problems. Evolutionary computation uses iterative progress.

- Machine Learning (ML): ML is a branch of artificial intelligence which is a scientific discipline concerned with the design and development of algorithms that allow computers to evolve behaviors based on empirical data, such as from sensor data or databases.
- Probabilistic Reasoning (PR): The aim of a probabilistic logic is to combine the capacity of probability theory to handle uncertainty with the capacity of deductive logic to exploit structure.
- Adaptive Neuro based Fuzzy Inference System (ANFIS): It is an integration of both neural networks and fuzzy systems. It can adapt to changes in the data because of their adaptive nature due to neural network and decides the if-then rules of the fuzzy systems by itself.

3.2 Artificial Neural Networks(ANNs)

The artificial neural networks are explained below in detailed:

3.2.1 Neural Computing

Artificial Neural Networks (ANNs) is an important processing paradigm that is inspired from the biological nervous system, such as brain. It is composed highly inter connected processing elements called as neurons. Artificial Neural Networks (ANNs), like people learn from example. It tries to simulate its learning process. An ANN is configured for a specific application, such as pattern recognition or data classification, through a learning process. Learning in biological systems involves adjustments to the synaptic connections that exist between the neurons. This is also true for ANNs [9].

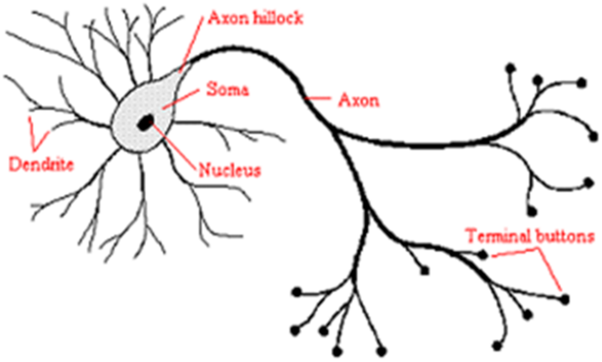


Figure 3.1: Schmetic Biological Neurons [3]

3.2.2 Advantages and Disadvantages

The principal advantages of ANNs are as follows:

- Model-free design

- Inherent parallelism
- Portable
- Fault tolerance
- Adaptive nature: It can adapt to changes in data and learn the characteristics of the input signals.
- Parallel nature: ANNs can perform the computation at high speed.
- Non-linear nature: It can accept the non-linear input and they can perform signal processing, data classification, and analysis and optimization of antenna.
- Self organization: It can create its own organization or the representation of the information it receive during learning time.
- Real time operation: It can be trained off-line and then implemented in hardware and embedded on any device.
- Faster convergence rate
- When no analytical tool exists
- It has a remarkable ability to derive meanings from the complicated or imprecise data.
- It detects the outputs that are too complex to be noticed by either humans or other computing techniques.

The principal limitations of microstrip antennas are as follows:

- Not exact
- Large complexity

3.2.3 ANNs Architecture

The basic architecture consists of three types of neuron layers: input, hidden, and output. ANN structure has two basic components, (1) the processing elements and (2) the interconnection between them. The processing elements are called neurons and the connections between the neurons are known as links or synapses, as shown in figure 3.2. Every link has the corresponding weight associated with it. Each neuron receives stimulus from other neurons connected to it, process the information and produce an output. Neurons that receive the stimuli or input from external environment are known as input neurons, while neurons whose outputs are given to the external environment are known as output neurons. Neurons that receive the stimuli or input from the other neurons and whose outputs are stimuli for other neurons in the networks are known as hidden neurons [9].

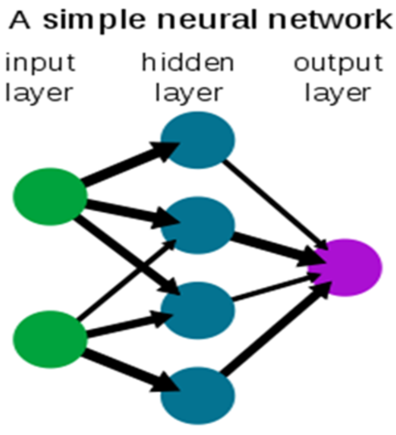


Figure 3.2: Neural Network Architecture[18]

3.2.4 ANNs versus Conventional Modeling

- **Digital Computers**
  - Deductive Reasoning. We apply known rules to input data to produce output.
  - Computation is centralized, synchronous, and serial.
  - Memory is packeted, literally stored, and location addressable.
  - Not fault tolerant. One transistor goes and it no longer works.
  - Exact.
  - Static connectivity.
  - Applicable if well defined rules with precise input data.
- **Neural Networks**
  - Inductive Reasoning. Given input and output data (training examples), we construct the rules.
  - Computation is collective, asynchronous, and parallel.
  - Memory is distributed, internalized, short term and content addressable.
  - Fault tolerant, redundancy, and sharing of responsibilities.
  - Inexact.
  - Dynamic connectivity.
  - Applicable if rules are unknown or complicated, or if data are noisy or partial.

3.2.5 Network Size and Layer

The number of hidden neurons depends on the degree of non-linearity of function and dimensionality of inputs and outputs. Highly non linear component needs more neurons and smoother needs fewer neurons. However, we do not specify the size of the networks. User can employ either experience or a trial and error process to judge the number of hidden neurons. Generally, one or two hidden layer is commonly used for antenna applications. But there is currently no theoretical reason to use neural networks more than two hidden layer. With no hidden layer is capable of representing linear separable functions or decisions [9].

Thumb rule for hidden neurons are::

- The number of hidden neurons should be 2/3 the size of the input layer, plus the size of the output layer.
- The number of hidden neurons should be less than twice the size of the input layer.
- For a three layer network with n input and m output neurons, the hidden layer would have (n x m) neurons.

For example: Character recognition
Number of input neurons is equal to the number of pixel that will be used to represent a given character. Let say, for 5 7 grid, the number of input neurons is equal to 35. Number output neurons is equal to the no of character that has been trained to recognize. Let 26 characters to be recognized. Therefore the total number of output neurons is 26. To determine the number of neurons to use in your output layer, you must first consider the intended use of the neural network. If the neural network is to be used to classify items into groups, then it is often preferable to have one output neuron for each group that input items are to be assigned into. If the neural network is to perform noise reduction on a signal, then it is likely that the number of input neurons will match the number of output neurons

3.3 Fuzzy System

The fuzzy system is explained below in detailed:

3.3.1 Fuzzy Logic

Definition of fuzzy: Fuzzy means the data or the object which is not cleared, distinct, or precisely the one which is blurred. Definition of fuzzy logic: A form of knowledge representation suitable for notions that cannot be defined precisely, but which depend upon their contexts. The basic of fuzzy logic is to map an input data to an output data, and the primary mechanism for doing this is a list of if-then statements called as rules. Here the order of the rules is unimportant, and all rules are evaluated in parallel [19].

3.3.2 Fuzzy Set

Fuzzy sets are sets whose elements have degrees of membership. Fuzzy set were introduced by Zadeh in 1965 as a mean of representing and manipulating data that was not precise, but rather fuzzy. A fuzzy set is an extension of the classical set theory [20]. In classical set theory, an element either belongs or does not belong to the set. In short, a classical set is a set with a crisp boundary. For example, a classical set A of real number greater than 10 can be expressed as

$$A = \{x/x > 10\} \tag{3.1}$$

In opposite to a classical set, a fuzzy set is a set without a crisp boundary. It means a transition from “belongs to a set ”to “not belong to a set”is gradual, and this smooth transition is characterized by membership functions. This gives the fuzzy set flexibility in modeling [20].

If X is the universe of discourse and its elements are denoted by x, then a fuzzy set A in X is defined as a set of ordered pairs.

$$A = (x, \mu_A\,(x)|x \in X) \tag{3.2}$$

where μA(x) is called the membership function (or MF) of x in A. The membership function maps each element of X to a membership value between 0 and 1.

Example: Set SMALL in set X consisting of natural numbers 1 to 12. Assume: SMALL(1) = 1, SMALL(2) = 1, SMALL(3) = 0.9, SMALL(4) = 0.6, SMALL(5) = 0.4, SMALL(6) = 0.3, SMALL(7) = 0.2, SMALL(8) = 0.1, SMALL(u) = 0 for u $\geq$ 9.

Then, following the notations described in the definition above: Set SMALL = 1, 1, 2, 1, 3, 0.9, 4, 0.6, 5, 0.4, 6, 0.3, 7, 0.2, 8, 0.1, 9, 0, 10, 0, 11, 0, 12, 0

3.3.3 Fuzzy Inference System

It is the process used for formulating the mapping from a given input to an output using fuzzy logic. The process of fuzzy inference involves membership functions, logical operations, and if-then Rules. Two types of fuzzy inference systems can be implemented in the toolbox: Mamdani-type and Sugeno-type. Automatic control, data classification and decision analysis are some of the fields where Fuzzy Inference System has been implemented successfully [19].

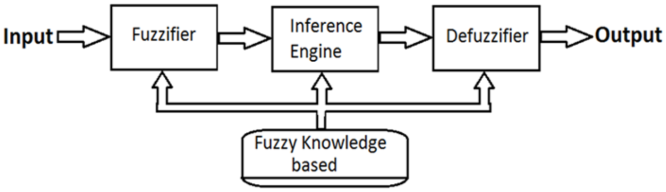


Figure 3.3: Fuzzy Inference System

- **Step1. Fuzzify Inputs**
  By using Membership function determine the input and the degree of appropriate fuzzy sets to which they belong. The input is numerical and output is always a fuzzy set. This process of converting this numerical data to the fuzzy value is called **fuzzification**.

- **Step2. Apply Fuzzy Operator**
  Once the inputs are fuzzified, the designer should know the degree to which each part of the antecedent is satisfied for each rule. If the antecedent of a given rule has more than one part, the fuzzy operator is applied to obtain one number that represents the result of the antecedent for that rule. This number is then applied to the output function.

- **Step3. Apply Implication Method**
  Designer must determine the rule's weight before applying this method. Every rule has a weight (a number between 0 and 1), which is applied to the number given by the antecedent.

- **Step4. Aggregate All Outputs**
  It is the process by which the fuzzy sets that represent the outputs of each rule are combined in order to make a decision into a single fuzzy set. The input of the aggregation process is the truncated output returned by the implication process for each rule. The output of the aggregation process is one fuzzy set for each output variable.

- **Step5. Defuzzify**
  The input for the defuzzification process is a fuzzy set (the aggregate output fuzzy set) and the output is a numerical value. A defuzzification converts the fuzzy results of the interference into a numerical output. The final desired output for each variable is generally a single number. Most popular defuzzification method is the centroid calculation, which is useful to find the center of the area under the curve.

3.3.4 Advantages and Limitations

The advantages of fuzzy logic are as follows:

- It is conceptually easy to understand.
- It is flexible.
- It is tolerant of imprecise data.
- It is able to be applied to control systems and other applications in order to improve the efficiency and simplicity of the design process

The limitations of fuzzy logic are as follows:

- Operator's experience required.
- System complexity.

3.4 Adaptive Neuro-Fuzzy Inference Systems

The aim of this chapter is to suggest a novel architecture called Adaptive-Network-based Fuzzy inference System, or simply ANFIS, which can serve as a basis for constructing a set of fuzzy if-then rules with appropriate membership functions to generate the stipulated input-output pairs.

3.4.1 Introduction

In ANFIS (Adaptive Neuro based Fuzzy Inference System), neural networks are used to adjust the membership functions of fuzzy systems. It is the model that explains past data and predicts future behavior. It can learn the characteristics of the given input/output data sets which are applied at the training time. ANFIS based models eliminate the complex and time consuming mathematical procedures for designing antennas.

3.4.2 About ANFIS

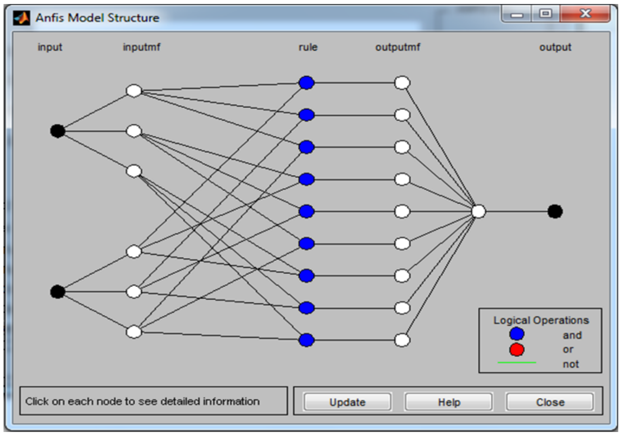
The word ANFIS derives its name from adaptive Neuro-Fuzzy inference system. Using a given input/output data set, the toolbox function ANFIS constructs a fuzzy inference system (FIS) whose membership function parameters are tuned (adjusted) using either a back propagation algorithm alone, or in combination with a least squares type of method. This allows your fuzzy systems to learn from the data they are modeling.

The fuzzy systems are most easily understandable because their behavior can be explained on the basis of the fuzzy if-then rules and the performance can be tuned by changing the rules. But fuzzy systems are restricted to the fields where the expert knowledge is required. Moreover, the data size and the number of input variable should be small. To overcome the problem of the knowledge acquisition neural networks are used. In ANFIS, it automatically extracts the fuzzy rules from the numeric data. It has the advantages of the fuzzy inference system and the learning capability of neural network. The training of the ANFIS parameters is one of the mains problems.

3.4.3 ANFIS Model Structure

The ANFIS approach learns the rules and membership functions from data. ANFIS is an adaptive network. An adaptive network is network of nodes and directional links especially the feed-forward type of neural network. Its called adaptive because the nodes have parameters which affect the output of the node and it changes the parameter by itself on the basis of the training data. These networks are learning a relationship between inputs and outputs.

The simple ANFIS model structure is shown below.



Click on each node to see detailed information

Figure 3.4: ANFIS Model Structure

The given structure has two input variables that use the 3 membership function and therefore total 9 fuzzy if-then rules are generated. At the output side 9 membership function are generated, this is because the output membership functions are always equal to the fuzzy if-then rules. Moreover it also use the logical and operation at the fuzzy if-then rule.

3.4.4 ANFIS Objectives

It integrates the best features of Fuzzy Systems and Neural Networks:

- From Fuzzy System: Representation of prior knowledge into a network topology to reduce the optimization
- From NN: Adaptation of back propagation to structured network to provide the automatic fuzzy logic

Therefore, the ANFIS provide the smoothness due to the fuzzy logic and adaptive learning due to neural network back propagation. However ANFIS has the strong computational complexity.

3.4.5 Importance of ANFIS compared to ANN & FS

Advantages of the ANFIS as compared to the neural network

- Faster convergence rate as compared to the feed-forward neural networks

- Small training data set gives the more accurate results as compared to the neural network. It can be possible by varying the number of the membership functions.

Advantages of the ANFIS as compared to the fuzzy system

- Fuzzy systems are more complex by increasing the number of input variables or/and by increasing the size of data set
- ANFIS creates its own representation or organization of the given information during the training time.
- It can generate its own fuzzy if-then rules depending on the data set given at the training time.

3.4.6 Constraints of ANFIS

ANFIS is not available for all of the fuzzy inference system options. They must have the following properties:

- It only supports Sugeno-type systems
- It has a single output, obtained using weighted average defuzzification.
- All output membership functions must be the same type and either is linear or constant.
- Have no rule sharing. The number of output membership functions must be equal to the number of rules.
- Have unity weight for each rule.

An error occurs if the FIS structure does not comply with these constraints. Moreover, ANFIS cannot make your own membership functions and defuzzification functions; you must use the ones provided [19].

3.4.7 ANFIS Funtions:

ANFIS uses GENFIS1 and GENFIS2 to create a default FIS that is used as the starting point for ANFIS training.

GENFIS1 function:

GENFIS1: Generates an initial Sugeno-type FIS for ANFIS training using a grid partition.

FIS = GENFIS1 (DATA) generates a single-output Sugeno-type fuzzy inference system (FIS) using a grid partition on the data (no clustering). FIS is used to provide initial conditions for ANFIS training. DATA is a matrix with N+ 1 column where the first N columns contain data for each FIS input, and the last column contains the output data. By default, GENFIS1 uses two 'gbellmf' type membership functions for each input. Each rule generated by GENFIS1 has one output membership function, which is of type 'linear' by default.

FIS = GENFIS1 (DATA, NUMMFS, INPUTMF, OUTPUTMF) explicitly specifies:
* NUMMFS: number of membership functions per input. A scalar value specifies the same number for all inputs and a vector value specifies the number for each input individually.

* INPUTMF: type of membership function for each input. A single string specifies the same type for all inputs; a string array specifies the type for each input individually.

* OUTPUTMF: output membership function type, either 'linear' or 'constant'

GENFIS2 function:

GENFIS2 generates a fuzzy inference system (FIS) using fuzzy subtractive clustering. GENFIS2 can be used to generate an initial FIS for ANFIS training by first applying subtractive clustering on the data. GENFIS2 accomplishes this by extracting a set of rules that models the data behavior.

FIS = GENFIS2 (XIN, XOUT, RADII) returns a Sugeno-type FIS given input data XIN and output data XOUT. The matrices XIN and XOUT have one column per FIS input and output, respectively. RADII specifies the range of influence of the cluster center for each input and output dimension, assuming the data falls within a unit hyperbox (range [0 1]).

FIS = GENFIS2 (..., XBOUNDS) also specifies a matrix XBOUNDS used to normalize the data XIN and XOUT into a unit hyperbox (range [0 1]).

FIS = GENFIS2 (..., XBOUNDS, OPTIONS) specifies options for changing the default algorithm parameters.

FIS = GENFIS2 (..., XBOUNDS, OPTIONS, USER_CENTERS) accepts user-supplied cluster centers. USER_CENTERS has size J-by-N where J is the number of clusters and N is the total number of inputs and outputs.

OPTIONS (1): The squash factor is used to multiply the RADII values to determine the neighborhood of a cluster center within which the existences of other cluster centers are discouraged.

OPTIONS (2): The accept ratio, sets the potential, as a fraction of the potential of the first cluster center, above which another data point will be accepted as a cluster center.

OPTIONS (3): The reject ratio sets the potential, as a fraction of the potential of the first cluster center, below which a data point will be rejected as a cluster center.

OPTIONS (4): Displays progress information unless it is set to zero.

The default values for the OPTIONS vector are [1.25 0.5 0.15 0].

3.5 Applications of Soft-Computing

The two main advantages of Soft Computing techniques are:

- First, in solving nonlinear problems, where mathematical models are not available, or not possible.
- Second, introducing the human knowledge such as cognition, recognition, understanding, learning, and others into the fields of computing.

The relevance of soft computing for pattern recognition and image processing is already established during the last few years. The subject has recently gained importance because of its potential applications in problems like:

- Remotely Sensed Data Analysis,
- Data Mining, Web Mining,
- Global Positioning Systems,
- Medical Imaging,
- Forensic Applications,
- Optical Character Recognition,
- Signature Verification,
- Multimedia,
- Target Recognition,
- Face Recognition and
- Man Machine Communication

3.6 Summary

For design of microstrip patch antennas, numbers of soft computing techniques are used. One of the most recognized soft computing techniques is Adaptive Neuro-Fuzzy Inference System (ANFIS). Basics of ANNs, Fuzzy Logic and ANFIS have been discussed in this chapter. To develop an ANFIS model, training is the most important parameter to be considered.

Chapter 4

Development of ANFIS Based CAD Model

4.1 Introduction

The primary objective of this chapter is to represent various simulation results. ANFIS based models are developed for the design of various microstrip patch antennas. To develop an ANFIS based model, the most important requirement is to generate proper data set used for training purpose. For the better operation of ANFIS, it needs to be trained properly by using proper number of membership function.

The Full-wave solver antenna design software is used for generation of training data set for the design of ANFIS model. This chapter includes results obtained from ANFIS are compared with results obtained from full-wave solver antenna design software.

4.2 ANFIS Models for Analysis of Microstrip Patch Antennas

This section includes ANFIS based models for analysis of the different geometries of microstrip patch antenna such as rectangular, circular, equilateral triangular and elliptical for L band of operation. ANFIS based model is built and trained using data which was generated by full-wave solver antenna design software. Results obtained from both full-wave antenna design software and ANFIS, are compared and it is found to be satisfactory for resonant frequency and not too much satisfactory for return loss.

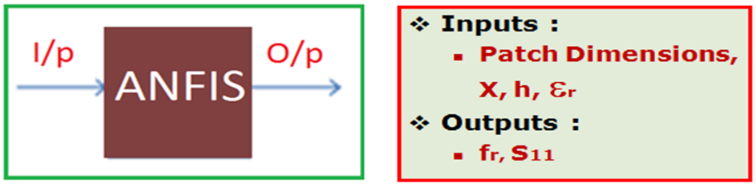


Figure 4.1: ANFIS based model

The steps for developing ANFIS based model are:

- Generation of training data set: To develop ANFIS based model, sufficient data set are required and these data set are generated using full-wave solver antenna design software.
- Training: After generating proper data set for training, ANFIS based model is constructed. Constructed ANFIS is trained using training data set.
- Testing data set: After training ANFIS, testing is required for better operation of developed ANFIS. Testing data sets are also obtained from full-wave solver antenna design software.

4.2.1 Analysis of RMA and Results

In the analysis model, resonant frequency (f_r) and return loss (RL) are obtained as a function of antenna dimensions (W, L), height of substrate (h), relative permittivity (ε_r) and feed location (a). To develop an ANFIS based model for analysis, data set are generated using full-wave solver antenna design software. Here, rectangular patch antenna is developed for h = 1.524 mm and $\varepsilon_r = 4.4$. Width of patch is varied between 34 to 66 mm, length of patch is varied between 34 to 70 mm and feed location, along x-axis is varied between 7 to 19 mm.

For testing purpose, the data other than that used in training are used. Table 4.1, 4.2, 4.3 and 4.4 shows some of the results for comparison of resonant frequency and return loss of designed ANFIS by using genfis1 function and full-wave solver antenna design software. Table 4.5 and 4.6 shows some of the results for comparison of return loss of designed ANFIS by using genfis2 function and full-wave solver antenna design software, and having the value of mod are as follows: fis=genfis2(x, y, 0.1), fis=genfis2(x, y, 0.05), fis=genfis2 (x, y, [0.5 0.5 0.5 0.5 0.01]) and fis=genfis2 ([0.05 0.05 0.05 0.05 0.01], [min;max]).

Table 4.1: Comparison of resonant frequency for rectangular geometry by using 3 & 5 gbell membership function

Sr. No.	**a (mm)**	**L (mm)**	**W (mm)**	**f_r (GHz) Full-wave solver**	**f_r_3mf**	**% Error**	**f_r_5mf**	**% Error**
1	9	38	34	1.8025	1.8391	-2.03051	1.8142	-0.6491
2	11	46	34	1.5325	1.5276	0.319739	1.5367	-0.27406
3	15	34	42	1.9775	1.9869	-0.47535	1.9894	-0.60177
4	17	58	42	1.2025	1.1984	0.340956	1.2018	0.058212
5	7	42	46	1.6225	1.6168	0.35131	1.6164	0.375963
6	7	46	50	1.5125	1.4416	4.687603	1.5176	-0.33719
7	15	34	54	1.9825	1.9666	0.802018	1.9854	-0.14628
8	9	50	58	1.3725	1.4036	-2.26594	1.3838	-0.82332
9	17	38	62	1.7875	1.805	-0.97902	1.7851	0.134266
10	11	50	66	1.385	1.3598	1.819495	1.3939	-0.6426

Table 4.2: Comparison of resonant frequency for rectangular geometry by using 6 & 7 gbell membership function

Sr. No.	**a (mm)**	**L (mm)**	**W (mm)**	**f_r (GHz) Full-wave solver**	**f_r_6mf**	**% Error**	**f_r_7mf**	**% Error**
1	9	38	34	1.8025	1.7886	0.771151	1.7913	0.621359
2	13	66	38	1.0675	1.062	0.515222	1.0687	-0.11241
3	15	34	42	1.9775	1.9917	-0.71808	1.9866	-0.46018
4	17	58	42	1.2025	1.1945	0.665281	1.1938	0.723493
5	7	42	46	1.6225	1.6131	0.579353	1.63	-0.46225
6	7	46	50	1.5125	1.6165	-6.87603	1.5085	0.264463
7	15	34	54	1.9825	2.1016	-6.00757	1.9828	-0.01513
8	13	62	54	1.1225	1.0919	2.726058	1.137	-1.29176
9	9	50	58	1.3725	1.3884	-1.15847	1.3819	-0.68488
10	17	38	62	1.7875	1.8102	-1.26993	1.7928	-0.2965

Table 4.3: Comparison of return loss for rectangular geometry by using 3 & 5 gbell membership function

Sr. No.	a (mm)	L (mm)	W (mm)	RL (dB) Full-wave solver	RL_3mf	% Error	RL_ 5mf	% Error
1	15	50	38	-9.6568	-9.6095	0.48981	-9.8362	-1.85776
2	13	66	38	-21.6628	-22.3473	-3.15979	-23.3629	-7.84802
3	7	46	50	-9.0238	-8.9758	0.531927	-7.7359	14.27226
4	15	34	54	-12.7565	-11.4133	10.52953	-12.604	1.195469
5	13	62	54	-13.9399	-14.2194	-2.00504	-14.4598	-3.72958
6	9	50	58	-9.9699	-10.5658	-5.97699	-9.9795	-0.09629

Table 4.4: Comparison of return loss for rectangular geometry by using 4 & 6 gbell membership function

Sr. No.	a (mm)	L (mm)	W (mm)	RL (dB) Full-wave solver	RL_4mf	% Error	RL_ 6mf	% Error
1	7	54	34	-8.7646	-7.3877	15.70979	-9.0397	-3.13876
2	15	50	38	-9.6568	-9.3877	2.786637	-9.6923	-0.36762
3	13	66	38	-21.6628	-23.8057	-9.89207	-24.4008	-12.6392
4	9	50	58	-9.9699	-8.727	12.46652	-10.0578	-0.88165
5	17	38	62	-14.5567	-10.2456	29.61592	-13.2586	8.917543
6	11	50	66	-13.8765	-13.4799	2.858069	-13.2114	4.792995

Table 4.5: Comparison of return loss for rectangular geometry by using genfis2 function

a (mm)	L (mm)	W (mm)	fr (GHz) Full-wave solver	RL (dB) Full-wave solver	genfis2 (0.1) ANFIS	% Error	genfis2 (0.05) ANFIS	% Error
15	34	34	2	-5.9925	-5.9924	-0.00167	-5.9924	-0.00167
13	46	38	1.53	-10.4065	-10.4924	0.818688	-10.4896	0.792213
17	58	46	1.2025	-15.5938	-15.6293	0.227137	-15.878	1.789898
7	58	54	1.1925	-4.4108	-4.6989	6.131222	-4.4968	1.912471
11	70	58	1.99	-9.378	-9.6753	3.072773	-9.8102	4.405619

Table 4.6: Comparison of return loss for rectangular geometry by using genfis2 function

a (mm)	**L (mm)**	**W (mm)**	**f_r (GHz) Full-wave solver**	**R_L (dB) Full-wave solver**	**genfis2 (mod) ANFIS**	**% Error**	**genfis2 (min;max) ANFIS**	**% Error**
16	36	36	1.915	-6.4998	-3.2719	49.66153	-6.2095	4.466291
16	44	36	1.6025	-6.5617	-6.7077	-2.22503	-6.7607	-3.03275
16	52	44	1.35	-11.5551	-13.938	-20.6273	-12.0354	-4.15661
16	60	44	1.165	-18.9524	-24.121	-27.2731	-21.0135	-10.8751
16	68	52	1.0275	-18.8752	-22.638	-19.9389	-19.5353	-3.49718

4.2.2 Analysis of CMA and Results

In the analysis model, resonant frequency (f_r) and return loss (R_L) are obtained as a function of antenna dimension (r), height of substrate (h), relative permittivity (ε_r) and feed location (a). To develop an ANFIS based model for analysis, data set are generated using full-wave solver antenna design software. Here, rectangular patch antenna is developed for h = 1.524 mm and ε_r = 4.4. Radius of patch is varied between 20 t0 42 mm and feed location along x-axis is varied between 6 to 19 mm.

For testing purpose, the data other than that used in training are used. Table 4.7 and 4.8 shows some of the results for comparison of resonant frequency and return loss of designed ANFIS by using different number of membership function and full-wave solver antenna design software. Table 4.9 and 4.10 shows some of the results for comparison of return loss of designed ANFIS by using genfis2 function and full-wave solver antenna design software, and having the value of mod are as follows: fis=genfis2(x, y, 0.4), fis=genfis2(x, y, 0.1) and fis=genfis2 ([0.05 0.05 0.05 0.01], [min; max]).

Table 4.7: Comparison of resonant frequency for circular geometry by using 3, 5 & 10 gbell membership function

Sr. No.	**a (mm)**	**r (mm)**	**f_r (GHz) Full-wave solver**	**f_r_3mf ANFIS**	**% Error**	**f_r_5mf ANFIS**	**% Error**	**f_r_10mf ANFIS**	**% Error**
1	9	20.5	1.985	1.9508	1.72292	1.9713	0.69017	1.9723	0.6397
2	12	20.5	1.995	1.9615	1.67919	1.9719	1.15789	1.9723	1.1378
3	14	24.5	1.695	1.7115	-1.209	1.6906	0.2595	1.6948	0.01179
4	7	28.5	1.455	1.4262	1.979	1.4404	1.003	1.4553	-0.0206
5	19	32.5	1.28	1.3805	-7.805	1.2037	5.96	1.2764	0.281
6	14	36.5	1.135	1.0354	8.7753	1.1695	3.039	1.1304	0.4052
7	20	40.5	1.02	1.0579	-3.715	1.055	-3.431	1.0014	1.823
8	11.5	20.5	1.99	1.9604	1.487	1.9715	0.929	1.9653	1.241
9	7.5	24.5	1.675	1.6898	-0.8835	1.6769	-0.113	1.6716	0.2029
10	11.5	32.5	1.265	1.318	-4.189	1.2896	-1.944	1.252	1.027

Table 4.8: Comparison of return loss for circular geometry by using 5 & 10 gbell membership function

Sr. No.	**a (mm)**	**r (mm)**	**R_L (dB) Full-wave solver**	**R_L _5mf ANFIS**	**% Error**	**R_L_10mf ANFIS**	**% Error**
1	7	28.5	-7.1045	-7.0215	1.168	-6.8178	4.035
2	14	36.5	-12.9534	-12.8867	0.5149	-12.6517	2.329
3	9	40.5	-3.5474	-3.7191	-4.84	-3.4986	1.375
4	7.5	24.5	-12.5107	-11.9691	4.329	-13.3166	-6.441
5	19.5	24.5	-6.7254	-6.5767	2.211	-6.8896	-2.441
6	15.5	28.5	-13.0613	-13.2192	-1.208	-13.3074	-1.884

Table 4.9: Comparison of return loss for circular geometry by using genfis2 function

Sr. No.	**a (mm)**	**r (mm)**	**f_r(GHz) Full-wave solver**	**R_L (dB) Full-wave solver**	**genfis2 (0.4) ANFIS**	**% Error**	**genfis2 (0.1) ANFIS**	**% Error**
1	11.5	20	2	-4.5649	-4.8108	5.38676	-4.8795	6.89172
2	13.25	20	2	-4.1567	-4.1852	0.68564	-4.1961	0.94787
3	19.25	20	2	-3.2754	-3.1967	2.40276	-3.3143	1.18764
4	11	20.5	1.985	-9.5367	-8.4905	10.97025	-9.3472	1.987061
5	14	20.5	2	-5.7282	-6.0926	6.36151	-5.7779	0.86764
6	17.5	20.5	2	-4.5645	-4.8014	5.19005	-4.9149	7.67663
7	11.5	21	1.955	-8.7935	-8.7814	0.137602	-8.894	1.14289
8	13	21	1.955	-7.231	-8.025	10.9805	-7.3467	1.60006

Table 4.10: Comparison of return loss for circular geometry by using genfis2 function

Sr. No.	**a (mm)**	**r (mm)**	**f_r(GHz) Full-wave solver**	**R_L (dB) Full-wave solver**	**genfis2 ANFIS**	**% Error**
1	7	28.5	1.455	-7.1045	-7.0849	0.275881
2	14	36.5	1.135	-12.9534	-13.4355	-3.7218
3	9	40.5	1.015	-3.5474	-3.5276	0.558155
4	7.5	24.5	1.675	-12.5107	-12.8112	-2.40194
5	19.5	24.5	1.705	-6.7254	-6.8096	-1.25197
6	15.5	28.5	1.465	-13.0613	-13.0271	0.261842
7	12	20.5	1.995	-7.6475	-4.8558	36.50474

4.2.3 Analysis of EMA and Results

In the analysis model, resonant frequency (f_r) and return loss (R_L) are obtained as a function of antenna dimension (b), height of substrate (h), relative permittivity (ε_r) and feed location (a). To develop an ANFIS based model for analysis, data set are generated using full-wave solver antenna design software. Here, rectangular patch antenna is developed for r = 4.4. Radius of patch is varied between 20 t0 42 mm, height of substrate is taken as 0.508mm, 0.762mm & 1.524mm and feed location along x-axis is varied between 5 to 15 mm.

For testing purpose, the data other than that used in training are used. Table 4.11 and 4.12 shows some of the results for comparison of resonant frequency and return loss of designed ANFIS by using different number of membership function and full-wave solver antenna design software. Table 4.13 shows some of the results for comparison of return loss of designed ANFIS by using different number of membership function and full-wave solver antenna design software, and having the value of mod are as follows: fis=genfis2(x, y, 0.1), fis=genfis2(x, y, 0.05) and fis=genfis2 ([0.05 0.05 0.05 0.01], [min; max]).

Table 4.11: Comparison of resonant frequency for elliptical geometry by using 5 & 10 gbell membership function

Sr. No.	**a (mm)**	**b (mm)**	**h (mm)**	**fr(GHz) Full-wave solver**	**fr_5mf (dB) ANFIS**	**% Error**	**fr_10mf ANFIS**	**% Error**
1	7	34	0.508	1.2375	1.2298	0.622222	1.2232	1.155556
2	14	28	0.508	1.515	1.5131	0.125413	1.519	-0.26403
3	9	22	0.508	1.9025	1.9097	-0.37845	1.8966	0.310118
4	7.5	31	0.508	1.36	1.3635	-0.25735	1.3575	0.183824
5	19.5	40	0.508	1.055	1.0506	0.417062	1.0235	2.985782
6	15.5	35	0.762	1.19	1.1869	0.260504	1.1594	2.571429
7	12	36	0.762	1.1625	1.165	-0.21505	1.1771	-1.25591
8	13	27	0.762	1.5725	1.5729	-0.02544	1.5609	0.737679
9	7.5	33	1.524	1.2625	1.2513	0.887129	1.256	0.514851
10	11.5	23	1.524	1.8075	1.7973	0.564315	1.7724	1.941909

Table 4.12: Comparison of return loss for elliptical geometry by using 3, 5 & 10 gbell membership function

Sr. No.	**a (mm)**	**b b**	**h (mm)**	**RL(GHz) Full-wave solver**	**RL_5mf (dB) ANFIS**	**% Error**	**RL_10mf ANFIS**	**% Error**
1	5.5	28	0.508	-2.917	-2.9815	-2.19646	-3.6967	-26.7113
2	7	40	0.508	-1.468	-1.4884	-1.38823	-1.059	27.86398
3	11.5	31	0.508	-8.88	-8.8994	-0.21012	-8.3856	5.575436
4	6	28	0.762	-5.205	-4.8837	6.183365	-3.6909	29.09724
5	7.5	35	0.762	-3.478	-3.4459	0.928641	-3.4104	1.949284
6	8	33	1.524	-9.293	-9.5724	-3.0028	-4.8964	47.31281

Table 4.13: Comparison of return loss for elliptical geometry by using genfis2 function

Sr. No.	**a (mm)**	**b (mm)**	**h (mm)**	**f_r(GHz) Full-wave solver**	**R_L (dB) Full-wave solver**	**genfis2 (0.1) b**	**% Error**	**genfis2 (0.05) ANFIS**	**% Error**
1	5.5	28	0.508	1.515	-2.91742	-3.0804	5.586	-3.037	4.09885
2	7	40	0.508	1.055	-1.44565	-1.6787	16.1208	-1.41	2.466008
3	11.5	31	0.508	1.3625	-8.88074	-7.2739	18.09349	-8.7474	1.501396
4	6	28	0.762	1.515	-5.20558	-6.3943	22.8355	-5.1087	1.861115
5	7.5	35	0.762	1.19	-3.47852	-2.7828	20.00054	-3.4836	0.14594
6	8	33	1.524	1.0975	-5.80674	-5.406	6.901341	-5.6174	3.260746
7	14.5	38	0.508	1.1175	-5.40466	-6.1828	14.3975	-5.5473	-2.63913

4.2.4 Analysis of ETMA and Results

In the analysis model, resonant frequency (f_r) and return loss (R_L) are obtained as a function of antenna dimension (S), height of substrate (h), relative permittivity (ε_r) and feed location (a). To develop an ANFIS based model for analysis, data set are generated using full-wave solver antenna design software. Here, rectangular patch antenna is developed for $\varepsilon_r = 4.4$. Effective side length of patch is varied between 45 to 95 mm and feed location along x-axis is varied between -2 to 0.5 mm.

For testing purpose, the data other than that used in training are used. Table 4.14 and 4.15 shows some of the results for comparison of resonant frequency of designed ANFIS by using different number of membership function and full-wave solver antenna design software. Table 4.16 shows some of the results for comparison of return loss of designed ANFIS by using different number of membership function and full-wave solver antenna design software, and having the value of mod are as follows: fis=genfis2 ([0.05 0.05 0.05 0.01], [min; max]).

Table 4.14: Comparison of resonant frequency for equilateral triangular geometry by using 3 & 5 gbell membership function

Sr. No.	**a (mm)**	**s (mm)**	**f_r(GHz) Full-wave solver**	**f_r_3mf ANFIS**	**% Error**	**f_r_3mf ANFIS**	**% Error**
1	-0.5	49	1.8475	1.8623	-0.80108	1.8597	-0.66035
2	-1	51	1.8075	1.8058	0.094053	1.7958	0.647303
3	0.5	53	1.73	1.738	-0.46243	1.7285	0.086705
4	-1.5	58	1.635	1.6291	0.360856	1.6403	-0.32416
5	0.5	61	1.5875	1.5873	0.012598	1.5898	-0.14488
6	0	64	1.565	1.5666	-0.10224	1.5606	0.28115
7	-2	67	1.5475	1.5518	-0.27787	1.5488	-0.08401
8	-2	86	1.475	1.4795	-0.30508	1.4756	-0.04068
9	-1.5	91	1.4675	1.4691	-0.10903	1.4674	0.006814
10	-2	94	1.4625	1.4599	0.177778	1.4627	-0.01368

Table 4.15: Comparison of return loss for equilateral triangular geometry by using 3, 5 & 10 gbell membership function

Sr. No.	**a (mm)**	**s (mm)**	**RL(dB) Full-wave solver**	**RL_5mf ANFIS**	**% Error**	**RL_10mf ANFIS**	**% Error**
1	0	64	-18.4544	-20.8995	-13.2494	-19.6516	-6.48734
2	-2	67	-21.5265	-23.5511	-9.40515	-21.8473	-1.49026
3	-1.5	71	-21.8197	-23.198	-6.31677	-19.12	12.37276
4	0	76	-7.329	-7.5622	-3.18188	-7.3061	0.312457
5	-1	82	-7.5317	-8.2047	-8.93557	-7.4202	1.480409
6	-1.5	91	-5.386	-5.4627	-1.42406	-5.4123	-0.4883

Table 4.16: Comparison of return loss for equilateral triangular geometry by using genfis2 function

Sr. No.	**a (mm)**	**S (mm)**	**f_r(GHz) Full-wave solver**	**RL (dB) Full-wave solver**	**genfis2 ANFIS**	**% Error**
1	-2	67	1.5475	-21.5265	-21.8694	-1.59292
2	-1.5	71	1.525	-21.8197	-21.2431	2.64256
3	0	76	1.5025	-7.329	-7.429	-1.36444
4	-1	82	1.485	-7.5317	-7.3469	2.453629
5	-1.5	91	1.4675	-5.386	-5.2628	2.28741

4.3 Summary

This chapter includes different ANFIS based models for different microstrip patch antenna parameters. The most important part of designing of ANFIS based models is training data sets which are generated using full-wave solver antenna design software. This chapter also includes ANFIS based models for analysis and synthesis of different geometries of microstrip patch antenna such as rectangular, circular, equilateral triangular and elliptical.

Chapter 5

Conclusion and Future Work

This chapter presents the conclusions and the summary of the investigations carried out on microstrip patch antenna design using ANFIS. Section 5.1 describes the conclusions. Scopes for future research are included in section 5.2.

5.1 Conclusion

The conclusions drawn from the investigations can be briefly summarized as follows:

- As discussed in the report, different ANFIS models for different geometries of patch antennas have been developed. From the detailed investigations, it is found that, ANFIS models require proper training to generate accurate results.

- Here for RMA, ANFIS models have been trained properly, such that the percentage errors between the results generated by the full-wave solver and that of the ANFIS model are within the limit of 0.75 % by using 7 gbell membership functions for resonant frequency.

- Here for CMA, ANFIS models have been trained properly, such that the percentage errors between the results generated by the full-wave solver and that of the ANFIS model are within the limit of 1.2 % by using 10 gbell membership functions for resonant frequency.

- Here for EMA, ANFIS models have been trained properly, such that the percentage errors between the results generated by the full-wave solver and that of the ANFIS model are within the limit of 0.9 % by using 5 gbell membership functions for resonant frequency.

- Here for ETMA, ANFIS models have been trained properly, such that the percentage errors between the results generated by the full-wave solver and that of the ANFIS model are within the limit of 0.7 % by using 5 gbell membership functions for resonant frequency.

- For RMA, CMA, ETMA & EMA percentage errors are within the limit of 5 % by using genfis2 function for almost 80% of the cases.
- Designing and optimizing microstrip antenna using a trained ANFIS model is very simple and effective. Once such models are prepared, it is possible to design antenna, without commercial full-wave solver antenna design software.
- Once the ANFIS model is trained properly, for fixed known inputs and outputs, it is possible to obtained results for any inputs (other than those of used for training) and unknown outputs.

5.2 Future Work

- In the present thesis, ANFIS models are developed for analysis of rectangular, circular, elliptical and equilateral triangular microstrip patch antennas geometries for return loss, resonant frequency, co-polarization and cross-polarization designed only over L band.
- In future, ANFIS models for analysis of the rectangular, circular, elliptical and equilateral triangular geometries of microstrip patch antennas can be developed which will give minimum return loss.
- In future, ANFIS models for analysis of the different geometries of microstrip patch antennas will be developed.
- In future, ANFIS models are developed for analysis of the different microstrip patch antennas geometries for the different parameters such as gain, directivity, bandwidth etc.
- In future, ANFIS models are developed for covering more frequency bands such as S-band, C-band, X-band etc.

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