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Design of a Microstrip Patch Antenna for ISM band using Artificial Neural Networks

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Abstract: In this study, we are interested to design a microstrip patch antenna using the artificial neural networks (ANN) based on the multilayer perceptrons (MLP). The designed antennas will operate at the Industrial, Scientific and Medical (ISM) band for the frequency range recommended by the Federal Communications Commission (FCC) 2400-2483.5 MHZ. The design process is achieved in two stages. In the first one, we estimated the resonant frequency using the antenna dimensions as inputs. In the second one; we evaluated the optimal antenna dimensions using the resonant frequency predicted in the first stage. To overcome the major drawback (narrow bandwidth) of the previous designed rectangular microstrip patch antenna, we built an E-shaped microstrip patch by adding two identical slots in the patch. The obtained results, demonstrate the perfect agreement between the estimated values of the resonant frequency, the antenna dimensions and the antenna bandwidth and the desired ones in terms of the mean squared error (MSE). The antenna performances like reflection coefficient, VSWR, surface current distribution, and radiation pattern are simulated and discussed using the HFSS electromagnetic simulator, good findings are attained.

Keywords: Artificial neural network (ANN), Bandwidth improvement, ISM band, Microstrip patch antenna, Resonant frequency.

1 Introduction

The rectangular microstrip antenna plays a very important role in the field of telecommunications. Indeed, this element is a primordial tool for the operation of a communication device used by different applications like wireless, GPS, Bluetooth, LTE, mobile phone, biomedical diagnosis [1]. The microstrip antennas become popular in the modern wireless applications because of many features like small size, light weight, easy fabrication, thin profile configurations, and the ability to integrate with the other planar components [2-3]. Often microstrip antennas are referred as patch antennas because of the radiating elements are photoetched on the dielectric substrate [4].

However, microstrip antennas inherently have the drawback of narrow bandwidth and low gain [5-8]. But, there are so many techniques in the literature that lead to larger bandwidths, the most known technique is modifying the shape of the patch by introducing slots. The successful examples include E-shaped patch antennas [9], U-slot patch antennas [10], and V-slot patch antennas [11]. In [12]- [13]- [14], different geometry shapes of the patch like H-shaped, E-shaped, and U-shaped have been used to increase the antenna bandwidth.

ANN models have been recently used efficiently in the design of antennas, circuits and microwave devices due to their ability to be an efficient alternative to conventional methods such as analytical methods, or numerical modeling method to model any arbitrary nonlinear input–output relationships between different data sets giving [15]. Artificial Neural Network (ANN) is a computational model inspired by networks of biological neurons, that was developed to model nonlinear problems by employing a mathematical model and by imitating data processing technique of human brain's structure [16].

ANN models have been also used in many design of microstrip patch antenna to compute the resonant frequency, the bandwidth or to determinate the antenna dimensions of a rectangular patch antenna [17-21]. The ANN model has been used to analyze microstrip patch antenna [22]. However, the ANN model is limited to a rectangular patch antenna and the antenna bandwidth is not reported. The development of the analysis and the synthesis methods of microstrip antennas with the ANN technique has been reported in [23]. For this paper, there is a lack of some technical discussion on the impact of the design parameters that were not analyzed. According to [17], ANN has been used as a tool to study the bandwidth of a microstrip antenna. An application of ANN based on multilayer perceptrons (MLP) is used to compute the resonant frequency of E-shaped compact microstrip antennas (ECMAs) [5]. The design and implementation of single-band E-shaped microstrip patch antenna for IEEE 802.11b (2.38GHz ~ 2.455 GHz) frequency band to estimate the parameters such as reflection coefficient (S_{11}), input impedance (R_{in}), gain, and radiation pattern are presented in [24]. However, the designed antenna bandwidth is very small, approximately 40 MHZ.

In this paper, we are interested to design a microstrip patch antenna for ISM band by applying an ANN model based on MLP structure. The designed antenna can operate at the resonant frequency of 2.45 GHz for ISM band applications and other systems covering the frequency band 2400-2483.5 MHZ. Our study is divided in two parts; in the first part we built a rectangular patch antenna while, in the second part we designed an E-shaped patch antenna in order to overcome the disadvantage of the rectangular patch antenna.

2. Studied geometry

2.1 Rectangular microstrip patch antenna

The geometry of the rectangular microstrip patch antenna is illustrated in figure 1. We used a dielectric substrate FR4_EPOXY with permittivity $\varepsilon_r = 4.4$ and thickness h = 1.6 mm. The radiating patch $(L \times W)$, is composed of copper with height t = 0.07 mm. Several techniques are used to feed the patch antenna. In this part, we used the microstrip line feed technique in which the antenna is fed directly by a metal strip connected to one of the edges of the patch [4]- [27]. The feed line is excited by a Radio Frequency (RF) source.

Transmission line model represents the rectangular patch antenna by two slots of width W and height h separated by a transmission line of length L [25]. The rectangular patch is electrically extended by a length ΔL in the two sides due to fringing effect.

The extended length ΔL is given by:

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{reff} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_{reff} - 0.258)(\frac{W}{h} + 0.8)} \quad (1)$$

The effective dielectric constant is determined using the following formula:

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}[1 + 12\frac{h}{W}]^{-\frac{1}{2}} \quad (2)$$

The length of the patch would be calculated as follows:

$$L = \frac{v_0}{2f_r\sqrt{\varepsilon_{reff}}} - 2\Delta L \quad 3)$$

With v_0 is the free space velocity of the light and f_r is the resonant frequency.
Using the equation (4), we can determine the width W of the patch by:

$$W = \frac{v_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \quad 4)$$

The transmission line model is applicable to infinite ground planes only. However, for practical considerations, it is essential to have a finite ground plane [18]. Indeed, the ground plane dimensions can be determined from the formulae (5) and (6):

$$L_g = 6h + L \quad 5)$$

$$W_g = 6h + W \quad 6)$$

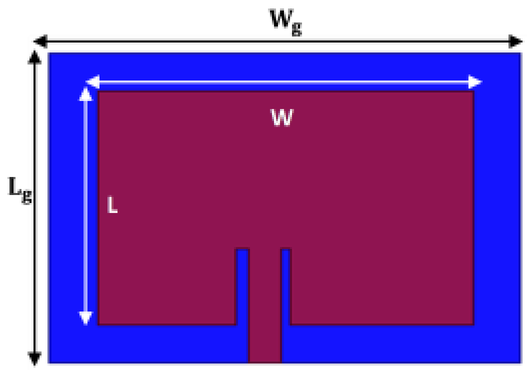

Figure. 1. Rectangular microstrip patch antenna.

2.2 E-shaped microstrip patch antenna

The E-shaped microstrip patch antenna (Fig. 2a, Fig. 2b) is developed from the rectangular patch antenna of length (L) and width (W) (Fig. 1). It consists of a radiating patch over a ground plane with two identical slots with the dimensions ($l_s \times w_s$) on a dielectric substrate with a thickness (h) and a dielectric permittivity (ε_r). The slots in the patch are used to improve the antenna bandwidth. The copper is the material used for the patch and the ground plane. FR-4 Epoxy is used as a dielectric substrate. In the simulation, the antenna was fed by a coaxial probe, in which the inner conductor of the coaxial connector is soldered to the radiating patch through the dielectric substrate while the outer conductor is connected to the ground plane [4, 25, 27].

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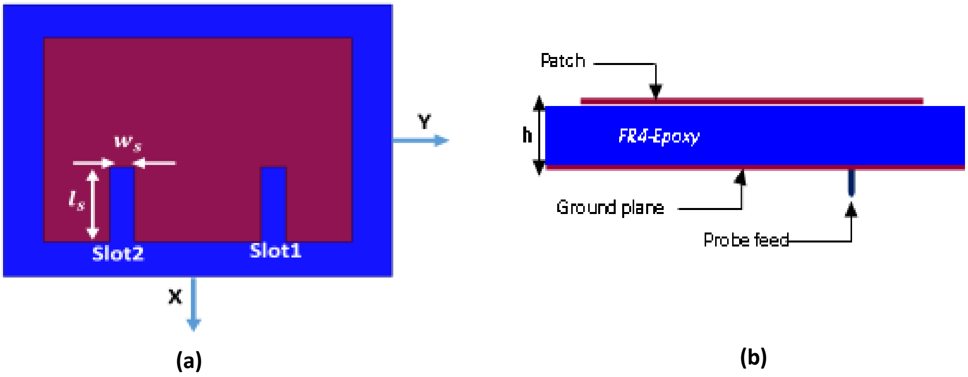

Figure. 2. E-shaped microstrip patch antenna: (a) top view, (b) side view.

3. Proposed method

Several techniques have been used to design the patch antenna, the ANN method with the MLP structure which is the most used models of artificial neural networks nowadays [26], can be a better alternative tool to analytical and numerical methods, the proposed technique can produce the desired result with high accuracy and minimal design time. The MLP architecture used for the proposed designs consists of three layers: input, hidden, and output, each layer is fully connected to the next layer. So, the information contained in the input layer is sent through one or more hidden layers to the output layer. The ANN can be trained to reach the target from a specific input using suitable training parameters until the ANN output matches the target. The weights and the biases are adjusted automatically in order to minimize the error between the desired output and the network output.

The creation of MLP network structure requires the determination of the appropriate neural architecture which typically consists of an input layer, one or more hidden layers, and an output layer. It needs afterwards to determine, the number of neurons in each layer, the activation function or the transfer function, and the suitable training algorithm.

3.1 Design of a rectangular microstrip patch antenna

The design of the antenna consists of predicting the resonant frequency and the patch dimensions, which are crucial parameters in deciding the behavior and the performance of a rectangular patch antenna [18]. The resonant frequency is determined using artificial neural network with analysis method. The structure used in this method is composed of four inputs: the length (L), the width (W), the thickness of dielectric substrate (h), and the dielectric permittivity (ε_r). The desired output is the resonant frequency (f_r) as shown in Fig. 3(a). In this case, the network consists of three layers of neurons: the input layer with 4 neurons, the hidden layer with 10 neurons, and the output layer. Then, we get the microstrip antenna dimensions through the synthesis method. For the synthesis problem, we will take the dimensions of the patch antenna (L, W) at the output side of ANN black box. The resonant frequency (f_r), the dielectric permittivity (ε_r), and the height of the dielectric substrate (h) are taken as input quantities of the ANN structure as illustrated in Fig. 3(b). So, in this case the structure consists of three layers of neurons: the input layer with 3 neurons, the hidden layer with 10 neurons, and the output layer with 2 neurons.

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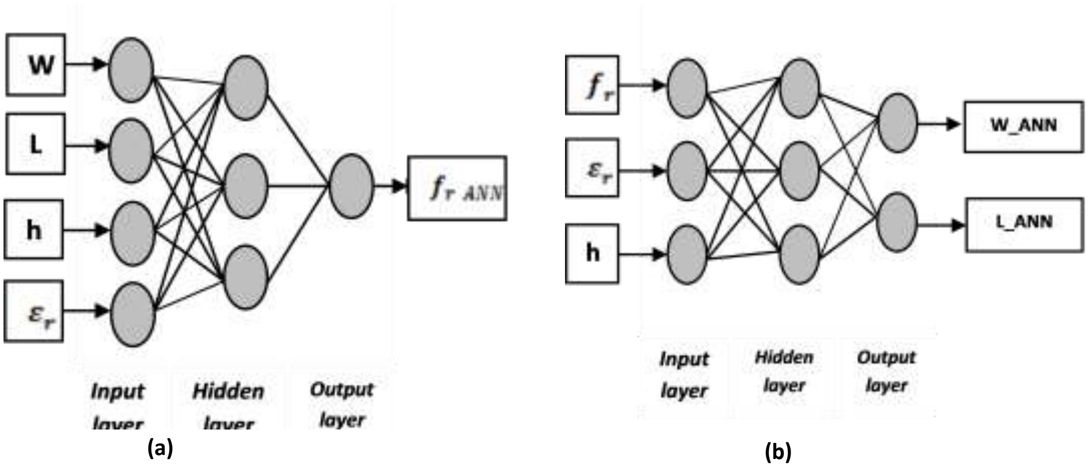

Figure. 3. MLP network structure: (a) analysis method, (b) synthesis method.

In order to improve the antenna bandwidth and to cover all the ISM band, we propose in the second part of this study to design an E-shaped microstrip patch antenna by adding two similar slots in the rectangular patch previously designed. One can improve the bandwidth of the antenna by adjusting the dimensions of the cutting slots and their positions.

3.2 Design of an E-shaped microstrip patch antenna

The used ANN model to predict the bandwidth of the E-shaped microstrip patch antenna is described in figure 4. The inputs of our network are the width of slots (w_s), the length of slots (l_s), the position (x_1, y_1) of slot1, and the position (x_2, y_2) of solt2. The patch antenna dimensions are maintained constant. The output of the network is the antenna bandwidth which can be calculated by predicting the lower and upper frequency (f_1, f_2) at -10 dB respectively.

Our goal in this part is to apply the ANN model based on multilayer perceptrons (MLP) for computing the E-shaped microstrip patch antenna bandwidth. The data are composed of 110 values input-output to train the network, while 15 input-output values are generated to test the performance of the network.

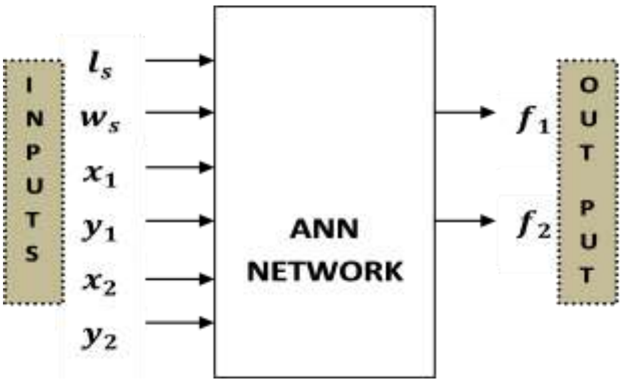

Figure. 4. MLP structure for E-shaped antenna design.

To achieve the training process network, we used the Multilayer Perceptrons Feed-Forward Back-Propagation (MLPFFBP) with different training algorithms. The determination of input, hidden, output layers, and their number of neurons is necessary to produce the upper and lower frequency hence, the E-shaped microstrip patch antenna bandwidth.

The network has been trained for various dimensions of the slots with different positions within a specific range. The neural network automatically adjusts its weights and threshold values during the training process to minimize the error between predicted and target data.

4. Results and discussions

4.1 Rectangular patch antenna

The training, validating, and testing data sets used for the analysis and the synthesis method in this work, have been obtained from the equations presented previously in paragraph 2.1. By trying different repartitions of datasets, the distribution which gives us the better results is shown in table 1.

Table 1. Data distribution

Phase	Number of Samples	Sample Percentage
Training	75	70%
Validation	16	15%
Test	16	15%

The MLP network is trained with various training algorithms to find the best suitable algorithm and to reduce the error between actual and estimated results: Resilient Backpropagation (RP), Scaled Conjugate Gradient (SCG), One Step Secant (OSS), and Levenberg Marquardt (LM). The network performance for each algorithm is evaluated by calculating the Mean Square Error MSE.

$$MSE = (\frac{1}{n})\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \quad (7)$$

Where y_i and $\hat{y}_i$ are respectively the target and the network output.

The obtained results (Table 2) show that the Levenberg Marquardt (LM) training algorithm presents the lowest MSE value, and then it seems more appropriate for our model with the structure (4-10-1) for the analysis method and the structure (3-10-2) for the synthesis method. Whereas, One Step Secant (OSS) is the worst training algorithm for this kind of problem (very high MSE).

Table 2. Variation of MSE for different training algorithm

Training Algorithm	Mean square error	
	Analysis method	Synthesis method
RP	3.0105e-04	0.1333
SCG	0.0024	0.0819
OSS	0.0027	0.3272
LM	2.0719e-07	5.0856e-05

To determine the suitable transfer function for the ANN structure, we used the same procedure adopted to choose the convenient training algorithm. As established from the table 3, the most appropriate transfer function to be used in this work in the hidden layer to train the MLP network is hyperbolic tangent sigmoid (tansig), because the tangent sigmoid transfer function can achieve a low value of (MSE).

Table 3. Variation of MSE for different training function

Transfer Function	Mean square error	
	Analysis method	Synthesis method
hardlim	0.0710	10.3106
purelin	0.0012	0.1839
satlin	9.5789e-06	0.1540
logsig	3.1366e-06	5.0856e-05
tansig	2.0719e-07	1.5981e-05

Furthermore, the different parameters identified to be used to train our ANN structures for the analysis and the synthesis methods are summarized in table 4:

Table 4. ANN network parameters

Parameter	Analysis method	Synthesis method
Number of samples	107	107
Training algorithm	LM	LM
Transfer function	Tangent Sigmoid	Tangent Sigmoid
Network structure	4-10-1	3-10-2

We present in figures (Fig. 5a, Fig. 5b) the network performance during the training, validation, and test phases of the converged training algorithm (Levenberg-Marquardt) using the MSE criterion. More MSE close to zero better is the result. It is clear from these results that the training phase is performed for analysis method in 24 iterations while in synthesis method is performed in 11 iterations.

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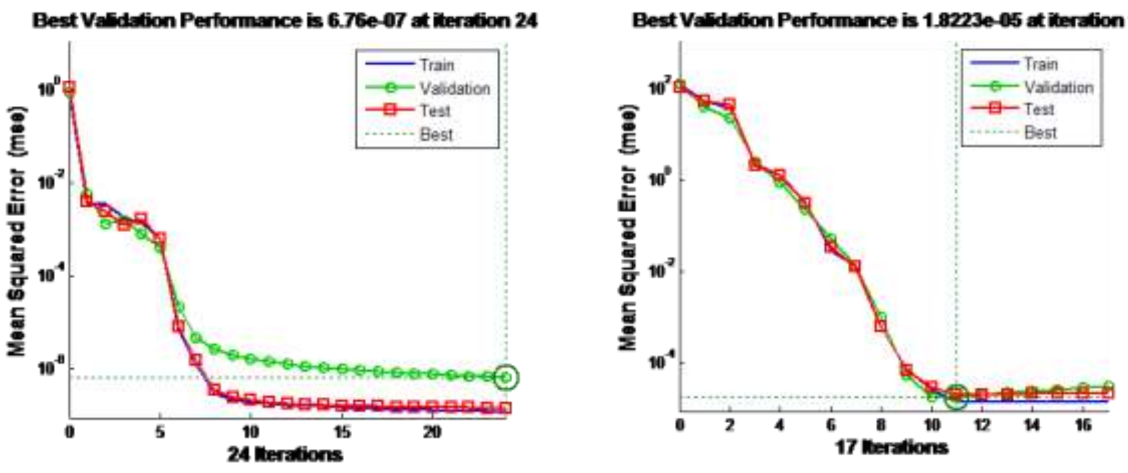

(a) (b)

Figure. 5. Mean squared error: (a) analysis method), (b) synthesis method.

To check our network structure, the testing procedure is performed by taking 12 distinct input data samples not included in the data set in the modeling process. The network resonant frequency output is then calculated and compared with the theoretical resonant frequency for the analysis design. Afterwards, we test the predicted results of the patch antenna dimensions with the calculated findings. The comparison results are presented respectively in tables 5 and 6.

Table 5. Comparison between ANN resonant frequency and calculated frequency (Analysis method)

W (mm)	L (mm)	h (mm)	ε_r	f_r_calculated (GHZ)	f_r_ANN (GHZ)
36.0	28.0	1.80	4.4	2.515	2.5161
30.0	22.0	2.00	4.4	3.160	3.1935
39.4	27.0	1.60	4.4	2.603	2.5841
34.0	25.0	1.75	4.4	2.805	2.8029
40.0	32.5	1.70	4.4	2.178	2.2249
35.0	28.0	1.80	4.4	2.517	2.5166
30.0	20.7	1.60	4.4	3.371	3.3579
37.5	28.5	1.80	4.4	2.470	2.4697
44.0	35.6	2.00	4.4	1.986	2.0024
37.5	28.7	2.00	4.4	2.447	2.4483
41.5	33.0	1.75	4.4	2.143	2.1632
30.0	21.0	1.80	4.4	3.312	3.3124

Table 6. Comparison between ANN dimensions and calculated target (Synthesis method)

f_r (GHZ)	h (mm)	ε_r	W_calculated (mm)	L_calculated (mm)	W_ANN (mm)	L_ANN (mm)
2.5161	1.80	4.4	36.281	27.981	36.2878	27.9857
3.1935	2.00	4.4	28.585	21.795	28.5901	21.7969
2.5841	1.60	4.4	35.326	27.303	35.3301	27.3065
2.8029	1.75	4.4	32.568	25.064	32.5765	25.0757

2.2249	1.70	4.4	41.029	31.769	41.0339	31.7530
2.5166	1.80	4.4	36.273	27.975	36.2806	27.9800
3.3579	1.60	4.4	27.185	20.863	27.2010	20.8935
2.4697	1.80	4.4	36.962	28.520	36.9696	28.5245
2.0024	2.00	4.4	45.588	35.259	45.4368	35.1377
2.4483	2.00	4.4	37.285	28.695	37.2911	28.6998
2.1632	1.75	4.4	42.200	32.675	42.2066	32.6569
3.3124	1.80	4.4	27.559	21.071	27.5629	21.0766

From these results, we conclude the efficiency of the proposed model as compared with the theoretical method. After verifying our ANN process, the proposed antenna with the obtained optimal dimensions is designed using HFSS simulator for a rectangular patch antenna operating at resonant frequency 2.45 GHZ, with a dielectric substrate FR4-epoxy ($\varepsilon_r = 4.4$), and a thickness h =1.6 mm. The simulated reflection coefficient S_{11} plot is illustrated in figure 6.

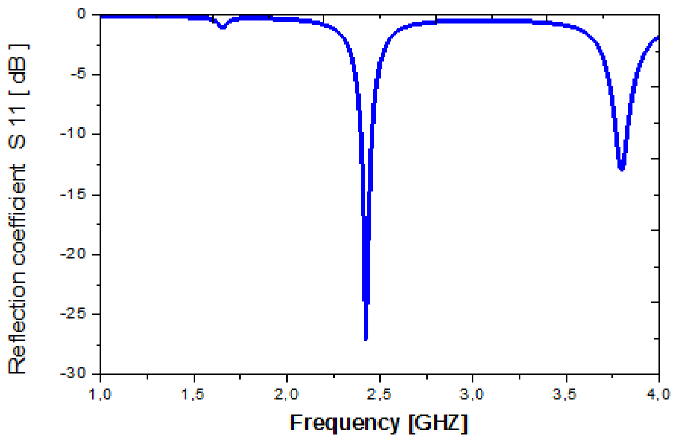

Figure. 6. Reflection coefficient vs. frequency of rectangular microstrip antenna.

The designed antenna covers the range 2.39-2.45 GHZ with a bandwidth of 60 MHZ and a good reflection coefficient ($S_{11} \leq$ -10 dB).

4.2 E-shaped patch antenna

ANN structure is not known in advance. Hence, the network model is analyzed with different: number of hidden layers, number of neurons in the hidden layer, training algorithms, and transfer functions as illustrated respectively in Fig. 7 (a), Fig. 7 (b), Fig. 7 (c), and Fig. 7 (d). To achieve a good accuracy, the ANN performance is checked using the lowest mean squared error.

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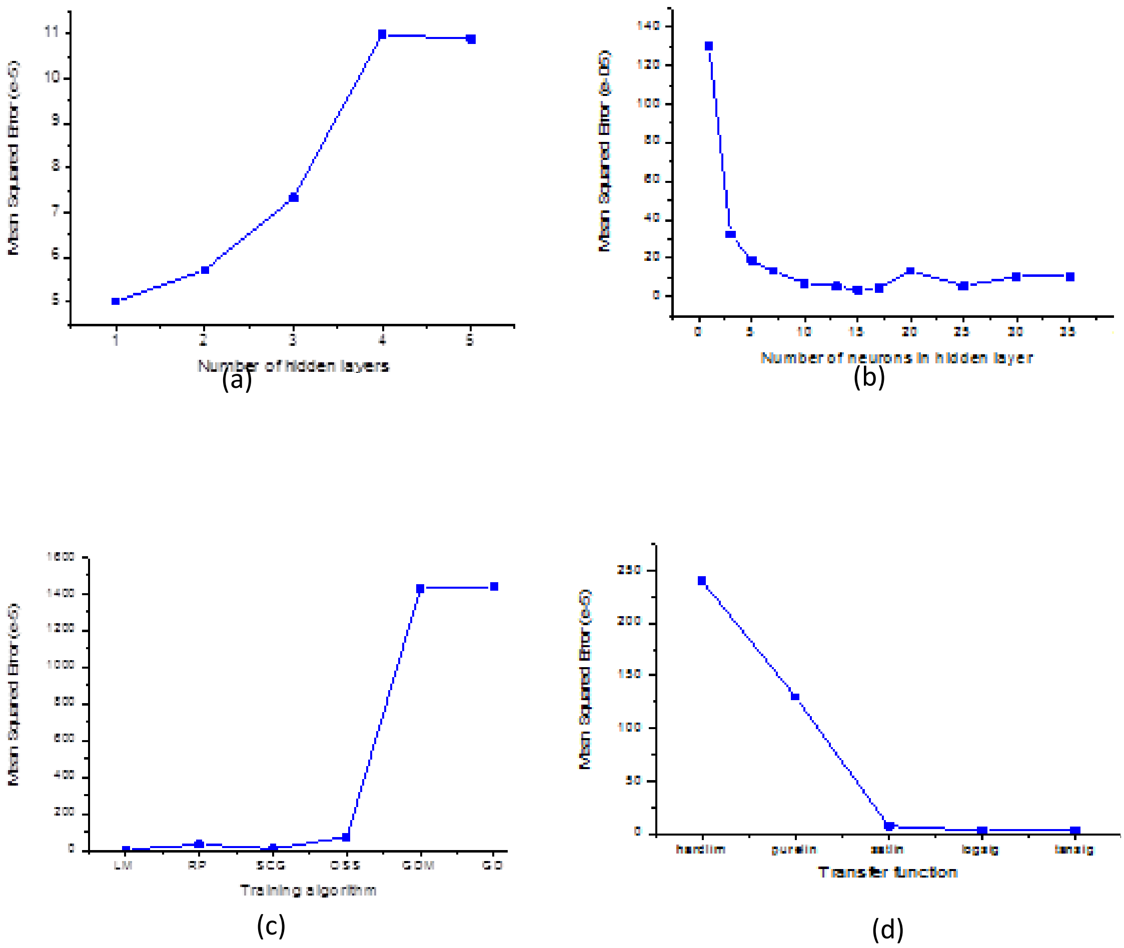

Figure. 7. Evaluation of MSE for: (a) number of hidden layers, (b) number of neurons in hidden layers, (c) training algorithm, and (d) transfer function.

After multiple training, we can conclude that the optimum network structure for the proposed problem consists of three layers of the MLP structure with: 6 neurons in the input layer, 15 neurons in the hidden layer, and 2 neurons in the output layer. The most suitable training algorithm for this structure is Levenberg Marquardt (LM). The transfer function in the hidden layer is the tangent sigmoid function, while the linear function is used in the output layer (Table 7).

Table 7. ANN network parameters

ANN parameter	Attributes
Number of samples	110
Training algorithm	LM
Transfer function (hidden layer)	Tangent Sigmoid
Transfer function (output layer)	Linear
Network structure	6-15-2

To confirm the efficiency of our developed model, we present in figure 8 and figure 9, the lower and the upper frequency at -10 dB vs antenna number simulated by HFSS and predicted by ANN. We can notice clearly that the obtained ANN results are in perfect agreement with the HFSS results.

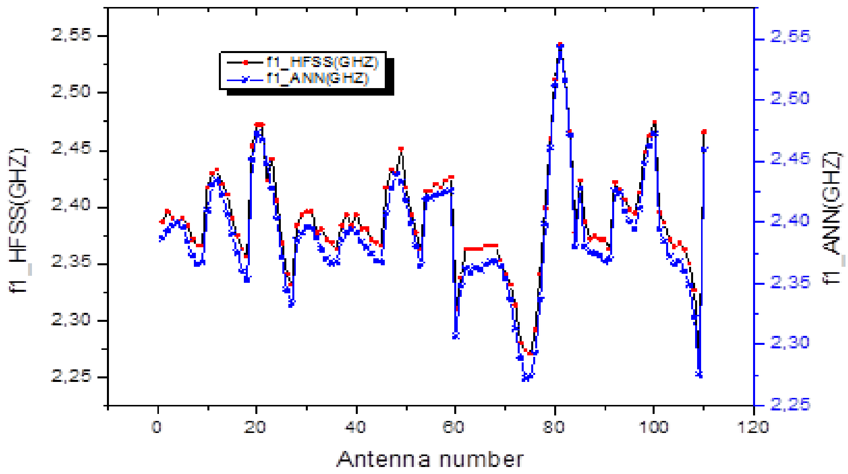

Figure. 8. Lower frequency f_1 at -10dB vs Antenna number.

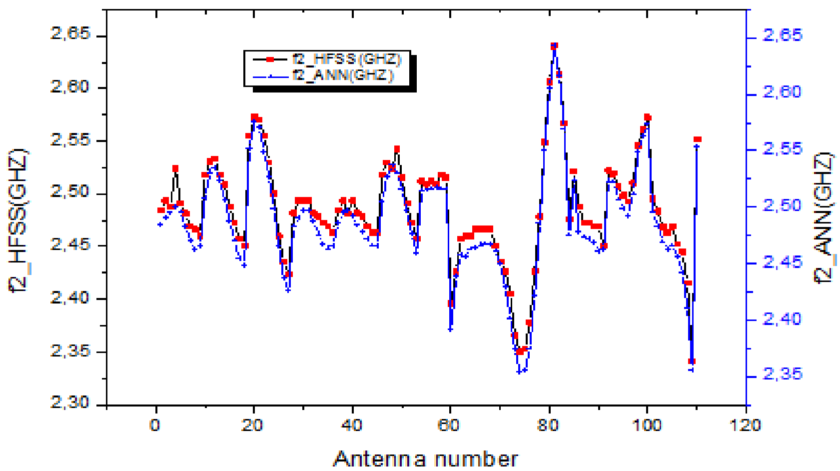

Figure. 9. Upper frequency f_2at -10dB vs Antenna number.

After training the network, we used 15 input output values to test the ANN model. By varying the dimensions of the slots and their positions, we can predict the lower and the upper frequency at -10dB hence, the bandwidth of the proposed antenna. We can notice that the frequencies (f_1, f_2) computed by the ANN network are much closer to the simulated ones by HFSS (Table 8).

The combination input which provides an important bandwidth is used to simulate the E-shaped antenna using the HFSS simulator. To further demonstrate the antenna performance, various parameters of the proposed antenna such as reflection coefficient, bandwidth, voltage standing wave ratio (VSWR), surface current distribution, and radiation pattern have been simulated and analyzed.

Table 8. Bandwidth determined by ANN compared with HFSS for testing process

l_s (mm)	w_s (mm)	(x_1, y_1) slot1 position	(x_2, y_2) slot2 position	f_1 _HFSS (GHZ)	f_2 _HFSS (GHZ)	f_1 _ANN (GHZ)	f_2 _ANN (GHZ)
5	4	(09.405 , 12)	(9.405 , -12)	2.3978	2.4985	2.3961	2.4938
17	3	(-2.595 , 15)	(-2.595 , -15)	2.3712	2.4716	2.3715	2.4694
11	7	(03.405 , 13)	(3.405 , -13)	2.4630	2.5607	2.4521	2.5486
10.5	3	(03.905 , 10)	(3.905 , -10)	2.3919	2.5281	2.3987	2.4995
2	10	(12.405 , 15)	(12.405 , -15)	2.4304	2.5311	2.4588	2.5571
8	2	(06.405 , 06)	(6.405 , -06)	2.3741	2.4748	2.3820	2.4844
13	5	(01.405 , 09)	(1.405 , -09)	2.4126	2.5074	2.3966	2.4957
19	5	(-4.595 , 09)	(-4.595 , -09)	2.3593	2.4571	2.3534	2.4481
3	6	(11.405 , 08)	(11.405 , -08)	2.4126	2.5163	2.4173	2.5177
15	7	(-0.595 , 14.5)	(-0.595 , -14.5)	2.4038	2.4956	2.4087	2.5022
22	4	(-7.595 , 13)	(-7.595 , -13)	2.3653	2.4630	2.3675	2.4656
14	8	(0.405 , 015)	(0.405 , -15)	2.4304	2.5222	2.4396	2.5320
20.605	9	(-6.2 , 14.5)	(-6.2 , -14.5)	2.2912	2.3771	2.2929	2.3773
8.605	5	(05.8 , 09.5)	(5.8 , -09.5)	2.4304	2.5311	2.4294	2.5321
14	8	(0.405 , 13.42)	(0.405 , -13.42)	2.4156	2.5074	2.4101	2.5024

S_{11} is the parameter which indicates the amount of power reflected back from the antenna, this parameter is known as the reflection coefficient. At the resonant frequency 2.43 GHZ, the reflection coefficient value of the designed antenna is about –28.00 dB (Fig.10). More the reflection coefficient is less than -10 dB, more the performance of the designed antenna is enhanced. The simulated bandwidth of the proposed antenna covers the range 2.38-2.53 GHZ, approximately 150 MHZ.

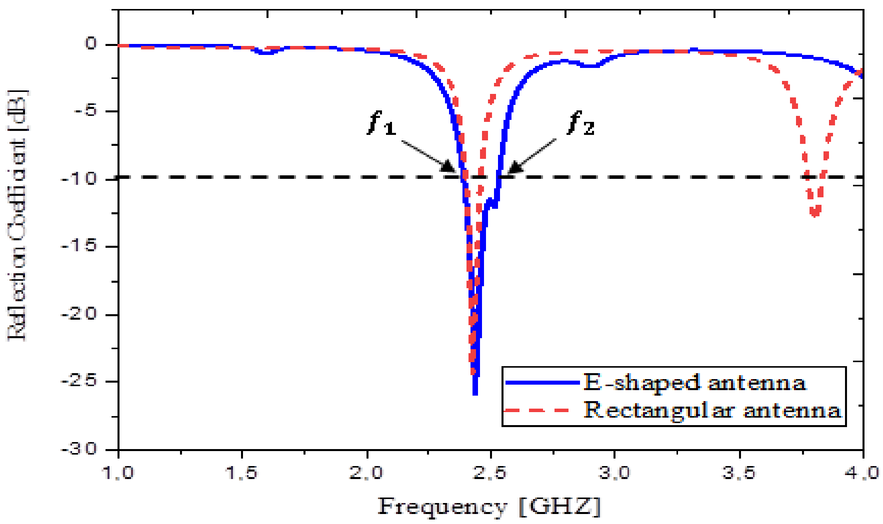

Figure. 10. Simulated reflection coefficient vs Frequency.

In order to demonstrate the contribution of the embedded symmetrical slots in the metal patch to the resonant frequency, we plotted in Figure 11 the proposed antenna's simulated surface current distribution at 2.43 GHz. From figure 11, it is clearly shown that most of the surface currents are concentrated around the slots, which provides the resonant mode 2.43 GHZ.

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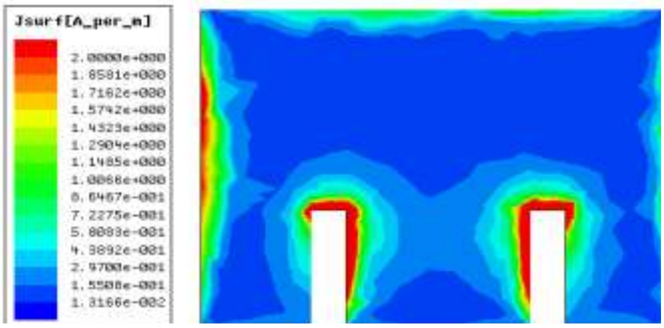

Figure. 11. Surface current distribution at 2.43GHZ.

A good antenna is defined by an acceptable value of VSWR (1 ≤ VSWR ≤ 2). The VSWR of the proposed antenna is found to be almost 1.14 at the resonant frequency 2.43 GHZ which indicates the better matching (Fig.12). The antenna exhibits a good impedance matching of 53.4 Ohms at the resonant frequency which is acceptably close to the desired value of 50 Ohms indicating minimal loss.

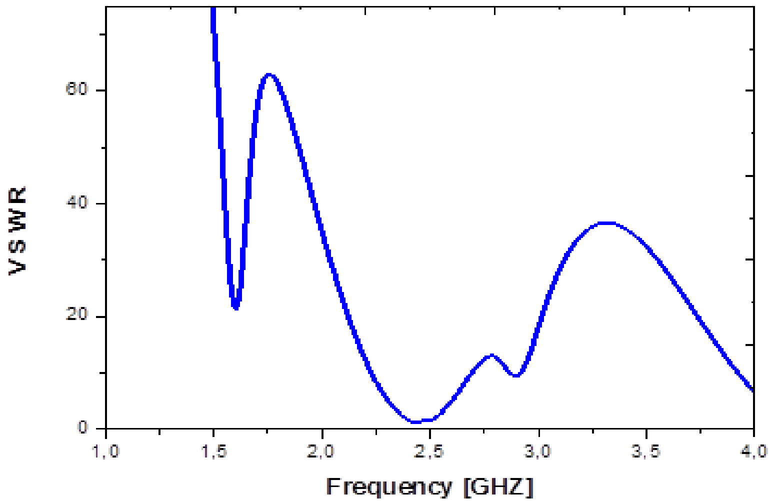

Figure. 12. Simulated VSWR vs. Frequency.

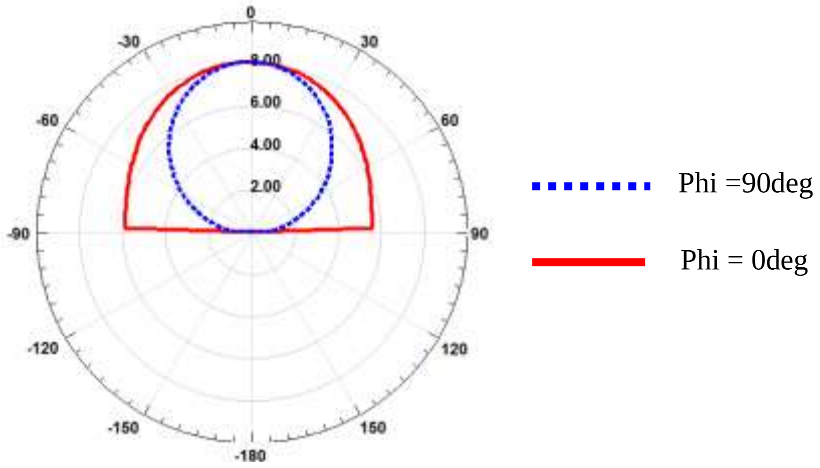

Figure. 13. E-plane and H-plane radiation patterns for the designed E-shaped antenna.

The simulated radiation pattern for H-plane and E-plane at 2.43 GHZ are plotted in Figure 13, the proposed antenna's radiation is directed in the perpendicular direction of the E-shaped patch plane and it's clearly symmetrical.

The designed E-shaped antenna shows reasonable characteristics for the fundamental parameters compared to other antennas operating at 2.45 GHZ (Table 9) namely, resonant frequency, bandwidth, reflection coefficient, and VSWR. The comparison between the proposed antenna and other researchers (Table 9), demonstrate the advantage of our antenna with a better bandwidth enhancement of 150 MHZ, centered at 2.43 GHz and will be suitable to operate in the frequency range of 2400-2483.5 MHZ.

Table 9. Compared results for antennas operating at 2.45GHZ

	Antenna type	f_r(GHZ)	BW (MHZ)	S_{11} (dB)	VSWR
Present work	Rectangular microstrip patch antenna	2.42	60	-27.48	1.26
	E-shaped microstrip patch antenna	2.43	150	-28.00	1.14
[28]	Dual band rectangular micro-strip patch antenna	2.45	90	-21.25	1.3846
[29]	Wideband microstrip patch antenna	2.45	120	-25	-----
[30]	Compact planar antenna	2.45	135	-39.68	1.03
[31]	Circular polarised (CP), microstrip (patch) antenna	2.47	70	-26.28	1.93

5. Conclusion

In this paper we designed a microstrip patch antenna using artificial neural network to operate at the resonant frequency of 2.45 GHZ for ISM band applications. The first design concerns a simple structure rectangular patch antenna, and in order to enhance the antenna bandwidth to cover the ISM band, we proposed another kind of antenna which is the E-shaped microstrip patch antenna. In terms of the mean squared error MSE, the obtained results, demonstrate the perfect agreement between the estimated values of the resonant frequency, the antenna dimensions and the antenna bandwidth and the desired ones. Both antennas present a good reflection coefficient ($S_{11} \leq$ -10dB) and are suitable for ISM band such as biomedical diagnosis applications (breast cancer detection) and other systems covering the frequency band 2400-2483.5 MHZ like, Bluetooth and WLAN IEEE 802.11b/g standards.

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