Progress In Electromagnetics Research, PIER 84, 253–277, 2008

CONCURRENT NEURO-FUZZY SYSTEMS FOR RESONANT FREQUENCY COMPUTATION OF RECTANGULAR, CIRCULAR, AND TRIANGULAR MICROSTRIP ANTENNAS

K. Guney

Department of Electrical and Electronics Engineering
Faculty of Engineering
Erciyes University
Kayseri 38039, Turkey

N. Sarikaya

Department of Aircraft Electrical and Electronics
Civil Aviation School
Erciyes University
Kayseri 38039, Turkey

Abstract—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. The resonant frequency results of CNFS for the rectangular, circular, and triangular MSAs are in very good agreement with the experimental results available in the literature.

1. INTRODUCTION

MSAs are used in a broad range of applications from communication systems to biomedical systems, primarily due to their simplicity, conformability, low manufacturing cost, light weight, low profile, reproducibility, reliability, and ease in fabrication and integration with microwave integrated circuit or monolithic microwave integrated circuit components [1–3]. Accurate determination of resonant frequency is important in the design of MSAs because of their narrow bandwidth. Several methods [1–36] have been proposed and used to calculate the resonant frequency of the rectangular, circular, and triangular MSAs. These methods have different levels of complexity and require vastly different computational efforts. The analytical methods use simplifying physical assumptions, but generally offer simple and analytical solutions that are well suited for an understanding of the physical phenomena and for antenna computer-aided design (CAD). However, these methods are not suitable for many structures, in particular, if the thickness of the substrate is not very thin. Most of the limitations of analytical methods can be overcome by using the numerical methods. The numerical methods are mathematically complex, take tremendous computational efforts, still can not make a practical antenna design feasible within a reasonable period of time, require strong background knowledge and have time-consuming numerical calculations which need very expensive software packages. So, they are not very attractive for the interactive CAD models.

The resonant frequencies of MSAs were calculated in [37] by using a neuro-fuzzy network. In [37], the number of rules and the premise parameters of fuzzy inference system (FIS) were determined by the fuzzy subtractive clustering method and then the consequent parameters of each output rule were determined by using linear least squares estimation method. The training data sets were obtained by numerical simulations using a moment-method code based on electric field integral equation approach. To validate the performances of the neuro-fuzzy network, a set of further moment-method simulations was realized and presented to the neuro-fuzzy network.

In our previous works [38–50], the methods based on genetic algorithm (GA) [38, 39], tabu search algorithm (TSA) [40, 41], ANN [42–45], and ANFIS [46–50] were used for calculating the resonant frequencies of various MSAs. It is well known that ANFIS can only produce single output. However, in [51, 52], more outputs were calculated by using multiple ANFIS. In general, in the literature, each different parameter of each different MSA was computed by using a different individual ANN [53–55] or ANFIS model [56–60]. Single neural models were proposed in [61, 62] for simultaneously calculating the resonant frequencies of the rectangular, circular, and triangular MSAs. The results of single neural models [61, 62] are not in very good agreement with the experimental results available in the literature [4, 5, 8, 12, 13, 16, 19, 22, 23, 30, 31]. For this reason, a hybrid method [63] based on a combination of ANN with ANFIS has been presented to improve the performance of single ANN models. In [63], the optimal values for the premise and consequent parameters of ANFIS were obtained by the hybrid learning (HL) algorithm [64, 65], and the ANN was trained with bayesian regularization (BR) algorithm [66]. In previous works [67–72], we successfully also used ANNs and ANFISs for computing accurately the various parameters of the transmission lines and for target tracking.

In this paper, a method based on CNFS [73, 74] is presented for computing simultaneously and accurately the resonant frequencies of the rectangular, circular, and triangular MSAs. The CNFS used in this paper comprises an ANN [75, 76] and an ANFIS [64, 65]. In the CNFS, the ANN assists the ANFIS continuously (or vice versa) to calculate the resonant frequency. The ANN is a computational system inspired by the structure, processing method, and learning ability of a biological brain. The ANFIS is a class of adaptive networks which are functionally equivalent to FISs. The ANN and ANFIS are very powerful approaches for building complex and nonlinear relationship between a set of input and output data. The high-speed real-time computation features of the ANN and ANFIS recommend their use in antenna CAD programs. The main advantage of the method proposed here is that the single CNFS model is used to simultaneously calculate the resonant frequencies of all three different types of MSAs including the rectangular, circular, and triangular MSAs.

In this paper, the next section briefly describes the resonant frequency computation of the MSAs and the CNFS. The application of the CNFS to the resonant frequency computation is given in the following section. The results are then presented and conclusion is made.

2. RESONANT FREQUENCY OF MICROSTRIP ANTENNAS (MSAs)

It is clear from the literature [1–36] that the resonant frequencies of the rectangular, circular, and triangular MSAs are determined by the substrate thickness h and relative dielectric constant ε_r, the mode numbers m and n, and the dimensions of the patch (the patch width W and the patch length L for the rectangular MSA, the patch radius a for the circular MSA, and the side length s for the triangular MSA). To compute simultaneously the resonant frequencies of the rectangular, circular, and triangular MSAs by using the CNFS model, the areas of the circular and triangular patches are equated to that of the rectangular MSA. The following formulas are then used for the equivalent dimensions of the circular and triangular patches with reference to Figure 1

$$W = \frac{\pi a}{2} \quad \text{and} \quad L = 2a \qquad \text{for the circular MSA} \tag{1}$$

$$W = \frac{s}{2} \quad \text{and} \quad L = d \qquad \text{for the triangular MSA} \tag{2}$$

where d is the height of the triangular patch. It is evident from Eqns. (1) and (2) that multiplying W by L is equal to the area of the corresponding patch.

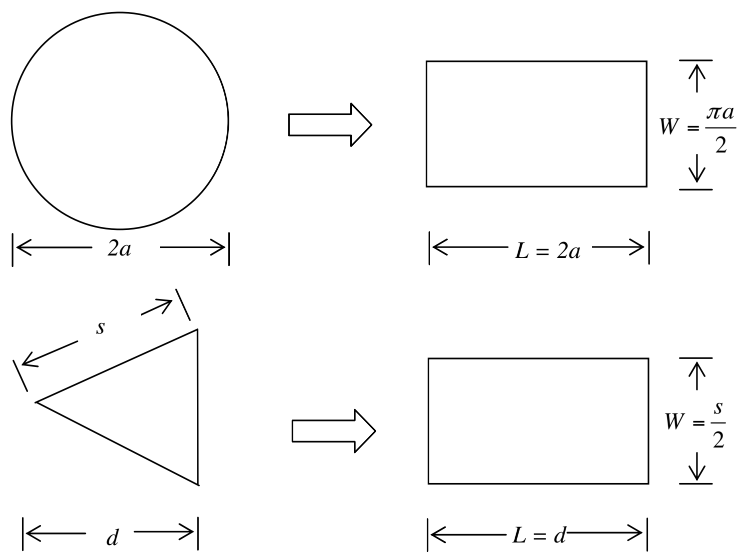


Figure 1. Diagram for equating the patch area of the circular and triangular MSAs with the rectangular MSA.

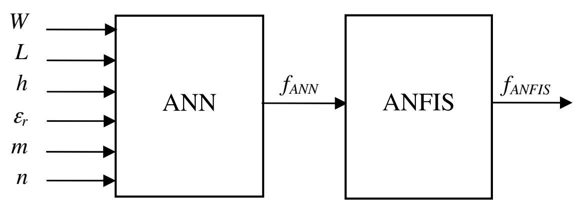
In the calculation of the resonant frequencies by using the single CNFS model, first the equivalent values of W and L for the circular and triangular MSAs should be obtained by using Eqns. (1) and (2). The resonant frequencies of the rectangular, circular, and triangular MSAs are then determined by W, L, h, ε_r, m, and n. The fundamental modes for the rectangular and circular MSAs are TM_{10} ($m = 1$ and $n = 0$) and TM_{11} ($m = n = 1$), respectively. These modes are widely used in MSA applications.

3. CONCURRENT NEURO-FUZZY SYSTEM (CNFS)

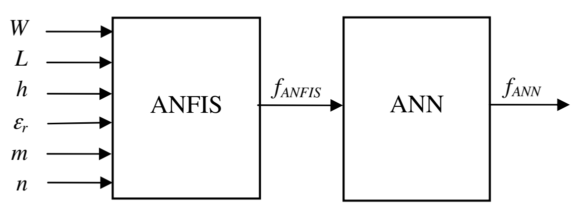
The ANN and ANFIS can simulate and analysis the mapping relation between the input and output data through a learning algorithm. In practice, ANNs and ANFISs can only approximate a system up to a certain degree. Therefore, it is always possible to further improve the output of ANN or ANFIS by using other appropriate tools.

There are many methods to combine FISs and ANNs in the literature [73, 74]. These methods can be broadly classified into three categories: the cooperative neuro-fuzzy systems, the concurrent neuro-fuzzy systems (CNFSs), and the integrated (fused) neuro-fuzzy systems [73, 74]. In this paper, a CNFS is used. The CNFS used in this paper comprises an ANN and an ANFIS. In the CNFS, ANN assists ANFIS continuously (or vice versa) to compute the resonant frequency.

In this paper, we present two CNFSs, called CNFS # 1 and CNFS # 2, to calculate the resonant frequencies of rectangular, circular, and triangular MSAs. In the CNFS # 1, first the resonant frequencies are computed by using ANN, and then the inaccuracies in the ANN computation are corrected by the ANFIS. In the CNFS # 2, first the resonant frequencies are computed by using ANFIS, and then the inaccuracies in the ANFIS computation are corrected by the ANN. The CNFSs # 1 and # 2 can be illustrated simply as shown in Figure 2.



(a) CNFS # 1



(b) CNFS # 2

Figure 2. CNFS models for resonant frequency calculation of rectangular, circular, and triangular MSAs.

For the ANN used in CNFS # 1, the inputs are W, L, h, ε_r, m, and n, and the output is the resonant frequencies f_{ANN} calculated by using ANN. For the ANFIS used in CNFS # 1, the input is f_{ANN}, and the output is the resonant frequencies f_{ANFIS} calculated by using

ANFIS.

For the ANFIS used in CNFS # 2, the inputs are W, L, h, ε_r, m, and n, and the output is the resonant frequencies f_{ANFIS} calculated by using ANFIS. For the ANN used in CNFS # 2, the input is f_{ANFIS}, and the output is the resonant frequencies f_{ANN} calculated by using ANN.

In the following sections, the ANN and the ANFIS used in CNFSs # 1 and # 2 are described briefly. The details on the ANN and ANFIS, and their training algorithms can be found in the previously published works of the authors [50, 77].

3.1. Artificial Neural Network (ANN)

An ANN is a highly simplified model of the biological structures found in a human brain [75, 76]. In the course of developing an ANN model, the architecture of ANN and the learning algorithm are the two most important factors. ANNs have many structures and architectures [75, 76]. The class of ANN and/or architecture selected for a particular model implementation depends on the problem to be solved. After several experiments using different architectures coupled with different training algorithms, in this paper, the multilayered perceptron (MLP) neural network architecture [75, 76] is used in calculating the resonant frequencies of MSAs. MLPs have a simple layer structure in which successive layers of neurons are fully interconnected, with connection weights controlling the strength of the connections. The MLP comprises an input layer, an output layer, and a number of hidden layers. MLPs can be trained using many different learning algorithms. In this paper, five different learning algorithms, BR [66], Levenberg-Marquardt (LM) [78], scaled conjugate gradient (SCG) [79], quasi-Newton (QN) [80], and conjugate gradient of Fletcher-Reeves (CGF) [81], are used to train the MLPs.

3.2. Adaptive-Network-Based Fuzzy Inference System (ANFIS)

The ANFIS is a class of adaptive networks which are functionally equivalent to FISs [64, 65]. The FIS forms a useful computing framework based on the concepts of fuzzy set theory, fuzzy if-then rules, and fuzzy reasoning. The selection of the FIS is the major concern in the design of an ANFIS. In this paper, the first-order Sugeno fuzzy model is used to generate fuzzy rules from a set of input-output data pairs. Among many FIS models, the Sugeno fuzzy model is the most widely applied one for its high interpretability and computational efficiency, and built-in optimal and adaptive techniques. The grid partitioning method [65] is used for the fuzzy rule extraction.

The ANFIS architecture consists of five layers: fuzzy layer, product layer, normalized layer, de-fuzzy layer, and summation layer. In the fuzzy layer, the crisp input values are converted to the fuzzy values by the membership functions (MFs). After, in the product layer, "*and*" operation is performed between the fuzzy values by using production so as to determine the weighting factor of each rule. Then, the normalized weighting factors are calculated in the normalized layer. In the de-fuzzy layer, the output rules are constructed. Finally, each rule is weighted by own normalized weighting factor and the output of the ANFIS is calculated by summing of all rule outputs in the summation layer.

The main objective of the ANFIS is to optimize the parameters of the fuzzy system parameters by applying a learning algorithm using input-output data sets. The parameter optimization is done in a way such that the error measure between the target and the actual output is minimized. During the learning process of the ANFIS, the premise parameters in the fuzzy layer and the consequent parameters in the de-fuzzy layer are tuned until the desired response of the FIS is achieved. In this paper, five different optimization algorithms, least-squares (LSQ) algorithm [82–84], nelder-mead (NM) algorithm [85, 86], GA [87, 88], HL algorithm [64, 65], and particle swarm optimization (PSO) [89, 90], are used to determine the optimum values of the fuzzy system parameters and adapt the FISs.

4. APPLICATION OF CNFS TO THE RESONANT FREQUENCY COMPUTATION

In this paper, the CNFSs # 1 and # 2 have been used to calculate simultaneously the resonant frequencies of the rectangular, circular, and triangular MSAs. In CNFSs # 1, first, the resonant frequencies are computed by using ANN models. Then, the resonant frequencies computed by ANN models are used in training the ANFISs. The ANN and ANFIS models in CNFSs # 1 are trained by (BR, LM, SCG, QN, and CGF) and (LSQ) algorithms, respectively.

In CNFSs # 2, first, the resonant frequencies are computed by using ANFIS models. Then, the resonant frequencies computed by ANFIS models are used in training the ANNs. The ANFIS and ANN models in CNFSs # 2 are trained by (LSQ, NM, GA, HL, and PSO) and (LM) algorithms, respectively.

The accuracy of a properly trained ANN and ANFIS depends on the accuracy and the effective representation of the data used for their training. A good collection of the training data, i.e., data which is well-distributed, sufficient, and accurately simulated, is the basic requirement to obtain an accurate model. There are two types of data generators for antenna applications. These data generators are the measurement and simulation. The selection of a data generator depends on the application and the availability of the data generator. The training and test data sets used in this paper have been obtained from the previous experimental works published by 11 sources [4, 5, 8, 12, 13, 16, 19, 22, 23, 30, 31], and are given in Tables 1, 2, and 3 for the rectangular, circular, and triangular MSAs, respectively. Total 68 data sets are listed in Tables 1–3. 54 data sets are used to train the CNFSs # 1 and # 2, and the remaining 14 data sets, marked with an asterisk in Tables 1–3, are used for testing. The equivalent values of W and L for the circular and triangular MSAs are calculated by using Eqns. (1) and (2). The input and output data sets are scaled between 0 and 1 before training.

Currently, there is no deterministic approach that can optimally determine the number of hidden layers and the number of neurons for ANNs. A common practice is to take a trial and error approach which adjusts the hidden layers to strike a balance between memorization and generalization. The training algorithms, and the number of neurons in the first and second hidden layers and training epochs for neural models used in CNFSs # 1 and # 2 are given in Tables 4 and 5. The tangent sigmoid function is used in the hidden layers. The linear activation function is used in the output layer. Initial weights of the neural models are set up randomly.

In the design of ANFIS, it is very important to determine the MFs. However, no common approach is available for determining these functions. A careful determination of MFs has to be performed in each problem. In some cases, they are attained subjectively as a model for human concepts. In other cases, they are based on statistical or/and empirical distributions, heuristic determination, reliability with respect to some particular problem, or theoretical demands. In this paper, MFs are selected heuristically and verified empirically. Therefore, the optimal fuzzy MF configuration which gives the best result is chosen for the resonant frequency calculation.

For the ANFIS used in CNFS # 1, the MF for the input variable f_{ANN} is the generalized bell. For the ANFIS used in CNFS # 2, the MFs for the input variables W, L, h, ε_r, m, and n are the gaussian, generalized bell, triangular, triangular, generalized bell, and gaussian, respectively. The training algorithms, and the number of MFs, epochs, rules, premise parameters, and consequent parameters of ANFIS used in CNFSs # 1 and # 2 are given in Tables 4 and 5.

Table 1. Resonant frequencies of rectangular MSAs for TM_{10} ($m = 1$ and $n = 0$) mode.

Patch No	W (cm)	L (cm)	h (cm)	ε_r	f_{ME} Measured (MHz) [30, 31]
1	0.850	1.290	0.017	2.22	7740
2*	0.790	1.185	0.017	2.22	8450
3	2.000	2.500	0.079	2.22	3970
4	1.063	1.183	0.079	2.55	7730
5	0.910	1.000	0.127	10.20	4600
6	1.720	1.860	0.157	2.33	5060
7*	1.810	1.960	0.157	2.33	4805
8	1.270	1.350	0.163	2.55	6560
9	1.500	1.621	0.163	2.55	5600
10*	1.337	1.412	0.200	2.55	6200
11	1.120	1.200	0.242	2.55	7050
12	1.403	1.485	0.252	2.55	5800
13	1.530	1.630	0.300	2.50	5270
14	0.905	1.018	0.300	2.50	7990
15	1.170	1.280	0.300	2.50	6570
16*	1.375	1.580	0.476	2.55	5100
17	0.776	1.080	0.330	2.55	8000
18	0.790	1.255	0.400	2.55	7134
19	0.987	1.450	0.450	2.55	6070
20*	1.000	1.520	0.476	2.55	5820
21	0.814	1.440	0.476	2.55	6380
22	0.790	1.620	0.550	2.55	5990
23	1.200	1.970	0.626	2.55	4660
24	0.783	2.300	0.854	2.55	4600
25*	1.256	2.756	0.952	2.55	3580
26	0.974	2.620	0.952	2.55	3980
27	1.020	2.640	0.952	2.55	3900
28	0.883	2.676	1.000	2.55	3980
29	0.777	2.835	1.100	2.55	3900
30	0.920	3.130	1.200	2.55	3470
31*	1.030	3.380	1.281	2.55	3200
32	1.265	3.500	1.281	2.55	2980
33	1.080	3.400	1.281	2.55	3150

*Test data sets.

Table 2. Resonant frequencies of circular MSAs for TM_{11} ($m = n = 1$) mode.

Patch No	a (cm)	h (cm)	ε_r	f_{ME} Measured (MHz)
1	6.800	0.08000	2.32	835$^{\square}$
2*	6.800	0.15900	2.32	829$^{\square}$
3	6.800	0.31800	2.32	815$^{\square}$
4	5.000	0.15900	2.32	1128$^{\triangle}$
5	3.800	0.15240	2.49	1443$^{\nabla}$
6	4.850	0.31800	2.52	1099^{x}
7*	3.493	0.15880	2.50	1570$^{\blacklozenge}$
8	1.270	0.07940	2.59	4070$^{\blacklozenge}$
9	3.493	0.31750	2.50	1510$^{\blacklozenge}$
10	4.950	0.23500	4.55	825
11	3.975	0.23500	4.55	1030
12	2.990	0.23500	4.55	1360
13*	2.000	0.23500	4.55	2003
14	1.040	0.23500	4.55	3750
15	0.770	0.23500	4.55	4945
16	1.150	0.15875	2.65	4425†
17	1.070	0.15875	2.65	4723†
18	0.960	0.15875	2.65	5224†
19*	0.740	0.15875	2.65	6634†
20	0.820	0.15875	2.65	6074†

$^{\square}$ These frequencies measured by Dahele and Lee [12]; $^{\triangle}$this frequency measured by Dahele and Lee [13]; $^{\nabla}$this frequency measured by Carver [8]; ^{x}this frequency measured by Antoszkiewicz and Shafai [22]; $^{\blacklozenge}$these frequencies measured by Howell [5]; †these frequencies measured by Itoh and Mittra [4]; the remainder measured by Abboud et al. [19]. *Test data sets.

Table 3. Resonant frequencies of triangular MSAs for various modes.

Mode	s (cm)	h (cm)	ε_r	f_{ME} Measured (MHz)
TM_{10}	4.1	0.070	10.50	1519^+
TM_{11}*	4.1	0.070	10.50	2637^+
TM_{20}	4.1	0.070	10.50	2995^+
TM_{21}	4.1	0.070	10.50	3973^+
TM_{30}	4.1	0.070	10.50	4439^+
TM_{10}	8.7	0.078	2.32	1489^+
TM_{11}	8.7	0.078	2.32	2596^+
TM_{20}	8.7	0.078	2.32	2969^+
TM_{21}*	8.7	0.078	2.32	3968^+
TM_{30}	8.7	0.078	2.32	4443^+
TM_{10}	10.0	0.159	2.32	1280
TM_{11}	10.0	0.159	2.32	2242
TM_{20}	10.0	0.159	2.32	2550
TM_{21}	10.0	0.159	2.32	3400
TM_{30}*	10.0	0.159	2.32	3824

$^+$These frequencies measured by Chen et al. [23]; the remainder measured by Dahele and Lee [16]. *Test data sets.

Table 4. Parameter values of ANN and ANFIS models used in CNFSs # 1 for resonant frequency computation of rectangular, circular, and triangular MSAs.

CNFS # 1 Models	ANN Models			ANFIS Models					
	Training Algorithms	Number of Neurons in Hidden Layers	Number of Training Epochs	Training Algorithm	Number of MFs	Number of Training Epochs	Number of Rules	Number of Premise Parameters	Number of Consequent Parameters
ANN_{BR} +$ANFIS_{LSQ}$	BR	6x12	381	LSQ	30	1770	30	90	60
ANN_{LM} +$ANFIS_{LSQ}$	LM	6x12	652	LSQ	27	261	27	81	54
ANN_{SCG}+$ANFIS_{LSQ}$	SCG	12x10	50000	LSQ	15	250	15	45	30
ANN_{QN} +$ANFIS_{LSQ}$	QN	3x12	100000	LSQ	17	35	17	51	34
ANN_{CGF}+$ANFIS_{LSQ}$	CGF	12x11	50000	LSQ	20	275	20	60	40

Table 5. Parameter values of ANFIS and ANN models used in CNFSs # 2 for resonant frequency computation of rectangular, circular, and triangular MSAs.

CNFS # 2 Models	ANFIS Models						ANN Models		
	Training Algorithms	Number of MFs	Number of Training Epochs	Number of Rules	Number of Premise Parameters	Number of Consequent Parameters	Training Algorithm	Number of Neurons in Hidden Layers	Number of Training Epochs
$ANFIS_{LSQ}$+ANN_{LM}	LSQ	2, 2, 3, 2, 2, 8	350	384	47	2688	LM	5x9	2267
$ANFIS_{NM}$+ANN_{LM}	NM	2, 2, 3, 2, 2, 8	500	384	47	2688	LM	6x6	3396
$ANFIS_{GA}$+ANN_{LM}	GA	2, 2, 3, 2, 2, 8	50	384	47	2688	LM	6x12	4034
$ANFIS_{HL}$+ANN_{LM}	HL	2, 2, 3, 2, 2, 8	50	384	47	2688	LM	6x6	10872
$ANFIS_{PSO}$+ANN_{LM}	PSO	2, 2, 3, 2, 2, 8	10	384	47	2688	LM	9x4	5941

5. RESULTS AND CONCLUSIONS

The resonant frequencies computed by using CNFSs # 1 and # 2 for the rectangular, circular, and triangular MSAs are given in Tables 6 and 7, respectively. For comparison, the resonant frequency results f_{ANN} and f_{ANFIS} obtained by using the single ANN models in CNFSs # 1 and the single ANFIS models in CNFSs # 2 are also given in Tables 6 and 7, respectively. The sum of the absolute errors between the theoretical and experimental results for every model is listed in Tables 6 and 7.

It is clear from Tables 6 and 7 that the results of CNFSs # 1 and # 2 show better agreement with the experimental results as compared to the results of the single ANN and ANFIS models. A significant improvement is obtained in the ANN and ANFIS results. The very good agreement between the measured values and our computed resonant frequency values supports the validity of CNFSs # 1 and # 2. When the performances of CNFS # 1 and # 2 models are compared with each other, the best result is obtained from the CNFS # 1 model, which comprises an ANN trained by the BR algorithm and an ANFIS trained by the LSQ algorithm, as shown in Tables 6 and 7. It needs to be emphasized that better results may be obtained from CNFSs # 1 and # 2 either by choosing different training and test data sets from the ones used in the paper or by supplying more input data set values for training. Better results can also be obtained by using different CNFS # 1 and # 2 models for each different MSA.

The results obtained by using the single neural models [61, 62] and the hybrid method [63] are given in Table 8. f_{EDBD}, f_{DBD}, f_{BP}, and f_{PTS} in Table 8 represent, respectively, the resonant frequency values computed by using the single neural model trained with extended delta-bar-delta, delta-bar-delta, back propagation, and parallel tabu

Table 6. Comparison of measured and calculated resonant frequencies obtained by using single ANN and CNFS # 1 models presented in this paper for rectangular, circular, and triangular MSAs.

Types of MSAs	f_{ME} Measured	Calculated Resonant Frequencies									
		Single ANN Models in CNFSs # 1					CNFS # 1 Models				
		ANN_{BR}	ANN_{LM}	ANN_{SCG}	ANN_{QN}	ANN_{CGF}	ANN_{BR}+$ANFIS_{LSQ}$	ANN_{LM}+$ANFIS_{LSQ}$	ANN_{SCG}+$ANFIS_{LSQ}$	ANN_{QN}+$ANFIS_{LSQ}$	ANN_{CGF}+$ANFIS_{LSQ}$
	7740	7741.4	7740.0	7740.8	7740.4	7760.1	7740.0	7739.7	7739.9	7739.2	7740.4
	8450	8438.0	8264.6	8254.2	8351.9	8333.0	8450.0	8449.9	8450.0	8449.9	8450.1
	3970	3971.3	3970.0	3970.5	3968.3	3973.8	3970.4	3968.7	3975.7	3969.3	3971.0
	7730	7724.0	7730.0	7726.3	7737.0	7685.0	7730.0	7729.1	7730.1	7729.5	7730.5
	4600	4600.0	4600.0	4600.0	4600.0	4595.8	4600.0	4599.4	4595.6	4593.2	4606.7
	5060	5058.5	5059.9	5060.6	5062.5	5013.3	5060.0	5061.4	5054.1	5053.0	5060.1
	4805	4845.2	4832.4	4815.1	4794.7	4822.9	4805.0	4804.9	4793.6	4796.4	4808.8
	6560	6577.6	6559.9	6569.7	6563.4	6580.8	6560.0	6561.8	6560.0	6564.8	6582.2
	5600	5590.6	5600.3	5591.8	5573.0	5653.7	5600.0	5600.2	5600.4	5589.7	5602.2
	6200	6206.6	6193.6	6205.8	6203.2	6208.1	6200.0	6200.1	6194.4	6181.7	6170.6
	7050	7061.1	7050.1	7052.6	7045.5	7049.0	7050.0	7049.7	7050.0	7049.0	7050.2
	5800	5796.5	5799.4	5805.2	5815.4	5800.7	5800.0	5799.0	5795.1	5811.9	5786.5
	5270	5276.4	5270.2	5271.4	5288.9	5258.3	5270.0	5271.6	5274.8	5268.7	5259.3
	7990	7986.7	7990.0	7990.1	7991.8	7994.2	7990.0	7990.1	7990.2	7994.3	7990.3
	6570	6552.5	6570.2	6560.1	6550.9	6555.7	6570.0	6568.6	6570.0	6557.0	6561.8
	5100	5098.5	4837.8	5154.9	5234.0	5150.4	5100.0	5101.8	5126.2	5209.2	5097.1
Rectangular	8000	7993.1	8000.0	8005.0	7993.1	7974.5	8000.0	7999.8	7999.9	7995.2	8000.3
	7134	7143.1	7133.9	7120.1	7134.0	7152.7	7134.0	7132.7	7134.0	7132.6	7134.4
	6070	6076.6	6069.8	6066.4	6078.6	6098.9	6070.0	6070.3	6070.5	6079.8	6089.3
	5820	5858.2	5832.3	5848.7	5859.3	5874.6	5820.0	5823.5	5839.3	5857.4	5894.8
	6380	6413.5	6380.2	6401.6	6414.0	6420.0	6380.0	6379.9	6380.2	6379.9	6383.6
	5990	5950.3	5989.9	5980.8	5954.7	5941.2	5990.0	5988.8	5985.5	5958.9	5974.0
	4660	4660.9	4660.0	4660.5	4653.9	4651.0	4660.0	4660.7	4667.7	4659.5	4658.1
	4600	4607.5	4600.0	4602.5	4609.5	4586.3	4600.1	4599.4	4598.1	4606.8	4596.2
	3580	3601.5	3542.8	3581.8	3597.3	3602.9	3580.1	3582.8	3578.1	3584.7	3581.7
	3980	3972.3	3979.6	3970.3	3970.5	3978.8	3978.7	3980.8	3975.4	3972.7	3976.3
	3900	3907.5	3900.3	3904.1	3905.4	3913.9	3900.0	3899.9	3904.8	3904.3	3910.0
	3980	3984.6	3980.1	3987.0	3986.7	3987.5	3980.0	3980.8	3972.2	3991.0	3984.4
	3900	3895.2	3900.0	3891.5	3896.4	3889.5	3900.0	3899.9	3892.7	3895.8	3906.3
	3470	3473.9	3469.9	3479.0	3473.3	3480.0	3470.0	3469.0	3468.9	3463.3	3469.4
	3200	3196.9	3222.4	3193.9	3190.9	3203.1	3200.0	3195.0	3203.1	3202.7	3213.2
	2980	2978.0	2980.0	2979.4	2980.3	2974.3	2980.0	2979.4	2979.6	2982.8	2972.0
	3150	3149.9	3150.1	3146.9	3146.0	3153.6	3150.0	3152.3	3149.4	3148.9	3146.2
Errors		337	557	444	546	737	2	34	136	335	274
	835	835.6	835.0	835.0	856.4	846.1	834.9	836.0	834.3	833.2	828.0
	829	824.1	823.5	823.9	836.5	809.5	824.2	823.5	824.5	825.5	823.5
	815	816.6	815.0	814.9	799.5	808.6	815.2	815.2	816.7	817.1	823.5
	1128	1128.2	1128.0	1128.1	1126.1	1104.7	1128.0	1128.0	1128.6	1131.3	1117.7
	1443	1444.7	1443.0	1442.6	1452.6	1459.2	1443.0	1442.8	1445.9	1441.8	1448.0
	1099	1098.5	1099.0	1099.1	1072.1	1114.2	1099.0	1098.9	1099.7	1094.4	1108.8
	1570	1572.8	1575.9	1600.9	1579.3	1650.7	1570.0	1570.0	1573.4	1562.9	1569.8
	4070	4070.3	4070.0	4070.2	4062.5	4070.0	4070.1	4070.0	4015.2	4071.9	4069.7
	1510	1511.5	1510.0	1510.1	1512.7	1504.6	1510.5	1510.1	1509.0	1515.7	1510.4
Circular	825	825.7	825.0	825.3	841.4	828.4	826.4	825.6	825.4	826.9	825.8
	1030	1032.3	1030.0	1029.8	1023.2	1016.8	1030.0	1030.0	1029.3	1033.1	1031.0
	1360	1359.3	1360.0	1360.0	1362.1	1363.0	1360.0	1360.1	1359.8	1362.2	1359.6
	2003	2032.1	2033.9	1959.3	2061.2	2527.7	2003.0	2003.0	2003.0	2007.4	2003.0
	3750	3750.1	3750.0	3750.0	3750.2	3759.0	3750.1	3750.0	3804.6	3758.8	3748.1
	4945	4945.0	4945.0	4944.9	4942.1	4945.0	4945.0	4951.7	4949.5	4941.6	4948.2
	4425	4424.3	4425.2	4425.3	4431.1	4407.0	4424.9	4423.4	4430.4	4424.1	4425.6
	4723	4722.6	4722.6	4721.4	4725.5	4719.7	4723.0	4722.7	4721.6	4729.6	4724.6
	5224	5224.7	5224.2	5225.8	5223.5	5246.3	5224.0	5221.3	5214.4	5199.1	5235.9
	6634	6701.4	6709.7	6687.2	6723.8	6587.5	6634.0	6634.2	6634.0	6633.5	6586.1
	6074	6073.4	6074.0	6073.5	6074.3	6060.2	6074.0	6074.6	6077.9	6075.3	6064.5
Errors		117	119	139	288	835	7	20	151	89	126
	1519	1519.1	1519.0	1519.0	1519.0	1521.9	1518.6	1519.1	1516.5	1521.9	1520.4
	2637	2634.0	2656.2	1858.4	2346.7	2698.2	2637.0	2637.1	2637.0	2635.3	2638.4
	2995	2995.7	2995.0	2995.0	2995.4	2997.6	2995.0	2993.4	2992.5	2995.5	2993.6
	3973	3973.2	3973.0	3973.0	3975.6	3973.2	3974.3	3971.6	3976.2	3978.4	3969.9
	4439	4438.7	4439.0	4439.0	4426.2	4436.4	4439.0	4440.9	4438.2	4418.0	4439.4
	1489	1489.9	1489.0	1488.4	1490.0	1480.3	1488.8	1488.9	1489.4	1488.9	1483.1
	2596	2595.4	2596.0	2596.1	2599.9	2599.6	2596.0	2595.9	2595.0	2587.4	2595.9
Triangular	2969	2967.9	2969.0	2968.9	2967.0	2981.1	2969.0	2969.9	2971.9	2971.9	2978.6
	3968	3977.6	3942.2	3750.8	4150.4	3825.7	3967.5	3969.7	3805.1	3965.5	3911.1
	4443	4442.4	4443.0	4443.0	4456.0	4440.5	4442.8	4445.7	4440.5	4449.2	4442.3
	1280	1278.7	1280.0	1280.5	1279.4	1282.2	1280.0	1280.2	1278.8	1279.3	1279.4
	2242	2242.9	2242.0	2241.9	2239.7	2236.6	2241.8	2242.0	2242.1	2246.9	2242.0
	2550	2550.6	2550.0	2550.1	2551.5	2546.7	2550.0	2550.3	2550.8	2566.8	2550.0
	3400	3400.1	3400.0	3400.0	3396.5	3403.6	3400.0	3400.5	3400.7	3405.6	3399.7
	3824	3832.1	3649.4	4066.4	4300.9	3783.0	3823.9	3823.7	4001.6	3831.3	3839.8
Errors		28	220	1240	993	294	3	12	359	87	98
Total absolute errors for the three MSAs in one model		482	896	1823	1827	1866	12	66	646	511	498

Resonant frequencies and errors are in MHz.

Table 7. Comparison of measured and calculated resonant frequencies obtained by using single ANFIS and CNFS # 2 models presented in this paper for rectangular, circular, and triangular MSAs.

Types of MSAs	f_{ME} Measured	Calculated Resonant Frequencies									
		Single ANFIS Models in CNFSs # 2					CNFS # 2 Models				
		$ANFIS_{LSQ}$	$ANFIS_{NM}$	$ANFIS_{GA}$	$ANFIS_{HL}$	$ANFIS_{PSO}$	$ANFIS_{LSQ}+ANN_{LM}$	$ANFIS_{NM}+ANN_{LM}$	$ANFIS_{GA}+ANN_{LM}$	$ANFIS_{HL}+ANN_{LM}$	$ANFIS_{PSO}+ANN_{LM}$
	7740	7738.3	7742.1	7750.8	7741.8	7734.6	7739.9	7743.2	7740.0	7740.0	7740.0
	8450	8450.1	8381.6	8391.2	8381.2	8373.4	8449.8	8437.7	8440.8	8501.0	8217.1
	3970	3969.9	3971.3	3972.1	3971.2	3967.9	3970.1	3972.1	3970.0	3972.9	3972.2
	7730	7729.5	7726.5	7733.0	7726.1	7719.0	7730.1	7726.7	7730.0	7730.0	7730.0
	4600	4599.5	4600.8	4655.1	4600.0	4596.1	4600.0	4597.5	4600.0	4595.4	4599.1
	5060	5056.3	5057.1	5059.4	5057.0	5052.6	5060.0	5061.7	5060.0	5056.0	5060.0
	4805	4807.2	4925.9	4927.9	4925.8	4921.5	4807.6	4946.2	4757.3	4929.4	4903.3
	6560	6560.0	6564.4	6572.4	6564.1	6558.2	6558.9	6556.9	6561.8	6560.0	6560.0
	5600	5598.4	5600.6	5607.3	5600.3	5595.4	5600.0	5605.1	5600.3	5600.1	5600.0
	6200	6201.0	6193.0	6203.8	6192.6	6187.1	6200.4	6193.4	6177.3	6179.0	6207.2
	7050	7045.1	7066.8	7082.2	7066.4	7059.9	7049.9	7056.0	7050.0	7050.0	7050.0
	5800	5803.7	5789.7	5805.7	5789.4	5784.2	5799.9	5798.1	5798.9	5799.8	5800.0
	5270	5266.3	5275.2	5284.8	5274.9	5270.3	5270.0	5261.8	5270.0	5266.9	5269.9
	7990	7988.5	7983.3	7993.4	7982.8	7975.4	7990.0	7991.4	7990.0	7990.0	7990.0
	6570	6573.5	6567.6	6577.4	6567.2	6561.3	6571.1	6560.8	6568.2	6570.0	6570.0
	5100	5099.6	4974.7	5021.4	4974.1	4969.9	5104.0	4991.5	5018.3	4976.2	4990.0
Rectangular	8000	8000.3	7990.2	8010.8	7989.6	7982.2	8000.0	7998.6	8000.0	8000.0	8000.0
	7134	7135.5	7140.8	7165.9	7140.2	7133.7	7134.1	7130.2	7134.0	7134.0	7134.0
	6070	6061.3	6065.2	6098.9	6064.6	6059.2	6067.6	6068.8	6081.5	6070.2	6070.1
	5820	5825.0	5841.1	5878.0	5840.6	5835.4	5820.1	5848.9	5865.1	5853.8	5853.4
	6380	6378.1	6398.1	6429.7	6397.6	6391.8	6380.0	6393.7	6379.8	6380.0	6380.0
	5990	5989.6	5978.7	6016.3	5978.2	5972.9	5990.4	5984.8	5998.7	5990.3	5990.0
	4660	4659.9	4661.7	4721.2	4661.0	4657.1	4661.4	4654.7	4660.0	4659.2	4659.7
	4600	4598.3	4610.3	4640.9	4609.6	4605.7	4599.0	4605.6	4600.0	4605.8	4601.1
	3580	3580.2	3551.3	3591.1	3550.5	3547.7	3580.0	3368.9	3453.8	3577.3	3572.2
	3980	3971.7	3973.1	4004.3	3972.3	3969.0	3972.1	3974.6	3979.9	3974.1	3973.3
	3900	3903.2	3903.2	3935.9	3902.4	3899.2	3903.1	3900.7	3900.0	3902.1	3905.3
	3980	3985.7	3980.0	4005.1	3979.2	3975.9	3986.2	3983.2	3980.0	3980.6	3980.5
	3900	3898.4	3889.8	3905.3	3889.0	3885.8	3898.1	3899.5	3900.0	3898.0	3896.2
	3470	3469.9	3485.1	3494.5	3484.1	3481.4	3470.1	3470.0	3470.0	3469.8	3469.9
	3200	3200.5	3198.1	3199.8	3197.1	3194.7	3201.3	3210.8	3204.5	3206.1	3208.2
	2980	2980.0	2981.8	2984.1	2980.9	2978.6	2980.2	2981.3	2982.6	2980.6	2980.8
	3150	3149.2	3145.5	3147.3	3144.5	3142.1	3149.3	3150.0	3150.0	3150.1	3149.6
Errors		69	535	860	537	592	37	614	365	396	520
	835	834.9	835.3	835.1	835.1	835.1	835.3	835.5	835.5	835.2	835.1
	829	829.1	683.5	683.3	683.1	683.3	829.4	844.5	697.0	677.0	712.7
	815	815.1	815.4	815.8	815.1	815.1	815.3	820.9	815.6	814.8	815.1
	1128	1127.7	1128.7	1127.5	1127.4	1127.0	1128.1	1122.3	1128.0	1127.4	1127.7
	1443	1444.2	1447.9	1443.8	1443.8	1443.2	1444.1	1443.2	1443.0	1443.5	1443.3
	1099	1098.7	1100.8	1099.3	1098.9	1098.6	1098.6	1105.6	1099.0	1099.6	1099.4
	1570	1569.5	1616.4	1611.0	1610.9	1610.1	1568.7	1522.5	1564.8	1612.0	1611.6
	4070	4070.1	4074.4	4070.3	4070.2	4066.8	4070.2	4069.9	4070.0	4070.0	4071.1
	1510	1510.3	1517.9	1510.3	1510.1	1509.3	1509.9	1514.0	1510.3	1509.9	1510.0
Circular	825	824.4	812.3	824.1	825.3	825.3	824.4	819.0	823.9	825.0	824.9
	1030	1031.8	1005.3	1024.2	1029.3	1029.1	1030.2	1028.3	1030.0	1030.0	1030.0
	1360	1358.3	1321.9	1344.3	1360.5	1359.9	1358.5	1359.3	1360.0	1360.4	1359.8
	2003	2003.5	2101.9	2102.0	2132.4	2131.0	2002.7	2028.5	2045.6	2135.4	2127.9
	3750	3749.6	3739.9	3747.2	3749.8	3746.7	3750.0	3750.0	3750.0	3750.0	3750.0
	4945	4944.7	4923.1	4982.6	4945.1	4940.8	4945.0	4943.3	4945.0	4948.0	4945.0
	4425	4424.7	4430.1	4421.7	4420.5	4416.8	4425.0	4426.5	4424.8	4424.8	4424.4
	4723	4720.8	4729.3	4722.1	4720.6	4716.5	4722.4	4726.1	4723.0	4722.0	4723.1
	5224	5228.4	5243.1	5238.2	5236.0	5231.4	5224.0	5229.8	5224.2	5228.6	5224.1
	6634	6634.8	6627.1	6629.4	6625.5	6619.6	6630.0	6619.1	6631.5	6775.3	6714.8
	6074	6069.4	6072.4	6071.8	6068.6	6063.1	6076.1	6075.6	6054.8	6073.7	6073.9
Errors		21	458	377	353	376	14	149	204	479	367
	1519	1519.0	1519.6	1519.0	1519.0	1518.3	1518.8	1515.4	1518.8	1518.9	1519.1
	2637	2636.9	2862.5	2484.9	3078.8	3076.5	2636.9	2860.2	2482.3	3081.2	3081.2
	2995	2995.0	2995.1	2995.0	2995.0	2992.7	2995.2	2994.4	2993.5	2994.6	2995.4
	3973	3973.0	3829.5	3911.0	3973.0	3969.7	3973.1	3973.0	3973.0	3975.3	3974.3
	4439	4439.1	4439.4	4439.0	4439.0	4435.3	4439.0	4437.2	4439.7	4439.4	4439.5
	1489	1488.9	1488.8	1489.0	1488.9	1488.2	1488.9	1488.2	1488.9	1488.7	1488.8
	2596	2596.0	2597.6	2595.6	2595.6	2593.8	2595.9	2596.0	2596.0	2596.7	2595.2
Triangular	2969	2969.0	2969.1	2969.0	2969.0	2966.7	2969.2	2968.3	2967.9	2968.5	2968.2
	3968	3968.0	3728.3	4021.2	3509.2	3506.4	3968.1	3982.8	4016.7	3880.1	3947.4
	4443	4443.0	4443.8	4443.1	4443.0	4439.3	4443.1	4443.0	4442.5	4442.8	4442.9
	1280	1280.1	1280.0	1280.2	1280.0	1279.6	1280.9	1281.1	1280.0	1279.6	1280.1
	2242	2242.0	2244.7	2242.3	2242.2	2240.8	2242.0	2242.0	2242.0	2242.0	2241.9
	2550	2550.0	2550.3	2551.7	2550.0	2548.2	2550.0	2550.0	2550.0	2549.4	2550.9
	3400	3400.0	3534.5	3673.4	3400.0	3397.3	3400.2	3400.0	3400.0	3399.8	3400.1
	3824	3824.0	3807.9	3810.7	3807.0	3804.0	3824.0	3955.9	3960.7	3861.7	3878.2
Errors		0	766	557	918	946	2	379	344	576	524
Total absolute errors for the three MSAs in one model		90	1759	1794	1808	1914	53	1142	913	1451	1411

Resonant frequencies and errors are in MHz.

Table 8. Resonant frequencies obtained from hybrid method and single neural models for rectangular, circular, and triangular MSAs.

Types of MSAs	f_{ME} Measured	Hybrid Method [63]	Single Neural Models [61, 62]			
			f_{EDBD} [61]	f_{DBD} [61]	f_{BP} [61]	f_{PTS} [62]
	7740	7743.8	7935.5	7890.1	7858.6	7847.4
	8450	8455.5	8328.2	8226.0	8233.1	8148.6
	3970	3971.1	4046.4	4023.0	4075.4	3971.5
	7730	7726.6	7590.1	7567.3	7616.8	7881.6
	4600	4598.8	4604.8	4573.9	4592.4	4603.4
	5060	5057.5	4934.2	4914.0	4930.3	4969.4
	4805	4842.6	4699.2	4684.8	4703.3	4879.0
	6560	6559.8	6528.6	6502.8	6516.5	6635.8
	5600	5594.7	5503.2	5473.3	5449.0	5516.3
	6200	6181.3	6176.6	6142.6	6147.2	6205.7
	7050	7048.9	7099.6	7064.3	7132.9	7113.8
	5800	5800.7	5805.6	5768.8	5765.7	5794.3
	5270	5277.6	5287.7	5260.3	5254.0	5313.0
	7990	7991.6	7975.5	7881.8	8002.2	7776.6
	6570	6570.1	6674.8	6632.8	6682.7	6481.9
	5100	5097.8	5311.8	5293.2	5291.4	5191.4
Rectangular	8000	7998.0	7911.1	7841.6	7942.5	7893.0
	7134	7134.9	7183.2	7162.1	7215.9	7267.0
	6070	6072.6	6173.0	6155.1	6170.2	6030.4
	5820	5863.2	5931.0	5918.0	5924.5	5780.3
	6380	6380.3	6424.0	6417.5	6430.7	6500.0
	5990	5990.0	5866.1	5873.9	5870.5	6004.0
	4660	4659.2	4699.0	4728.3	4718.9	4562.8
	4600	4606.3	4459.1	4517.1	4519.2	4591.2
	3580	3600.5	3659.8	3655.7	3644.6	3685.2
	3980	3972.1	3952.9	3982.6	3975.9	3948.5
	3900	3907.0	3905.4	3930.0	3922.2	3891.4
	3980	3984.5	3938.8	3970.7	3965.3	3969.4
	3900	3894.7	3825.5	3851.1	3845.9	3893.0
	3470	3472.5	3481.4	3466.2	3458.4	3456.9
	3200	3194.9	3230.3	3184.7	3178.0	3167.0
	2980	2979.4	3036.1	2965.6	2961.2	3035.5
	3150	3148.5	3191.2	3140.4	3134.0	3135.3
Errors		204	2392	2427	2372	2239
	835	834.6	822.9	793.9	818.4	848.5
	829	823.3	820.2	792.4	817.4	850.4
	815	815.8	814.5	789.4	815.5	857.9
	1128	1128.0	1108.1	1092.1	1034.6	1102.3
	1443	1444.4	1430.4	1452.1	1449.4	1437.0
	1099	1097.7	1109.6	1095.0	1039.6	1128.5
	1570	1570.3	1565.5	1584.6	1623.9	1566.9
	4070	4070.7	4144.3	4149.5	4191.4	4092.4
	1510	1510.0	1561.7	1573.2	1602.6	1506.0
	825	824.8	882.4	892.2	889.1	895.6
Circular	1030	1030.5	1028.0	1064.5	1040.5	1003.5
	1360	1360.3	1312.6	1352.6	1347.8	1330.5
	2003	2034.8	1979.1	1960.6	1975.4	2030.8
	3750	3749.5	3732.2	3716.4	3615.9	3777.1
	4945	4942.9	4965.5	4934.6	5024.6	4927.9
	4425	4424.2	4428.7	4424.1	4457.4	4371.7
	4723	4720.4	4712.3	4700.1	4728.3	4707.2
	5224	5225.3	5198.0	5166.0	5188.2	5256.3
	6634	6671.8	6662.5	6584.8	6636.8	6616.4
	6074	6071.5	6045.0	5983.3	6011.9	6095.7
Errors		91	462	727	922	508
	1519	1517.5	1527.0	1540.8	1557.6	1510.8
	2637	2635.8	2623.5	2632.3	2609.5	2633.1
	2995	2996.8	2983.3	2990.3	2976.9	2989.7
	3973	3973.0	3992.1	3954.0	4005.6	3974.8
	4439	4438.6	4424.5	4410.7	4410.8	4440.3
	1489	1488.8	1503.7	1541.3	1557.4	1493.2
	2596	2595.8	2600.6	2526.8	2597.7	2609.4
Triangular	2969	2969.5	2986.6	3007.1	2995.8	2969.6
	3968	3977.4	3945.6	3891.2	3854.8	3969.1
	4443	4442.3	4440.2	4472.3	4505.0	4443.5
	1280	1280.4	1257.7	1318.2	1250.8	1276.1
	2242	2242.4	2224.1	2194.6	2134.9	2227.7
	2550	2549.4	2500.9	2505.3	2512.2	2553.1
	3400	3398.2	3416.5	3491.5	3497.7	3395.5
	3824	3831.5	3861.2	3768.4	3784.5	3821.6
Errors		27	272	622	729	68
Total absolute errors for the three MSAs in one model		322	3126	3776	4023	2815

Resonant frequencies and errors are in MHz

Table 9. Resonant frequencies obtained from the conventional methods for rectangular MSAs.

Patch No	f_{ME} Measured	[5]	[6]	[8]	[1]	[2]	[11]	[15]	[17]	[25]	[31]	[36]
1	7740	7804	7697	7750	7791	7635	7737	7763	7720	7717	412	7765
2	8450	8496	8369	8431	8478	8298	8417	8446	8396	8389	488	8451
3	3970	4027	3898	3949	3983	3838	3951	3950	3917	3887	510	3977
4	7730	7940	7442	7605	7733	7322	7763	7639	7551	7376	1610	7730
5	4600	4697	4254	4407	4641	4455	4979	4729	4614	4430	113	4618
6	5060	5283	4865	4989	5070	4741	5101	4958	4924	4797	1621	5077
7	4805	5014	4635	4749	4824	4520	4846	4724	4688	4573	1460	4830
8	6560	6958	6220	6421	6566	6067	6729	6382	6357	6114	2550	6563
9	5600	5795	5270	5424	5535	5158	5625	5414	5374	5194	1769	5535
10	6200	6653	5845	6053	6201	5682	6413	5987	5988	5735	2860	6193
11	7050	7828	6566	6867	7052	6320	7504	6682	6769	6433	4792	7030
12	5800	6325	5435	5653	5801	5259	6078	5552	5586	5326	3259	5787
13	5270	5820	4943	5155	5287	4762	5572	5030	5081	4842	3383	5273
14	7990	9319	7334	7813	7981	6917	8885	7339	7570	6822	8674	8101
15	6570	7412	6070	6390	6550	5794	7076	6135	6264	5951	5486	6543
16	5100	5945	4667	4993	5092	4407	5693	4678	4830	4338	5437	5193
17	8000	8698	6845	7546	7519	6464	8447	6889	7160	6367	8067	7948
18	7134	7485	5870	6601	6484	5525	7342	5904	6179	5452	7242	7169
19	6070	6478	5092	5660	5606	4803	6317	5125	5341	4735	6103	6026
20	5820	6180	4855	5423	5352	4576	6042	4886	5100	4513	5875	5817
21	6380	6523	5101	5823	5660	4784	6453	5122	5396	4729	6546	6515
22	5990	5798	4539	5264	5063	4239	5804	4550	4830	4196	5976	6064
23	4660	4768	3746	4227	4141	3526	4689	3770	3949	3479	4600	4613
24	4600	4084	3201	3824	3615	2938	4209	3168	3446	2921	4603	4550
25	3580	3408	2668	3115	2983	2485	3430	2670	2845	2461	3574	3628
26	3980	3585	2808	3335	3162	2590	3668	2790	3015	2572	3955	3956
27	3900	3558	2785	3299	3133	2573	3629	2771	2987	2555	3895	3907
28	3980	3510	2753	3294	3112	2522	3626	2721	2966	2509	3982	3922
29	3900	3313	2608	3147	2964	2364	3473	2554	2823	2356	3903	3747
30	3470	3001	2358	2838	2675	2146	3129	2317	2549	2137	3493	3381
31	3200	2779	2183	2623	2474	1992	2889	2151	2357	1983	3197	3123
32	2980	2684	2102	2502	2370	1936	2752	2086	2259	1924	2982	2972
33	3150	2763	2168	2600	2453	1982	2863	2139	2338	1972	3160	3096
Errors		13136	24097	11539	12322	30669	8468	22572	18148	30504	56698	1393

Resonant frequencies and errors are in MHz.

search algorithms. In the hybrid method, the resonant frequencies were obtained by using ANFIS after ANN. The ANN and ANFIS were trained by BR and HL algorithms, respectively. Therefore, the hybrid method can also be called as a CNFS. It is apparent from Tables 6 and 8 that the results of all single ANN models in CNFSs # 1 are better than those predicted by the single neural models in [61, 62]. When the performances of the single ANN models in CNFSs # 1 and the single ANFIS models in CNFSs # 2 are compared with each other, the best result is obtained from the single ANFIS model trained by the LSQ algorithm, as shown in Tables 6 and 7. The LSQ is a very powerful algorithm that allows us to design highly accurate and efficient ANFIS. Better results can also be obtained by using a different individual ANN

Table 10. Resonant frequencies obtained from the conventional methods and the methods based on GA and TSA for circular MSAs.

Patch No	f_{ME} Measured	[8]	[5]	[9]	[19]	[18]	[24]	[28]	[29]	[41]	[39]	[32]	[33]
1	835	845	849	840	842	844	838	841	840	843	840	842	839
2	829	842	849	833	837	839	831	836	832	838	831	837	833
3	815	834	849	821	826	829	819	826	818	828	815	827	824
4	1128	1141	1154	1127	1133	1136	1124	1132	1125	1135	1123	1133	1129
5	1443	1445	1466	1427	1436	1439	1423	1435	1423	1438	1432	1436	1431
6	1099	1115	1142	1098	1105	1109	1095	1105	1091	1107	1100	1107	1103
7	1570	1565	1580	1545	1555	1559	1541	1554	1539	1558	1550	1556	1550
8	4070	4203	4290	4145	4175	4187	4134	4173	4120	4183	4168	4179	4163
9	1510	1539	1580	1513	1522	1529	1509	1523	1498	1524	1510	1525	1520
10	825	818	833	818	827	827	816	825	817	824	823	827	823
11	1030	1014	1037	1016	1027	1027	1013	1026	1013	1024	1022	1028	1023
12	1360	1339	1379	1344	1358	1360	1340	1359	1336	1355	1352	1361	1355
13	2003	1972	2061	1990	2009	2012	1984	2012	1966	2007	2002	2015	2009
14	3750	3627	3963	3749	3744	3737	3739	3752	3634	3750	3750	3750	3751
15	4945	4722	5353	5001	4938	4922	4987	4943	4817	4948	4945	4932	4944
16	4425	4461	4695	4399	4413	4437	4388	4422	4328	4422	4413	4423	4415
17	4723	4776	5046	4712	4723	4749	4699	4731	4630	4730	4722	4733	4725
18	5224	5289	5625	5223	5226	5257	5209	5237	5121	5231	5224	5237	5231
19	6634	6733	7297	6679	6644	6684	6661	6658	6499	6634	6636	6652	6651
20	6074	6125	6585	6063	6047	6084	6046	6061	5920	6046	6043	6057	6054
Errors		965	3341	337	253	383	380	253	1047	253	207	275	235

Resonant frequencies and errors are in MHz.

Table 11. Resonant frequencies obtained from the conventional methods and the methods based on GA and TSA for triangular MSAs.

Mode	f_{ME} Measured	[1]	[7]	[20]	[21]	[23]	[26]	[27]	[38]	[40]	[34]
TM_{10}	1519	1725	1498	1494	1577	1509	1511	1541	1501	1501	1505
TM_{11}	2637	2988	2594	2588	2731	2614	2617	2669	2601	2600	2629
TM_{20}	2995	3450	2995	2989	3153	3018	3021	3082	3003	3002	3013
TM_{21}	3973	4564	3962	3954	4172	3993	3997	4077	3972	3971	3985
TM_{30}	4439	5175	4493	4483	4730	4528	4532	4623	4504	4503	4519
TM_{10}	1489	1627	1500	1480	1532	1498	1486	1481	1489	1488	1485
TM_{11}	2596	2818	2599	2564	2654	2595	2573	2565	2579	2577	2580
TM_{20}	2969	3254	3001	2961	3065	2996	2971	2962	2978	2976	2969
TM_{21}	3968	4304	3970	3917	4054	3963	3931	3918	3940	3937	3940
TM_{30}	4443	4880	4501	4441	4597	4494	4457	4443	4468	4464	4456
TM_{10}	1280	1413	1299	1273	1340	1296	1280	1280	1281	1281	1277
TM_{11}	2242	2447	2251	2206	2320	2244	2217	2218	2219	2218	2224
TM_{20}	2550	2826	2599	2547	2679	2591	2560	2561	2562	2562	2555
TM_{21}	3400	3738	3438	3369	3544	3428	3387	3387	3389	3389	3397
TM_{30}	3824	4239	3898	3820	4019	3887	3840	3841	3843	3842	3835
Errors		5124	424	326	1843	408	314	590	273	273	233

Resonant frequencies and errors are in MHz.

or ANFIS model for each different MSA.

In order to make a further comparison, the resonant frequency results of conventional methods [1, 2, 5–9, 11, 15, 17–21, 23–29, 31–34, 36] and the methods based on GA [38, 39] and TSA [40, 41] for the rectangular, circular, and triangular MSAs are given in Tables 9–11. The sum of the absolute errors between the experimental results and the theoretical results in Tables 9–11 for every method is also given in Tables 9–11. It can be clearly seen from Tables 9–11 that the conventional methods and the methods based on GA and TSA give comparable results. Some cases are in good agreement with measurements, and others are far off. It should be noted that the conventional methods and the methods based on GA and TSA were used to compute the resonant frequencies of each different MSA. However, the CNFSs # 1 and # 2 presented in this paper are valid for the resonant frequency computation of all three different types of MSAs including the rectangular, circular, and triangular MSAs.

As a result, a method based on CNFS is used to accurately and simultaneously compute the resonant frequencies of the rectangular, circular, and triangular MSAs. The CNFS comprises an ANN and an ANFIS. The ANNs are trained with BR, LM, SCG, QN, and CGF algorithms. The LSQ, NM, GA, HL, and PSO are used to identify the parameters of ANFIS. In order to verify the validity and accuracy of the CNFS models for resonant frequency computation, comprehensive comparisons are made. The results of CNFS models are in very good agreement with the measurements. A significant improvement is obtained in the ANN and ANFIS results. The proposed method is not limited to the calculation of the resonant frequency of MSAs. This method can easily be applied to other antenna and microwave circuit problems. Accurate, fast, and reliable CNFS models can be developed from measured/simulated antenna data. Once developed, these CNFS models can be used in place of computationally intensive numerical models to speed up antenna design. We expect that the CNFS will find wide applications in solving antenna and microwave integrated circuit problems.

REFERENCES

1. Bahl, I. J. and P. Bhartia, *Microstrip Antennas*, Artech House, Dedham, MA, 1980.
2. James, J. R., P. S. Hall, and C. Wood, *Microstrip Antennas-Theory and Design*, Peter Peregrisnus Ltd., London, 1981.
3. Garg, R., P. Bhartia, I. Bahl, and A. Ittipiboon, *Microstrip Antenna Design Handbook*, Artech House, Canton, MA, 2001.

4. Itoh, T. and R. Mittra, "Analysis of a microstrip disk resonator," *Archiv für Electronik und Übertrugungstechnik*, Vol. 27, 456–458, 1973.
5. Howell, J. Q., "Microstrip antennas," *IEEE Trans. Antennas Propagat.*, Vol. 23, 90–93, 1975.
6. Hammerstad, E. O., "Equations for microstrip circuits design," *Proceedings of the 5th European Microwave Conference*, 268–272, Hamburg, 1975.
7. Helszajn, J. and D. S. James, "Planar triangular resonators with magnetic walls," *IEEE Trans. Microwave Theory Tech.*, Vol. 26, 95–100, 1978.
8. Carver, K. R., "Practical analytical techniques for the microstrip antenna," *Proceedings of the Workshop on Printed Circuit Antenna Tech.*, 7.1–7.20, New Mexico State University, Las Cruces, 1979.
9. Derneryd, A. G., "Analysis of the microstrip disk antenna element," *IEEE Trans. Anten. Propagat.*, Vol. 27, 660–664, 1979.
10. Chew, W. C. and J. A. Kong, "Resonance of axial and non-axial symmetric modes in circular microstrip disk antenna," *Proceedings of the IEEE AP-S Int. Symposium, Dig.*, 621–625, 1980.
11. Sengupta, D. L., "Approximate expression for the resonant frequency of a rectangular patch antenna," *Electronics Lett.*, Vol. 19, 834–835, 1983.
12. Dahele, J. S. and K. F. Lee, "Effect of substrate thickness on the performance of a circular-disk microstrip antenna," *IEEE Trans. Antennas Propagat.*, Vol. 31, 358–364, 1983.
13. Dahele, J. S. and K. F. Lee, "Theory and experiment on microstrip antennas with airgaps," *IEE Proc. Microwaves, Antennas Propagat.*, Vol. 132, 455–460, 1985.
14. Chang, E., S. A. Long, and W. F. Richards, "An experimental investigation of electrically thick rectangular microstrip antennas," *IEEE Trans. Antennas Propagat.*, Vol. 34, 767–772, 1986.
15. Garg, R. and S. A. Long, "Resonant frequency of electrically thick rectangular microstrip antennas," *Electronics Lett.*, Vol. 23, 1149–1151, 1987.
16. Dahele, J. S. and K. F. Lee, "On the resonant frequencies of the triangular patch antenna," *IEEE Trans. Antennas Propagat.*, Vol. 35, 100–101, 1987.
17. Chew, W. C. and Q. Liu, "Resonance frequency of a rectangular microstrip patch," *IEEE Trans. Antennas Propagat.*, Vol. 36, 1045–1056, 1988.

18. Liu, Q. and W. C. Chew, "Curve-fitting formulas for fast determination of accurate resonant frequency of circular microstrip patches," *IEE Proc. Microwaves, Antennas Propagat.*, Vol. 135, 289–292, 1988.
19. Abboud, F., J. P. Damiano, and A. Papiernik, "New determination of resonant frequency of circular disc microstrip antenna: Application to thick substrate," *Electronics Lett.*, Vol. 24, 1104–1106, 1988.
20. Garg, R. and S. A. Long, "An improved formula for the resonant frequency of the triangular microstrip patch antenna," *IEEE Trans. Antennas Propagat.*, Vol. 36, 570, 1988.
21. Gang, X., "On the resonant frequencies of microstrip antennas," *IEEE Trans. Antennas Propagat.*, Vol. 37, 245–247, 1989.
22. Antoszkiewicz, K. and L. Shafai, "Impedance characteristics of circular microstrip patches," *IEEE Trans. Antennas Propagat.*, Vol. 38, 942–946, 1990.
23. Chen, W., K. F. Lee, and J. S. Dahele, "Theoretical and experimental studies of the resonant frequencies of the equilateral triangular microstrip antenna," *IEEE Trans. Antennas Propagat.*, Vol. 40, 1253–1256, 1992.
24. Roy, J. S. and B. Jecko, "A formula for the resonance frequencies of circular microstrip patch antennas satisfying CAD requirements," *Int. J. Microwave Millimeter-Wave Computer-Aided Eng.*, Vol. 3, 67–70, 1993.
25. Guney, K., "A new edge extension expression for the resonant frequency of electrically thick rectangular microstrip antennas," *Int. J. Electronics*, Vol. 75, 767–770, 1993.
26. Guney, K., "Resonant frequency of a triangular microstrip antenna," *Microwave Opt. Technol. Lett.*, Vol. 6, 555–557, 1993.
27. Guney, K., "Comments on: On the resonant frequencies of microstrip antennas," *IEEE Trans. Antennas Propagat.*, Vol. 42, 1363–1365, 1994.
28. Guney, K., "Resonant frequency of electrically-thick circular microstrip antennas," *Int. J. Electronics*, Vol. 77, 377–386, 1994.
29. Lee, K. F. and Z. Fan, "CAD formulas for resonant frequencies of TM_{11} mode of circular patch antenna with or without superstrate," *Microwave Opt. Tech. Lett.*, Vol. 7, 570–573, 1994.
30. Kara, M., "The resonant frequency of rectangular microstrip antenna elements with various substrate thicknesses," *Microwave Opt. Technol. Lett.*, Vol. 11, 55–59, 1996.
31. Kara, M., "Closed-form expressions for the resonant frequency of

rectangular microstrip antenna elements with thick substrates," *Microwave Opt. Technol. Lett.*, Vol. 12, 131–136, 1996.
32. Gurel, C. S. and E. Yazgan, "Resonant frequency of an air gap tuned circular disc microstrip antenna," *Int. J. Electronics*, Vol. 87, 973–979, 2000.
33. Gurel, C. S. and E. Yazgan, "New determination of dynamic permittivity and resonant frequency of tunable circular disk microstrip structures," *Int. J. RF and Microwave Computer-Aided Eng.*, Vol. 10, 120–126, 2000.
34. Gurel, C. S. and E. Yazgan, "New computation of the resonant frequency of a tunable equilateral triangular microstrip patch," *IEEE Trans. Microwave Theory Tech.*, Vol. 48, 334–338, 2000.
35. Guha, D. and J. Y. Siddiqui, "Resonant frequency of equilateral triangular microstrip antenna with and without air gap," *IEEE Trans. Antennas Propagat.*, Vol. 52, 2174–2177, 2004.
36. Guney, K., "A new edge extension expression for the resonant frequency of rectangular microstrip antennas with thin and thick substrates," *J. Communications Tech. and Electronics*, Vol. 49, 49–53, 2004.
37. Angiulli, G. and M. Versaci, "Resonant frequency evaluation of microstrip antennas using a neural-fuzzy approach," *IEEE Trans. Magnetics*, Vol. 39, 1333–1336, 2003.
38. Karaboga, D., K. Guney, N. Karaboga, and A. Kaplan, "Simple and accurate effective side length expression obtained by using a modified genetic algorithm for the resonant frequency of an equilateral triangular microstrip antenna," *Int. J. Electronics*, Vol. 83, 99–108, 1997.
39. Akdagli, A. and K. Guney, "Effective patch radius expression obtained using a genetic algorithm for the resonant frequency of electrically thin and thick circular microstrip antennas," *IEE Proc. Microwaves, Antennas Propagat.*, Vol. 147, 156–159, 2000.
40. Karaboga, D., K. Guney, A. Kaplan, and A. Akdagli, "A new effective side length expression obtained using a modified tabu search algorithm for the resonant frequency of a triangular microstrip antenna," *Int. J. RF and Microwave Computer-Aided Eng.*, Vol. 8, 4–10, 1998.
41. Karaboga, N., K. Guney, and A. Akdagli, "A new effective patch radius expression obtained by using a modified tabu search algorithm for the resonant frequency of electrically thick circular microstrip antenna," *Int. J. Electronics*, Vol. 86, 825–835, 1999.
42. Sagiroglu, S. and K. Guney, "Calculation of resonant frequency

for an equilateral triangular microstrip antenna with the use of artificial neural networks," *Microwave Opt. Technol. Lett.*, Vol. 14, 89–93, 1997.

43. Sagiroglu, S., K. Guney, and M. Erler, "Resonant frequency calculation for circular microstrip antennas using artificial neural networks," *Int. J. RF and Microwave Computer-Aided Eng.*, Vol. 8, 270–277, 1998.
44. Karaboga, D., K. Guney, S. Sagiroglu, and M. Erler, "Neural computation of resonant frequency of electrically thin and thick rectangular microstrip antennas," *IEE Proc. Microwaves Antennas Propagat.*, Vol. 146, 155–159, 1999.
45. Guney, K., S. Sagiroglu, and M. Erler, "Comparison of neural networks for resonant frequency computation of electrically thin and thick rectangular microstrip antennas," *J. of Electromagn. Waves and Appl.*, Vol. 15, 1121–1145, 2001.
46. Ozer, S., K. Guney, and A. Kaplan, "Computation of the resonant frequency of electrically thin and thick rectangular microstrip antennas with the use of fuzzy inference systems," *Int. J. RF and Microwave Computer-Aided Eng.*, Vol. 10, 108–119, 2000.
47. Guney, K. and N. Sarikaya, "Computation of resonant frequency for equilateral triangular microstrip antennas using adaptive neuro-fuzzy inference system," *Int. J. RF and Microwave Computer-Aided Eng.*, Vol. 14, 134–143, 2004.
48. Guney, K. and N. Sarikaya, "Adaptive neuro-fuzzy inference system for computing the resonant frequency of circular microstrip antenna," *The Applied Computational Electromagnetics Society J.*, Vol. 19, 188–197, 2004.
49. Guney, K. and N. Sarikaya, "Adaptive neuro-fuzzy inference system for computing the resonant frequency of electrically thin and thick rectangular microstrip antennas," *Int. J. Electronics*, Vol. 94, 833–844, 2007.
50. Guney, K. and N. Sarikaya, "Resonant frequency calculation for circular microstrip antennas with a dielectric cover using adaptive network-based fuzzy inference system optimized by various algorithms," *Progress In Electromagnetics Research*, PIER 72, 279–306, 2007.
51. Guney, K. and N. Sarikaya, "Adaptive neuro-fuzzy inference system for computing the physical dimensions of electrically thin and thick rectangular microstrip antennas," *Int. J. Infrared and Millimeter Waves*, Vol. 27, 219–233, 2006.
52. Guney, K. and N. Sarikaya, "Multiple adaptive-network-based fuzzy inference system for the synthesis of rectangular microstrip

antennas with thin and thick substrates," *Int. J. RF and Microwave Computer-Aided Eng.*, Vol. 18, 359–375, 2008.

53. Sagiroglu, S., K. Guney, and M. Erler, "Calculation of bandwidth for electrically thin and thick rectangular microstrip antennas with the use of multilayered perceptrons," *Int. J. RF and Microwave Computer-Aided Eng.*, Vol. 9, 277–286, 1999.
54. Guney, K. and N. Sarikaya, "Artificial neural networks for calculating the input resistance of circular microstrip antennas," *Microwave Opt. Technol. Lett.*, Vol. 37, 107–111, 2003.
55. Guney, K. and S.S. Gultekin, "A comparative study of neural networks for input resistance computation of electrically thin and thick rectangular microstrip antennas," *J. Communications Tech. and Electronics*, Vol. 52, 483–492, 2007.
56. Kaplan, A., K. Guney, and S. Ozer, "Fuzzy associative memories for the computation of the bandwidth of rectangular microstrip antennas with thin and thick substrates," *Int. J. Electronics*, Vol. 88, 189–195, 2001.
57. Guney, K. and N. Sarikaya, "Adaptive neuro-fuzzy inference system for the input resistance computation of rectangular microstrip antennas with thin and thick substrates," *J. of Electromagn. Waves and Appl.*, Vol. 18, 23–39, 2004.
58. Guney, K. and N. Sarikaya, "Input resistance calculation for circular microstrip antennas using adaptive neuro-fuzzy inference system," *Int. J. Infrared and Millimeter Waves*, Vol. 25, 703–716, 2004.
59. Guney, K. and N. Sarikaya, "Adaptive neuro-fuzzy inference system for the computation of the bandwidth of electrically thin and thick rectangular microstrip antennas," *Electrical Eng.*, Vol. 88, 201–210, 2006.
60. Guney, K. and N. Sarikaya, "Adaptive-network-based fuzzy inference system models for input resistance computation of circular microstrip antennas," *Microwave Opt. Technol. Lett.*, Vol. 50, 1253–1261, 2008.
61. Guney, K., S. Sagiroglu, and M. Erler, "Generalized neural method to determine resonant frequencies of various microstrip antennas," *Int. J. RF and Microwave Computer-Aided Eng.*, Vol. 12, 131–139, 2002.
62. Sagiroglu, S. and A. Kalinli, "Determining resonant frequencies of various microstrip antennas within a single neural model trained using parallel tabu search algorithm," *Electromagnetics*, Vol. 25, 551–565, 2005.

63. Guney, K. and N. Sarikaya, "A hybrid method based on combining artificial neural network and fuzzy inference system for simultaneous computation of resonant frequencies of rectangular, circular, and triangular microstrip antennas," *IEEE Trans. Antennas Propagat.*, Vol. 55, 659–668, 2007.
64. Jang, J.-S. R., "ANFIS: Adaptive-network-based fuzzy inference system," *IEEE Trans. Systems, Man, and Cybernetics*, Vol. 23, 665–685, 1993.
65. Jang, J.-S. R., C. T. Sun, and E. Mizutani, *Neuro-Fuzzy and Soft Computing: A Computational Approach to Learning and Machine Intelligence*, Prentice-Hall, Upper Saddle River, NJ, 1997.
66. Mackay, D. J. C., "Bayesian interpolation," *Neural Computation*, Vol. 4, 415–447, 1992.
67. Guney, K., C. Yildiz, S. Kaya, and M. Turkmen, "Artificial neural networks for calculating the characteristic impedance of air-suspended trapezoidal and rectangular-shaped microshield lines," *J. of Electromagn. Waves and Appl.*, Vol. 20, 1161–1174, 2006.
68. Yildiz, C., K. Guney, M. Turkmen, and S. Kaya, "Neural models for coplanar strip line synthesis," *Progress In Electromagnetics Research*, PIER 69, 127–144, 2007.
69. Kaya, S., M. Turkmen, K. Guney, and C. Yildiz, "Neural models for the elliptic- and circular-shaped microshield lines," *Progress In Electromagnetics Research B*, Vol. 6, 169–181, 2008.
70. Turkmen, M., S. Kaya, C. Yildiz, and K. Guney, "Adaptive neuro-fuzzy models for conventional coplanar waveguides," *Progress In Electromagnetics Research B*, Vol. 6, 93–107, 2008.
71. Sarikaya, N., K. Guney, and C. Yildiz, "Adaptive neuro-fuzzy inference system for the computation of the characteristic impedance and the effective permittivity of the micro-coplanar strip line," *Progress In Electromagnetics Research B*, Vol. 6, 225–237, 2008.
72. Turkmen, I. and K. Guney, "Tabu search tracker with adaptive neuro-fuzzy inference system for multiple target tracking," *Progress In Electromagnetics Research*, PIER 65, 169–185, 2006.
73. Abraham, A., "Neuro fuzzy systems: State-of-the-art modeling techniques," *Lecture Notes in Computer Science*, 269–276, 2001.
74. Abraham, A., "Adaptation of fuzzy inference system using neural learning," *Fuzzy Systems Engineering: Theory and Practice (Studies in Fuzziness and Soft Computing)*, N. Nedjah and L. M. Mourelle (eds.), Chapter 3, 53–83, Springer Berlin, Heidelberg, 2005.

75. Maren, A. C., C. Harston, and R. Pap, *Handbook of Neural Computing Applications*, Academic Press, London, 1990.
76. Haykin, S., *Neural Networks: A Comprehensive Foundation*, Macmillan College Publishing Company, New York, 1994.
77. Guney, K., C. Yildiz, S. Kaya, and M. Turkmen, "Neural models for the V-shaped conductor-backed coplanar waveguides," *Microwave Opt. Technol. Lett.*, Vol. 49, 1294–1299, 2007.
78. Hagan, M. T. and M. Menjah, "Training feedforward networks with the Marquardt algorithm," *IEEE Trans. Neural Netw.*, Vol. 5, 989–993, 1994.
79. Moller, M. F., "A scaled conjugate gradient algorithm for fast supervised learning," *Neural Networks*, Vol. 6, 525–533, 1993.
80. Gill, P. E., W. Murray, and M. H. Wright, *Practical Optimization*, Academic Press, New York, 1981.
81. Fletcher, R. and C. M. Reeves, "Function minimization by conjugate gradients," *Computer J.*, Vol. 7, 149–154, 1964.
82. Levenberg, K., "A method for the solution of certain nonlinear problems in least-squares," *Quart. Appl. Math. II*, 164–168, 1944.
83. Marquardt, D. W., "An algorithm for least-squares estimation of nonlinear parameters," *SIAM J. Appl. Math.*, Vol. 11, 431–441, 1963.
84. Dennis, J. E., *State of the Art in Numerical Analysis*, Academic Press, 1977.
85. Spendley, W., G. R. Hext, and F. R. Himsworth, "Sequential application of simplex designs in optimization and evolutionary operation," *Technometrics*, Vol. 4, 441–461, 1962.
86. Nelder, J. A. and R. Mead, "A simplex method for function minimization," *Computer J.*, Vol. 7, 308–313, 1965.
87. Holland, J., *Adaptation in Natural and Artificial Systems*, University of Michigan Press, MI, 1975.
88. Goldberg, D. E., *Genetic Algorithms in Search, Optimization and Machine Learning*, Addison-Wesley, Reading, MA, 1989.
89. Kennedy, J. and R. Eberhart, "Particle swarm optimization," *Proceedings of the IEEE Int. Conference on Neural Networks*, 1942–1948, Perth, Australia, 1995.
90. Eberhart, R. C. and J. Kennedy, "A new optimizer using particle swarm theory," *Proceedings of the Sixth International Symposium on Micro Machine and Human Science*, 39–43, Nagoya, Piscataway, NJ, 1995.