Notch Antenna Analysis: Artificial Neural Network-based Operating Frequency Estimator

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Abstract **─** An artificial neural network (ANN) based estimator is presented for notch antenna analysis in terms of the operating frequency. The notch antenna is formed by loading an asymmetric slot on one side of a rectangular patch. Architecture of the estimator is constructed over an ANN model trained with the simulated data of the notch antennas. In order to constitute a data pool for training and testing the ANN model, 96 notch antennas with seven antenna parameters are simulated with respect to the operating frequency. Antenna parameters including the patch dimensions, height and relative permittivity of the substrate are used as input vector of the ANN model. The simulated data of 80 notch antennas are employed to train the ANN model. The estimator is corroborated through testing with the remainders 16 antenna data, verifying with antenna data in the literature and validating with a prototyped notch antenna data. The results show that the estimator simply and fast computes the operating frequency of the notch antennas in very close to real one without performing simulations or measurement.

Index Terms **─** Antenna, antenna analysis, Artificial Neural Network (ANN), estimator, notch antenna, operating frequency, patch antenna.

I. INTRODUCTION

Slot loading technique are widely used to form small and comfortable patch antennas suitable for modern wireless technologies, since it yields a miniaturization in size and tuning the operating frequency [1-13]. Therefore, various slot antennas with *C* [1-4], *E* [5, 6], *H* [1, 7], *L* [8, 9] and rectangular ring [1, 10] shapes are well studied in the literature. The slots of those antennas are loaded in symmetrical with respect to the edge of the patch. However, notch antenna is a form of slot antenna constituted by asymmetrical notching one side of the patch [11]. Thus, lower operating frequency according to rectangular patch antenna can be achieved by notching the patch with the same outer size. Note that the analysis of such antennas needs great effort because of having irregular shapes. There exist several analytic techniques like cavity model [12] and transmission line model [13] inspired from waveguide and transmission line theory, especially for regular shapes such as rectangular, triangular and circular. However, the mentioned techniques could not be employed to analyze the slot antennas alone. Nevertheless, analysis of the slot antennas may be facilitated thanks to computer-based software incorporated with computational electromagnetic (CEM) [14]. The CEMs generally employ complicated numerical method such as finite difference time domain (FDTD) [15] and method of moment (MoM) [16]. CEMs numerically solve the rigorous Maxwell equations in integral or differential forms by discretizing simulated model. On the other hand, the ownership cost of the CEM-based simulation tools are very expensive and one requires deep background knowledge to model and simulate an antenna. Therefore, finding alternative ways for simply analyzing the antennas, especially determining the operating frequency is promising research. Expert systems using artificial intelligence are interesting methods being developed for analyzing the antenna structures [4, 6, 9, 10, 17-20] and estimating various antenna parameters. The well-known computer-based artificial intelligent techniques are the artificial neural network (ANN) [21] and the adaptive neuro-fuzzy interference system (ANFIS) [22] and the support vector machine (SVM) [23].

ANN has evolved in various engineering applications owing to being accurate simulation and modelling with fast and simple manner. It has remarkably advanced in field of wireless communication as well. ANN contains artificial neurons designed into several layers. The neurons resembling the human brain are the processing elements of the network and they consist of non-linear types of functions that are mutually connected by synaptic weights. ANN can be trained through measured or simulated data pool having inputs and outputs with respect to objective of minimizing the error between target and output. During the training, the synaptic weights weaken or strengthen to bring closer output to the target. Meanwhile, the ANN is modelling the nonlinear relationship between the output and the target

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by utilizing some mathematical functions.

In this study, a robust ANN-based estimator for operating frequency is proposed. To this end, a notch antenna is formed and the estimator built on multilayer perceptron (MLP) [21, 24] is constructed for analyzing the antenna. The notch antenna is designed with six physical parameters and a relative permittivity of the substrate. To generate the training and testing data pool, 96 notch antenna with different parameters are simulated in terms of operating frequency by using a CEM software. The simulated data of 80 notch antenna representing the overall problem space is employed to train the estimator and the remainders 16 are utilized to test the accuracy. Hence, the estimator is successfully trained with mean absolute errors (MAE) of 0.003. The estimator is then tested through 16 testing data with MAE of 0.022, and verified via 19 simulated and measured data of notch antennas reported elsewhere [1, 3, 4, 11] with MAE of 0.023. Finally, the proposed estimator is validated using notch antenna prototyped in this study.

II. DESIGN OF NOTCH ANTENNA STRUCTURE

The geometry of the notch antenna is illustrated in Fig. 1. The antenna consists of a rectangular patch of *LxW* fed by a probe feed, ground layer, substrate with *h* thickness and ε_r relative permittivity therein between the patch and ground layer. The probe feed is positioned in the point of (x_0, y_0). The rectangular patch is loaded with a *lxw* slot shifted as *d* from the upper side.

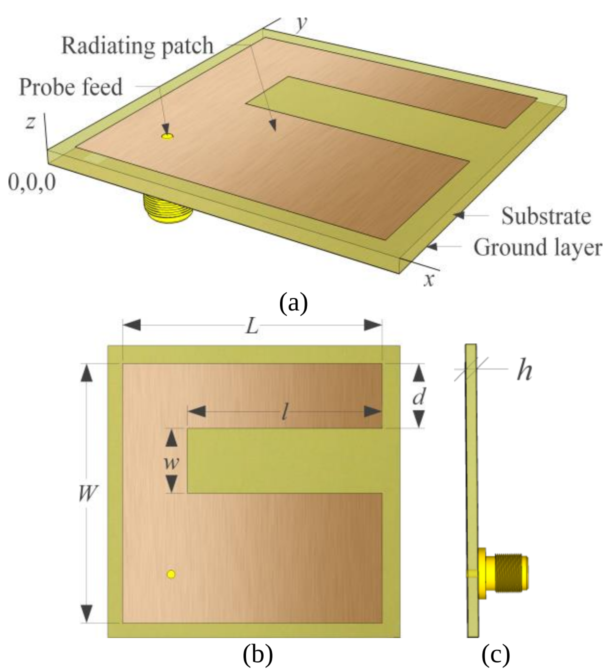


Fig. 1. Geometry of the notch antenna: (a) 3D view, (b) front view, and (c) side view.

III. CONSTRUCTING THE ESTIMATOR

The construction of operating frequency estimator is outlined in Fig. 2. The notch antenna with 7 parameters are simulated to determine the operating frequency (f_{sim}), which is the target of the ANN model. These antenna parameters are also used as input vector of the ANN model so as to estimate the operating frequency (f_{est}). The ANN model is trained with 80 antenna data so that fitting the estimator's outputs to simulated operating frequency in the objective of minimizing MAE calculating the mean absolute error between the target and output.

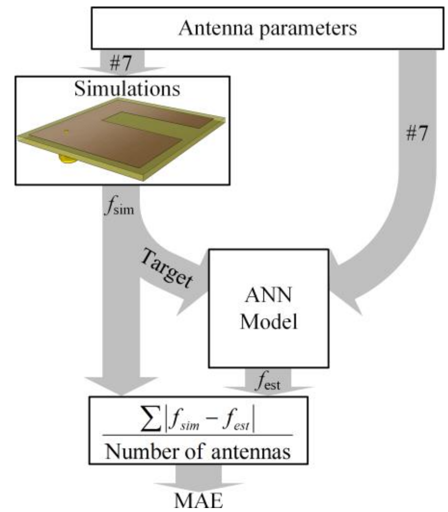


Fig. 2. The working principle of the estimator.

A. Simulations

Simulations of 96 notch antennas are performed with respect to the operating frequency according to parameters given in Table 1. The antennas' parameters are determined so that they operate between 1.15 GHz and 3.35 GHz, which appropriates to ultra-high frequency (UHF) band applications. The notch antenna structures are modelled and simulated by means of CEM software HyperLynx® 3D EM [25] running method of moment (MoM). In order to constitute a uniformly distributed data pool, the outer dimensions (*L* and *W*) are selected in three groups each of which has 32 antenna, and the outer dimensions of the groups are 30, 20; 40, 30 and 50, 40, including different parameters of *l*, *w*, *d*, *h* and relative permittivity ε_r. In the simulations, the antennas are fed with a probe of 1 Volt wave source in the point of x_0=5 mm, y_0=5 mm. The antenna models are meshed with lines per wavelength ratio of 30 and maximum frequency of 5 GHz. It is simulated at the frequency range of 1 GHz and 5 GHz on 81 discrete frequency points.

B. The ANN model

The ANN model is constructed over MLP with 3 layers as shown in Fig. 3. In the MLP, the neurons are inter-connected in feed forward back propagation (FFBP).

The layers of input, hidden and output layers have 7, 4 and 1 neurons, respectively. In order to investigate a proper model, networks with higher hidden layers are also essayed. However, merely slightly improvement is achieved with those networks rather than with single hidden layer. Therefore, the network with single hidden layer is preferred for the sake of simplicity. For both input and hidden layers, "tangent sigmoid" function is used; in output layer "purelin" function is utilized.

Table 1: Simulated notch antenna parameters

Patch Dimension (mm)					h (mm)	ε_r
L	W	l	w	d		
30	20	10; 20	5; 10	3; 6	1.6; 2.5	2.33; 4.4
40	30	15; 30	7.5; 15	5; 10		
50	40	20; 40	10; 20	7; 14		

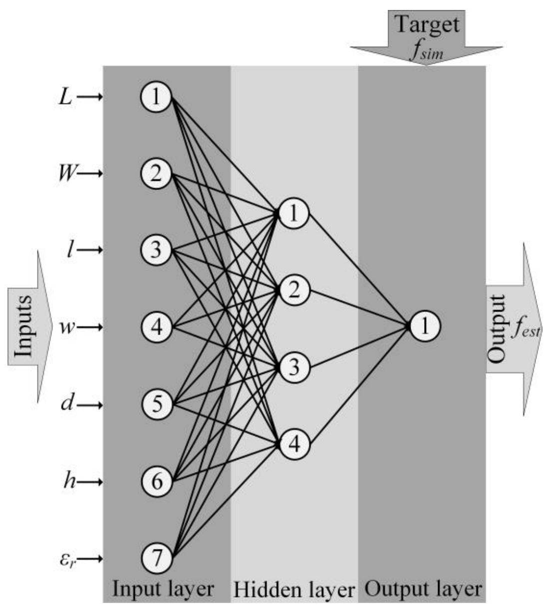


Fig. 3. The proposed ANN model.

C. Training the ANN model

The ANN model is trained with Levenberg-Marquardt learning algorithm [26-28] according to the flowchart given in Fig. 4. Training data set in Table 1 with respective operating frequency values is firstly loaded once starting the algorithm. Training of the ANN starts with a random seed value and it is being trained through the loaded data for 350 epochs, which is the number of return cycles in this step. Seed value is a factor that fixes the weights of the network for getting the same result in every run. After training the model, if MAE is less than objective values of 0.005; the seed value is saved for subsequent runs of the trained ANN. Otherwise, the training repeat with a new random seed value. Therefore, the ANN model is properly trained with MAE of 0.003. In the proposed ANN model, learning coefficient, epoch number, momentum parameter and seed number are determined as 0.5, 350, 0.001 and 1681524111, respectively.

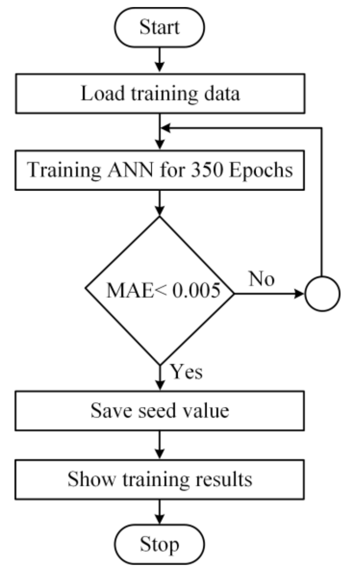


Fig. 4. Flowchart for training the ANN model.

IV. CORROBORATING THE ESTIMATOR

The estimator is corroborated via a graphical user interface (GUI) created in MATLAB® software as given in Fig. 5. The trained estimator is corroborated in three phase: testing with simulated data, verifying with simulated/ measured data in the literature and validating with data of a prototyped notch antenna in this study.

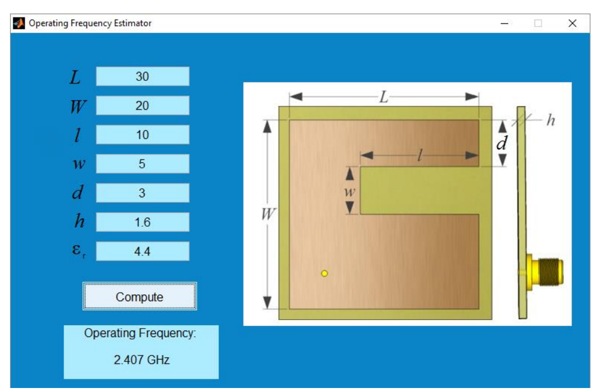


Fig. 5. A screenshot for GUI of the estimator.

A. Testing the estimator

The accuracy of the estimator is tested through 16 notch antenna data that is not utilized in training the estimator. Parameters of 16 simulated antennas with respective operating frequency values are given in

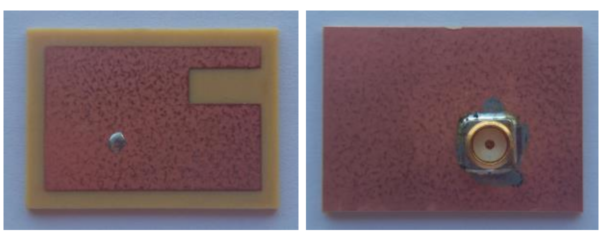
Table 2. The trained estimator successfully computes the frequency (f_{est}) with MAE of 0.022.

B. Verifying the estimator

The proposed estimator is verified over the simulated and measured results reported elsewhere [1, 3-4, 11]. Data of 19 notch antennas including parameters with respective simulated and measured operating frequency values are tabulated in Table 3. The estimators' frequencies are compared with both of the simulated and measured value in terms of absolute error (AE). The estimated operating frequencies well match with the results in the literature. The frequencies computed by the estimator remain less than absolute error of 0.08 for simulated results. Hence, the estimator simply calculates the operating frequency with MAE of 0.023 and 0.072 for simulated and measured values.

C. Validating the estimator

The notch antenna illustrated in Fig. 6 is printed on a 25x35 mm^2 FR4 PCB substrate of which dielectric permittivity, tangent loss and thickness are 4.4, 0.02 and 1.6 mm, respectively. The prototyped antenna of which parameters given in Table 4 is measured by the agency of Keysight Technologies N5224A PNA network analyzer. The measured $|S_{11}|$ parameter is shown in Fig. 7 in comparison with the simulated one.



(a) (b)

Fig. 6. The photograph of prototyped notch antenna: (a) front view and (b) back view.

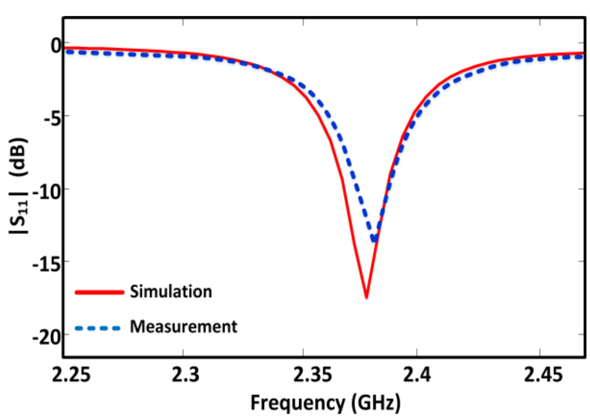


Fig. 7. S_{11} parameter of simulated and measured prototyped notch antenna.

Simulated 2D gain radiation patterns of the notch antenna at the operating frequency points of 2.38 GHz are illustrated in Fig. 8. The maximum gains are -4.12 dBi (in direction of 180° on *x-z* plane), -4.11 dBi (in direction of 355° on *y-z* plane) and -6.84 dBi (in direction of 165° on *x-y* plane).

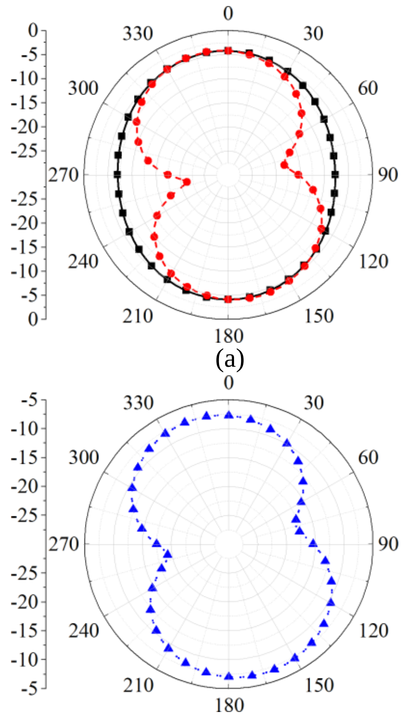


Fig. 8. Radiation patterns of the notch antenna at 2.38 GHz: (a) *x-z* plane (black solid line) and *y-z* plane (red dashed line), and (b) *x-y* plane (blue dot line).

Figure 9 indicates the peak gain plot versus frequency. The peak gain varies between -4.0 dBi and -8.0 dBi levels across 2.3 GHz to 2.5 GHz, whereas a maximum gain occurs 4.0 dBi at 2.38 GHz. It has minus gain in relative to an isotropic radiation, since the antenna radiates nearly omnidirectional pattern.

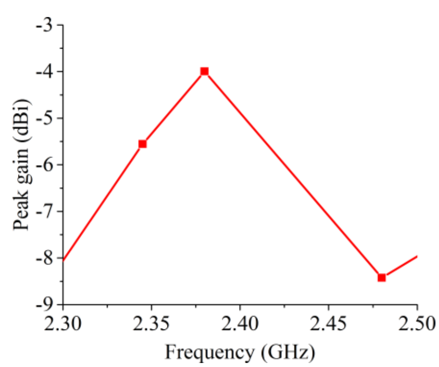


Fig. 9. Peak gain variation of the notch antenna.

From Tables 2-4, the estimator's operating frequencies are much close to the simulated/measured results. Therefore, the estimator can be successfully used to compute the operating frequency of the notch antennas without handling sophisticated mathematical functions and transformations. Moreover, the proposed estimator can be modified or improved to use similar tasks of nonlinear electromagnetic problems. The proposed estimator for notch antenna analysis is more versatile than methods suggested for C or U-shaped patch antennas, since the slot's position of the notch antenna varies rather than the mentioned antennas.

Table 2: The simulated notch antennas for testing the estimator

Antenna Parameter							Operating Frequency		Absolute Error (AE)
Patch Dimension (mm)					h (mm)	ε_r			
L	W	l	w	d			f_{sim}	f_{est}	
30	20	10	5	3	2.5	4.4	2.426	2.415	0.012
30	20	10	5	6	1.6	2.33	3.348	3.151	0.197
30	20	10	10	6	2.5	2.33	3.140	3.145	0.004
30	20	20	5	3	1.6	4.4	1.611	1.605	0.006
30	20	20	5	6	1.6	2.33	2.015	2.045	0.030
30	20	20	10	6	1.6	4.4	1.512	1.505	0.007
40	30	15	7.5	5	1.6	4.4	1.860	1.864	0.004
40	30	15	15	5	2.5	2.33	2.107	2.096	0.011
40	30	30	7.5	5	1.6	2.33	1.357	1.369	0.012
40	30	30	7.5	10	2.5	2.33	1.311	1.301	0.010
40	30	30	15	5	2.5	4.4	1.695	1.691	0.004
50	40	20	10	7	1.6	4.4	1.466	1.478	0.011
50	40	20	10	14	2.5	4.4	1.174	1.179	0.005
50	40	20	20	14	1.6	2.33	1.585	1.586	0.000
50	40	40	10	7	2.5	4.4	1.421	1.407	0.014
50	40	40	20	7	2.5	2.33	1.814	1.813	0.001
MAE									0.022

Table 3: Simulated and measured notch antennas in the literature for verifying the estimator

Ref. #	Antenna Parameter							Operating Frequency			Absolute Error (AE)	
	Patch Dimension (mm)					h (mm)	ε_r					
	L	W	l	w	d			f_{sim}	f_{mea}	f_{est}	AE_{sim}	AE_{mea}
[1]	40	60	5	5	27.50	1.5900	2.33	1.562	–	1.578	0.016	–
[1]	40	60	10	10	25.00	1.5900	2.33	1.445	–	1.419	0.026	–
[1]	40	60	15	15	22.50	1.5900	2.33	1.286	–	1.289	0.003	–
[1]	40	60	20	20	20.00	1.5900	2.33	1.130	–	1.176	0.046	–
[1]	40	60	25	25	17.50	1.5900	2.33	0.991	–	1.010	0.019	–
[1]	40	60	30	40	10.00	1.5900	2.33	0.899	–	0.900	0.001	–
[1]	40	60	30	5	27.50	1.5900	2.33	0.929	–	0.928	0.001	–
[1]	40	60	30	10	25.00	1.5900	2.33	0.887	–	0.935	0.048	–
[1]	40	60	30	2	29.00	1.5900	2.33	0.964	–	0.957	0.007	–
[3]	20	30	7	3	13.50	1.5700	2.33	2.810	2.822	2.813	0.003	0.009
[4]	20	30	5	20	5.00	1.5700	2.33	2.870	2.930	2.951	0.081	0.021
[11]	38	30	4	5	6.50	1.5875	2.4	2.987	2.957	3.066	0.079	0.109
[11]	38	30	6	5	6.50	1.5875	2.4	2.901	2.921	2.965	0.064	0.044
[11]	38	30	8	5	6.50	1.5875	2.4	2.777	2.477	2.778	0.000	0.301
[11]	38	30	10	5	6.50	1.5875	2.4	2.623	2.603	2.597	0.026	0.006
[11]	38	30	12	5	6.50	1.5875	2.4	2.416	2.316	2.422	0.006	0.106
[11]	38	30	14	5	6.50	1.5875	2.4	2.256	2.270	2.255	0.001	0.015
[11]	38	30	16	5	6.50	1.5875	2.4	2.101	2.200	2.099	0.002	0.101
[11]	38	30	18	5	6.50	1.5875	2.4	1.956	1.960	1.957	0.001	0.003
MAE											0.023	0.072

Table 4: Simulated and measured notch antenna prototyped in this study for validating the estimator

Antenna Parameter							Operating Frequency			Absolute Error (AE)	
Patch Dimension (mm)					h (mm)	ε_r					
L	W	l	w	d			f_{sim}	f_{mea}	f_{est}	AE_{sim}	AE_{mea}
30	20	10	5	3	1.6	4.4	2.380	2.390	2.407	0.027	0.017

V. CONCLUSION

In this article, an estimator using ANN built on MLP is implemented for computing the operating frequencies of the notch antennas. An ANN including three layers is modelled: input layer with 7 neurons, hidden layer with 4 neurons and output layer with 1 neuron. In order to constitute data for training and testing the estimator, number of 96 notch antennas having various physical and electrical parameters is simulated with the help of HyperLynx® 3D EM in terms of the operating frequency. The seven antenna parameters are also input to the ANN model to compute the operating frequency of the notch antenna. Number of 80 antennas are used for training and the remainders 16 antennas are utilized for testing the ANN model. In training, the ANN model is optimized by fitting the output of operating frequency to the simulated one. The proposed estimator is corroborated through three steps: testing with simulated antennas, verifying with literature and validating with prototyped antenna data. It is pointed out that the estimator computes operating frequency closely to real one. Once the estimator is properly trained, it can fast and accurately compute the operating frequency of patch antennas.

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