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Predicting the notch band frequency of an ultra-wideband antenna using artificial neural networks

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ABSTRACT

In this paper we propose to predict the notch frequency of an ultra-wideband (UWB) antenna which operates in the frequency band from 3.85 GHz to 12.38 GHz. The prediction of the notch frequency in order to avoid interferences between (WLAN) IEEE802.11a and HIPERLAN/2 WLAN applications and UWB technology is achieved using the artificial neural networks (ANN) technique. The developed ANN is optimized with the help of K-fold cross validation method which allows us to divide the datasets into 10 subsets in the training phase. The simulated datasets are generated by controlling high frequency structural simulator (HFSS) from MATLAB using a VB script. The performance of the ANN technique is assessed using some statistical criteria. During the training process, the mean absolute percentage error (MAPE) between the simulated and the predicted ANN notch frequencies is 0,125. A comparison between simulated, theoretical, and ANN results has been achieved during the test and validation process, good accuracy is obtained between the simulated and the ANN predictions. The proposed UWB antenna exhibits a notch band from 5.1 GHz to 6.0 GHz with a notch frequency of approximately 5.51 GHz.

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1. INTRODUCTION

In wireless communications systems, the antenna is one of the most important elements. Technologies, such as: global positioning system (GPS), wireless local-area network (WLAN)/worldwide interoperability for microwave access (WIMAX), ultra-wideband (UWB), need an indispensable part to transmit and receive the information, which is the micro-strip patch antenna. The principal components of a simplest patch antenna are a conductive layer, a substrate layer, and a ground plane [1, 2]. Consequently, multiple patch antennas have been fabricated with different shapes, different dimensions, and various dielectric substrates in order to satisfy the desired specifications [3, 4]. UWB is characterized by many advantages like: high bandwidth, huge data rate, very low power consumption, and low cost [5, 6]. The small size, the light weight, the easy fabrication, and the thin profile configurations [7] make the miniaturized microstrip patch antenna a better candidate to be used in UWB applications. These antennas have to satisfy performances such as; good impedance bandwidth, constant gain, good radiation pattern, and small design. The Federal Communications Commission (FCC) approved the use of the spectrum 3.1-10.6 GHz for UWB applications [8]. But there are already licensed applications using a part of this frequency band such as WLAN IEEE802.11a and HIPERLAN/2 WLAN operating in the 5.15–5.825 GHz band. For this reason, designers and researchers have proposed many shapes and many techniques to notch the frequency band 5.15–5.825 GHz in order to overcome interferences with UWB.

In the literature, the most used technique to notch a band is cutting a slot, either on the radiating patch or on the ground plane [9-11]. In [9], the notch band is realized by inserting a U-shaped slot on the radiating patch to design a patch antenna with the rejection of WLAN band. A coplanar waveguide fed compact UWB antenna is proposed in [11]. The notch of WLAN band is achieved by etching half wavelength C-shaped annular ring slot in the radiating patch. In another research, multiple bands are achieved. In [12], authors propose an UWB antenna with two slits to avoid the interference with WLAN and 5G bands. In [13], an inset-fed UWB antenna with three notches is generated by introducing U-shaped, crescent-shaped, and L-shaped slots. A wide bandwidth for UWB applications is achieved using a monopole antenna with single and dual band-notched characteristics [14]. A C-shaped slot in the patch to implement a planar UWB antenna with 3.4/5.5 GHz dual band-notched is presented in [10].

Over these designs, theoretical method is used to determine the notch band frequency. Other techniques are used to notch the UWB band. The notch frequency of slot-loaded printed UWB antennas can be predicted by applying the slot-line theory [15]. Use of genetic algorithms to place frequency notches within UWB band is presented [16]. Since, artificial neural networks (ANN) are widely used in the design of microstrip patch antenna [17-23]. The originality of this work is the implementation of the ANN technique using k-fold cross-validation method in order to enhance the performance of the proposed ANN model and to accurately predict the notch frequency of the proposed UWB antenna. Related to the researches cited above, the antenna presented in this paper, is physically small with a partial ground plane, and has the notch band characteristic besides good impedance bandwidth.

2. ANN MODEL

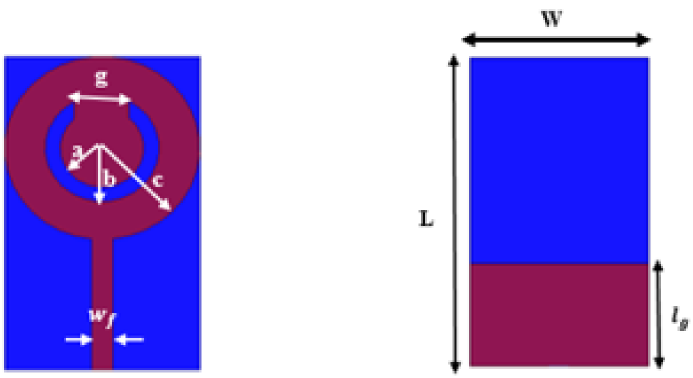
2.1. Proposed antenna

In this work, we are based on the ANN technique to predict the notch frequency of an UWB antenna. The proposed UWB antenna consists of a dielectric substrate FR4-epoxy with dielectric permittivity ($\varepsilon\_r = 4.3$), loss tangent ($tan\,\delta = 0.025$), length ($L = 24\,mm$), width ($W = 14\,mm$), and thickness ($h = 0.8\,mm$). In the bottom side of the substrate we have a partial ground plane ($l_g = 9\,mm$) to ensure a good impedance bandwidth. In the other side of the substrate, we have a circular patch of copper ($c = 7\,mm$) in which we inserted a split ring to achieve the notch band characteristic. The configuration of the proposed antenna is illustrated in Figure 1. The split ring is characterized by the dimensions a, b, and g, these dimensions can be used to calculate the notch band frequency by applying the given formula [15] as shown in (1):

$$f_c = \frac{c}{2L_{NB}\sqrt{\varepsilon_{eff}}} \quad (1)$$

where c is the speed of light, L_{NB} is the length of the etched split ring in the circular patch which is $(2\pi a + 2(b - a) - g)$, and ε_{eff} is the effective dielectric constant (2).

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} \quad (2)$$



(a) (b)

Figure 1. Configuration of the proposed antenna; (a) front view and (b) back view

2.2. Parametric analysis

As demonstrated in (1), the physical dimensions of the split ring a, b, g and the electrical parameter ε_r affect directly the notch band frequency. For this reason, we have done a parametric analysis in which we study the effect of changing the parameters a, b, g, and ε_r on the VSWR and consequently the notch band frequency as shown in Figure 2. We can notice from Figure 2 (a), the increase of the parameter a (inner radius of the split ring) from 1.41 to 3.81 mm, the central frequency shifted to the lower frequencies until its disappearance. While, by increasing the outer radius of the split ring (parameter b), the VSWR increases and the notch frequency shifted to lower frequencies as shown in Figure 2 (b).

The gap of the split ring (parameter g) affects also the VSWR and the notch band frequency. By varying the gap g from 1.42 to 3.82 mm, the central frequency moves slightly to high frequencies as illustrated in Figure 2 (c). The last parameter which affects the VSWR is the electrical parameter ε_r. We have taken three different dielectric substrates (2.2, 4.3, and 6.15), as given in Figure 2 (d), the notch band frequency took three different values 4.8 GHz, 5.5 GHz, and 6.5 GHz. It is clear from these results that the parameters a, b, g, and ε_r affect directly the VSWR and the notch band frequency.

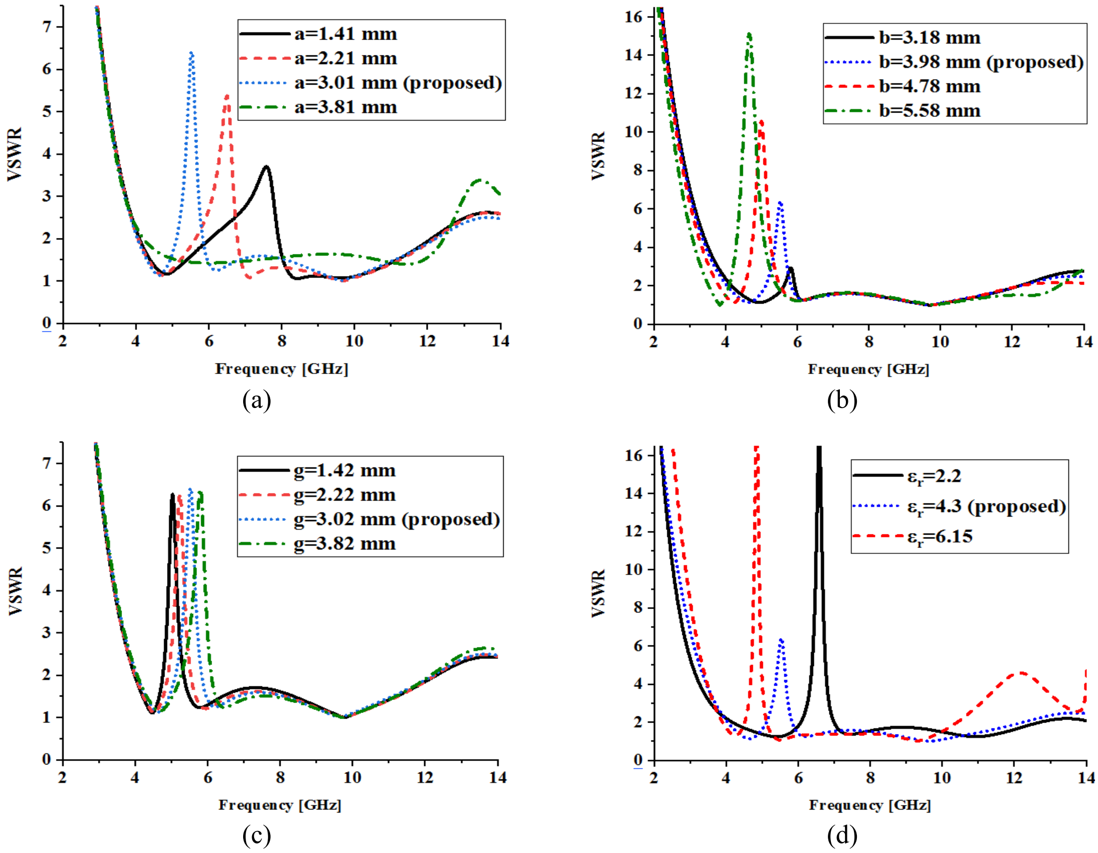


Figure 2. Parametric analysis; (a) parameter a, (b) parameter b, (c) parameter g, (d) parameter ε_r

2.3. Developed ANN model

To establish the ANN model, we followed the steps described below. As a first step in creating an ANN network, we generated the database by varying the parameters a, b, g, and ε_r within a specified range and recording the corresponding frequency for VSWR > 2 which defines the notch frequency. The collecting of datasets was realized using a visual basic (VB) script which controls the HFSS simulator from MATLAB. Hence, 360 simulations have been carried out with variant dimensions a, b, g, and different dielectric substrate characterized by ε_r as shown in Table 1 and Figure 3. The notch frequency f_c was used as the output of the model, while the parameters a, b, g, and ε_r are used as the input of the model.

Another step to create the ANN model is to determine the number of hidden layers and the number of neurons in each hidden layer, these parameters are determined accurately by observing some statistical criteria like mean squared error (MSE) and mean absolute percentage error (MAPE). In this work, we adopted two hidden layers with 25 neurons each. Afterwards, we choose the appropriate training algorithm among resilient backpropagation (RP), Polak-Ribiere conjugate gradient (CGP), one step secant (OSS), scaled conjugate gradient (SCG), and Levenberg-Marquardt (LM). It seems that the LM algorithm gives a better accuracy. The parameters of the ANN model used in this study are summarized in Table 2. The flowchart methodology of this research is shown in Figure 4.

Table 1. 360 generated datasets

Number of samples	a	b	g	ε_r
120	2,3,4,5	2.5,3.5,4.5,5.5	1,2,3,4	2.2,4.3,6.15
120	2.5,3.5,4.5,5.5	3,4,5,6	1,2,3,4	2.2,4.3,6.15
120	2,3,4,5	2.3,3.3,4.3,5.3	1.5,2.5,3.5,4.5	2.2,4.3,6.15

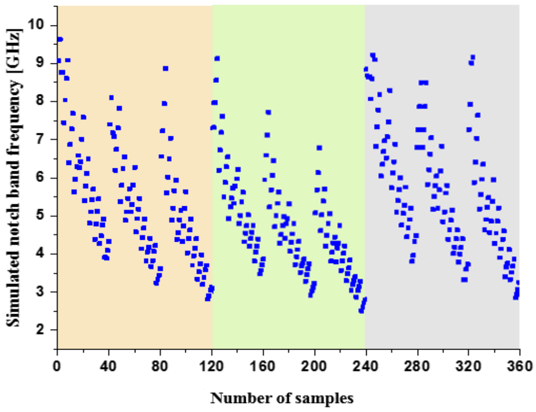


Figure 3. Simulated notch band frequency

Table 2. ANN model parameters

ANN parameters	Attributes
Data base	360
Input	a, b, g, ε_r
Output	f_c
Training algorithm	LM
Activation function	'Tansig'(hidden layer), 'purelin'(output layer)
Structure	4-25-25-1

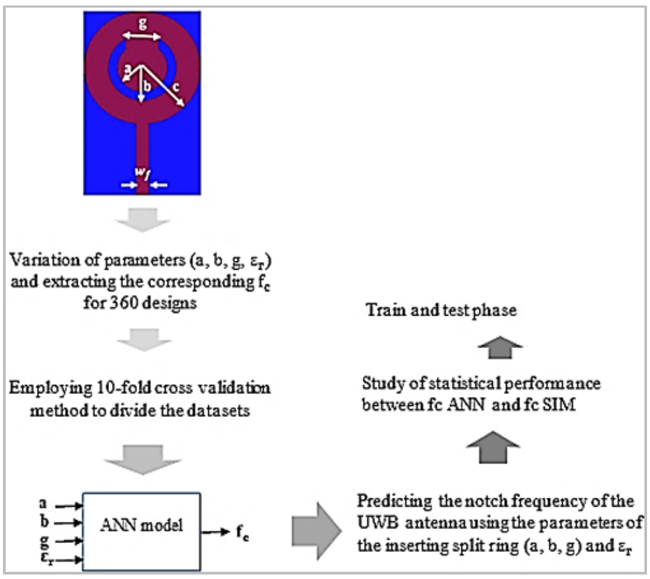


Figure 4. Flowchart of the study

3. K-FOLD CORSS VALIDATION METHOD

In this study, we applied the k-fold cross validation method to divide the datasets. In the training phase, we used 10-fold cross validation method. The datasets are divided in 10 subsets; where each time, one of the 10 subsets is used as the test set and the remaining 9 subsets are joined together to form the training set. The training process is then repeated 10 times. The advantage of this method is that every subset has one chance to be in a test set exactly once, and has the chance to be in a training set 9 times. The 10-fold cross-validation method is illustrated in Figure 5.

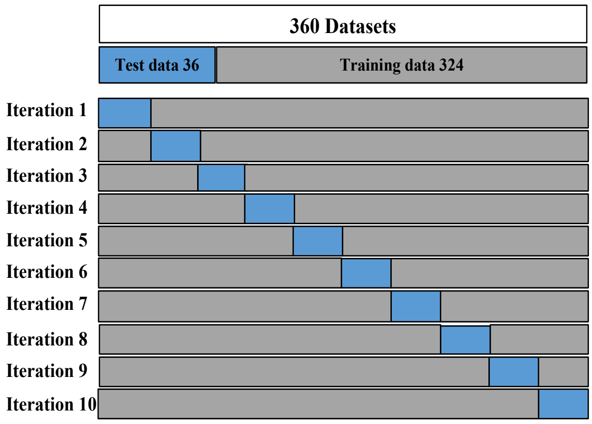


Figure 5. 10-fold cross-validation method

For each time, we calculate the mean squared error (MSE) and the mean absolute percentage error (MAPE) after each iteration during the test phase. The MSE and the MAPE are given by the following equations [24, 25]:
Mean squared error:

$$\mathrm{MSE} = \left(\frac{1}{n}\right) \sum_{i=1}^{n} (t_i - \alpha_i)^2 \tag{3}$$

Mean absolute percentage error:

$$\mathrm{MAPE} = \left(\frac{100}{n} \sum_{i=1}^{n} \left|\frac{t_i - \alpha_i}{t_i}\right|\right) \tag{4}$$

where n is the total number of samples, and t_i and α_i represent, respectively, the target and output data. The MSE and MAPE after 10 turns are given in Table 3. The MSE (Total) and MAPE (Total) are respectively 0.039 and 0.125.

$$\mathrm{MSE\ (Total)} = \frac{1}{10} \sum \mathrm{MSE} \tag{5}$$

$$\mathrm{MAPE\ (Total)} = \frac{1}{10} \sum \mathrm{MAPE} \tag{6}$$

Table 3. MSE and MAPE for 10 iterations

Iteration	MSE	MAPE
1 fold	0.314	0.499
2 fold	0.042	0.256
3 fold	0.020	0.170
4 fold	0.015	0.133
5 fold	0.003	0.078
6 fold	0.001	0.056
7 fold	7.47E-04	0.030
8 fold	6.64E-05	0.012
9 fold	3.70E-05	0.010
10 fold	1.45E-05	0.005

4. RESULTS AND DISCUSSIONS

In order to evaluate the performance of the developed model, we present in Figure 6 the regression coefficient R of our ANN network which describes the relationship between the predicted values (output) and the simulated values (target). The data should fall along a 45-degree line, for a perfect fit, where the network outputs are equal to the targets. For this problem, the fit is good for all data sets, with R values in each case is R=1. In term of the value of this coefficient, the built ANN network with the structure (4-25-25-1) is efficient to predict the notch band frequency of the presented UWB antenna.

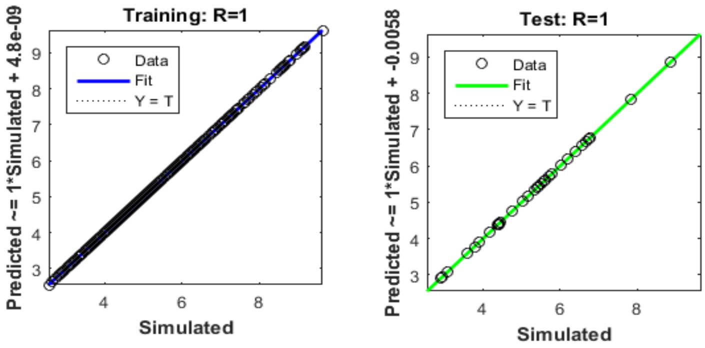


Figure 6. Regression curves of trained ANN

The difference between the notch frequency obtained by ANN, simulated, and calculated results during the training process is plotted in Figure 7. As shown in Figure 7, we can notice a good matching between the simulated and the predicted ANN notch frequency. In the testing process, 36 datasets which are not involved in the training phase are used to evaluate the performance of the proposed ANN model. During this evaluation, the ANN notch band frequency output is compared with the theoretical and simulated findings as shown in Table 4.

In order to validate the proposed ANN model performed by the k-fold cross validation method, we simulate the proposed UWB antenna using the high frequency structural simulator (HFSS) simulator. The validation consists of determining the corresponding notch frequency by exploiting the VSWR result and comparing it with the theoretical one, and the ANN findings as shown in Table 5. During the test and validation process, good accuracy is attained between the simulated and the ANN results. In Figure 8, we plotted the simulated S_{11} result using both electromagnetic simulators HFSS and CST. From the -10 dB bandwidth simulated results illustrated in Figure 8, it is clear that the antenna covers the entire band from 3.85-12.38 GHz except the notched band 5.1- 6 GHz, this result indicates that the proposed antenna can be a better candidate for UWB applications. The difference between the HFSS and CST results is due to the fact that the used methods by the two simulators are different; HFSS is based on finite element method (FEM) while CST is based upon finite integration technique (FIT).

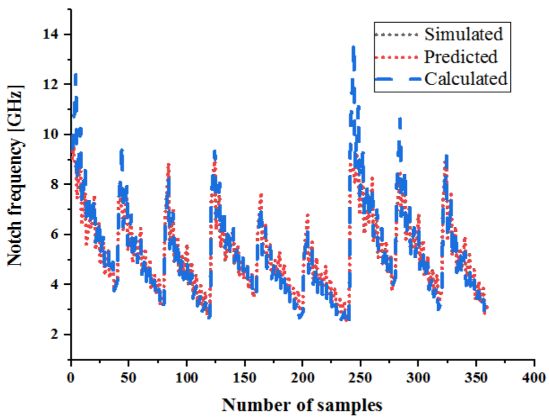


Figure 7. Comparative results of the notch frequency: simulated, predicted, and calculated

Table 4. Testing process

Antenna parameters				fc [GHz]			Antenna parameters				fc [GHz]		
a	b	g	ε_r	SIM	ANN	CAL	a	B	g	ε_r	SIM	ANN	CAL
2	4.5	1	2.2	6,392	6,3926	7,161	3.5	5	4	22	5,624	5,6133	5,6523
2	5.5	1	2.2	5,624	5,6206	6,3893	3.5	6	4	2.2	5,036	5,0344	5,1604
2	5.5	4	2.2	6,584	6,5848	7,6212	3.5	4	1	4.3	4,436	4,4419	4,1922
4	4.5	4	2.2	5,444	5,4464	5,361	4.5	5	3	4.3	3,788	3,7801	3,5089
5	5.5	1	22	3.92	3.92	3,7766	2.5	3	4	6.15	6,776	6,7849	6,2467
2	3.5	2	4.3	6.74	6,7411	6,7953	2	53	15	2.2	6,032	6,0287	6,7149
2	3.5	4	4.3	7.82	7,8234	7,971	2	5.3	3.5	2.2	6,668	6,6686	7,5725
2	5.5	4	4.3	5,708	5,7071	5,9219	3	4.3	1.5	2.2	5.72	5.72	5,9471
4	4.5	3	4.3	4,172	4,1687	3,9855	3	5.3	25	2.2	5,396	5,3972	5,6631
4	4.5	4	4.3	4,412	4,4101	4,1657	4	4.3	15	2.2	4.76	4,761	4,8962
5	5.5	4	4.3	3,608	3,606	3,2445	2	5.3	1.5	4.3	5,168	5,1686	5,2177
2	2.5	4	6.15	8,864	8,8713	8,2984	2	5.3	2.5	4.3	5,504	5,5033	5,5309
3	4.5	2	6.15	4.4	4,3989	3,9986	2	5.3	4.5	4.3	6,032	6,0256	6,2854
5	5.5	2	6.15	2,912	2,916	2,6096	3	4.3	3.5	4.3	5.59	5,5926	5,1362
2.5	4	1	2.2	6.2	6,2004	6,6997	4	5.3	3.5	4.3	4,172	4,1716	3,8045
3.5	4	1	2.2	5,336	5,3334	5,3952	3	5.3	3.5	6.15	4,388	4,3877	3,9786
3.5	4	2	2.2	5,792	5,788	5,6523	5	5.3	2.5	6.15	2.96	2,9555	2,6893
3.5	5	2	2.2	5,024	5,0241	5,1604	5	5.3	3.5	6.15	3.08	3,0781	2,7836

Table 5. Comparative results of the notch frequency of the proposed antenna

Method	Simulated	ANN	Calculated
Notch frequency [GHz]	5,517	5,516	5,170

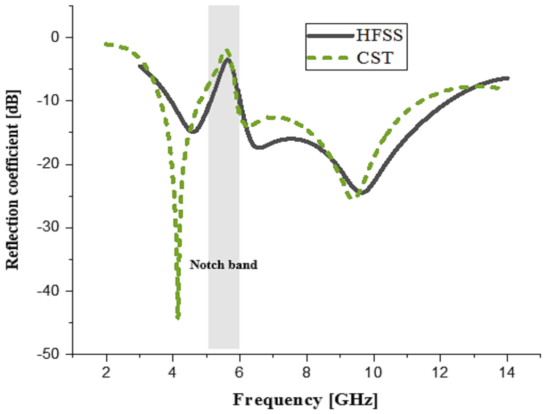


Figure 8. Reflection coefficient of the presented antenna

5. CONCLUSION

In this paper we used the ANN technique to predict with high accuracy the notch frequency of an UWB antenna. The precision of the proposed technique has been improved by employing the k-fold cross validation method. The developed ANN technique was evaluated using different criteria. Hence, during the training and testing phases, we have determined the mean absolute percentage error (MAPE) and the mean squared error (MSE) between the simulated and the predicted ANN notch frequency, good findings are attained. Furthermore, we determined the regression coefficient which indicates a value of R=1 verifying a good consistency between the simulated and the predicted notch frequency. The proposed UWB antenna designed in HFSS and CST simulators exhibits a notch band from 5.1 to 6.0 GHz centered at 5.51 GHz, this characteristic allows to avoid interferences between (WLAN) IEEE802.11a and HIPERLAN/2 WLAN applications and UWB technology.

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