

Surrogate-Based Design Optimization of Multi-Band Antenna

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Abstract – In this work, design optimization process of a multi-band antenna via the use of artificial neural network (ANN) based surrogate model and meta-heuristic optimizers are studied. For this mean, first, by using Latin-Hyper cube sampling method, a data set based on 3D full wave electromagnetic (EM) simulator is generated to train an ANN-based model. By using the ANN-based surrogate model and a meta-heuristic optimizer invasive weed optimization (IWO), design optimization of a multi-band antenna for (1) 2.4–3.6 GHz for ISM, LTE, and 5G sub-frequencies, and (2) 9–10 GHz for X-band applications is aimed. The obtained results are compared with the measured and simulated results of 3D EM simulation tool. Results show that the proposed methodology provides a computationally efficient design optimization process for design optimization of multi-band antennas.

Index Terms – Artificial Neural Network (ANN), multi-band antenna, optimization, surrogate modeling.

I. INTRODUCTION

With the rapid improvement in wireless communication systems, many systems with different standards, global system for mobile communications (GSM), universal mobile telecommunications system (UMTS), wireless local area network (WLAN) [1], have been developed in the last decades. Since each of the mentioned systems may require to operate in different frequencies, instead of having multiple antenna designs, it is more convenient to have an antenna with broadband or multi-band characteristics [2–5].

Many works had been proposed for achieving designs with multi-band characteristics using 3D printed multi-layer antenna [6], stacked designs with novel meta-material [7], designs comprising two planar inverted F antenna (PIFA) elements integrated with two PIN diodes [8], alongside of unique designs such as star-shaped patch and their performance evaluations [9].

However, optimization of such designs is a challenging problem where increases in the complexity of design for achieving multi-band characteristics would also increase the simulation duration of these designs. Ultimately, this leads designers to choose between using a coarse model for the design optimization process at the expense of accuracy or using a fine model at the expense of having a computationally inefficient design optimization process [10].

One of the commonly used methods proposed for achieving mentioned design optimization problem is to employ data-driven surrogate models for design optimization. Surrogate-based models have many applications such as parameter tuning [11, 12], statistical analysis [13–15], and multi-objective design [16–18]. Although there are a series of techniques that can be used for surrogate-based modeling such as polynomial regression [19], Kriging interpolation [20], radial basis functions [21], support vector regression [22], and polynomial chaos expansion [23], one of the commonly used technique is artificial neural networks (ANNs) [10, 24].

Herein, to achieve a computationally efficient design optimization process for designing a multi-band antenna, ANN-based surrogate modeling of an antenna design is studied. First, a 3D electromagnetic (EM)

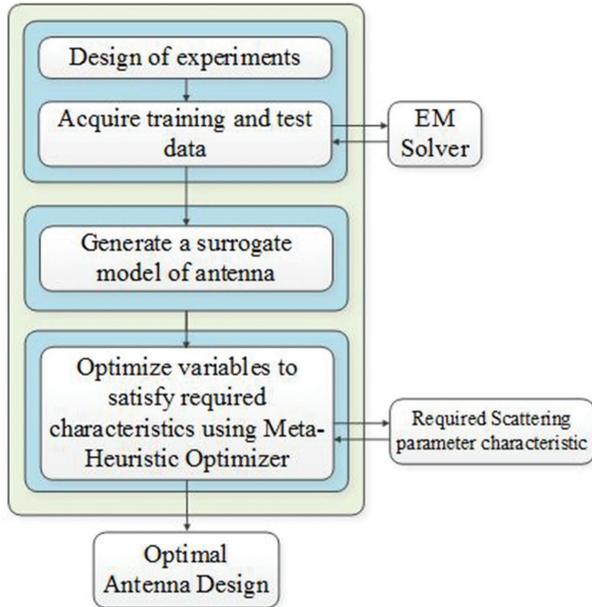


Fig. 1. Flow chart of the proposed design optimization process.

simulation-based data set of the antenna design has been generated using the 3D full-wave EM-simulator tool. Here, a novel regression ANN algorithm, modified multi-layer perceptron (M2LP) [25, 26] is used for creating the mapping between input and output of the data set. After that, by using M2LP, a surrogate model of the design has been generated. Finally, the surrogate model is used alongside of a meta-heuristic optimization algorithm to achieve the desired antenna design. The general procedures of the study are presented in Figure 1.

II. SURROGATE-BASED MODELING OF ANTENNA

A. Proposed multi-band antenna and its data set

In this work, a microstrip antenna (Figure 2) with an E-shaped defected ground structure is taken for study to achieve the requested multi-band characteristics [27]. The antenna consists of a rectangular radiator, a 50- Ω microstrip feed line, and a ground plane. An E-shaped defected ground structure had been placed in the ground layer to tune the resonance frequency of the design without increasing the overall size of the antenna.

In Table 1, the variable space of data set belonging to the proposed antenna design has been presented alongside of their upper and lower limitations. In order to reduce the total number of design variables, some of the design parameters are taken as constants. $S1 = 2 \times W1$, $S5 = S2 + 2 \times S6$, $W2 = 11.6$ (mm), and $L2 = 3$ (mm) for having a transmission line with 50- Ω for FR4 substrate, and $S3 = 0.5$ (mm). Furthermore, in order to have a computationally efficient modeling, the number

Table 1: Design variables and their variation limits

Variable	Min	Max
$W1$	15	25
$L1$	10	20
$S2$	5	15
$S4$	10	20
$S6$	2	8
$S7$	2	8

of training samples should be low as much as possible. For this mean, instead of using traditional linear sampling which might end up making the required training samples size up to thousands, Latin-Hyper cube sampling (LHS) method is used for generating design samples from the ranges given in Table 1. By using LHS, a training data set with 500 samples and a test data set with 100 samples had been generated to be used for training the proposed surrogate model. The frequency range is 1–10 GHz with a step size of 0.1.

B. ANN-based surrogate model

In this sub-section, the generated data set is used for creating a surrogate model to create a mapping between the given input parameters in Table 1 and scattering parameters of the proposed antenna design. Herein, in order to compare the performance of the M2LP model, traditional counterpart and commonly used state-of-the-art regression algorithms in literature such as (1) multi-layer perceptron, (2) support vector regression machine [22], (3) gradient boosted tree [28], (4) Keras deep residual neural network regressor [29], and (5) Gaussian process regression [30] are taken into consideration. The performance of the mentioned methods is presented in Table 2. The given performance belongs to the k -fold validation results where $k = 5$. Furthermore, for checking the overfitting performance of the models, the holdout performance of the models evaluated using 100 sample test data sets are presented. The given values are calculated using relative mean error (RME) metric:

$$\text{RME} = \frac{1}{N} \sum_{i=1}^N \frac{|T_i - P_i|}{|T_i|}. \quad (1)$$

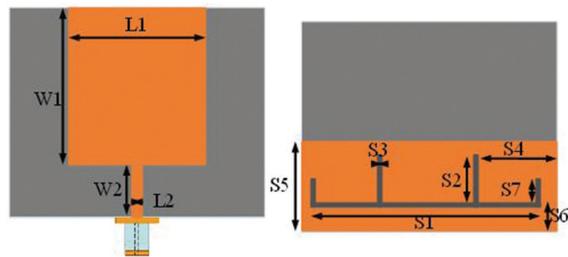


Fig. 2. Schematic of the proposed multi-band antenna.

Table 2: Performance results of surrogate models

Model	HP	K-fold/holdout
MLP	Two layers with 20 and 30 neurons	5.8%/6.8%
SVRM [22]	Epsilon SVR, Epsilon = 0.1, with radial basis kernel	7.1%/8.5%
Gradient boosted tree [28]	Learning rate of 0.02 6250 number of estimators and depth of 5	6.6%/7.5%
Keras deep residual neural network regressor [29]	Two layers: 512, 512 units	4.8%/5.3%
Gaussian process regression [30]	Kernel function “matern5/2,” prediction method of block coordinate descent with block size of 1500	4.4%/5.2%
M2LP	Depth size of 2, initial neuron number of 32	3.9%/4.8%

Here, T_i is the i th sample targeted value, P_i is the i th sample predicted value, and N is the total number of tested samples over the given operation frequency.

As it can be seen from the table, the M2LP method achieves better k -fold and holdout performance compared to other counterpart algorithms where both of the metrics are less than 5%. Thus, the M2LP does not fall into overfitting while having a good validation error. Thus, from now on, M2LP will be used as the surrogate model of the antenna for the design optimization process.

III. STUDY CASE: DESIGN OPTIMIZATION USING ANN-BASED SURROGATE MODEL

Herein, for the determination of optimal design variables of the proposed multi-band antenna, a population-based meta-heuristic optimization algorithm, invasive weed optimization (IWO) [31], has been used (Figure 3). IWO is inspired from the behavior of weed colonies, in which the population members are in search of an optimal environment to live [31]. Some of the applications of IWO in design optimization of microwave antennas can be named as aperiodic planar thinned array antennas [32], the shape of non-planar electronically scanned arrays [33], directivity maximization of uniform linear array of half-wavelength dipoles [34], low-pass elliptic filter [35], reflector antenna [36], design of a compact step impedance transmission line low-pass filter [37], and design optimization of di-electric loaded horn

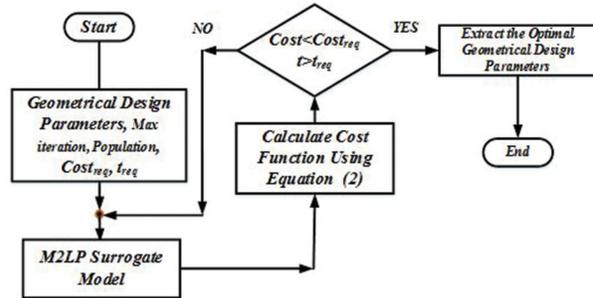


Fig. 3. Flow chart of the IWO search.

Table 3: Optimally selected design values in [mm]

W1	19	S4	13.8
L1	15	S6	3.6
S2	8.5	S7	5.5

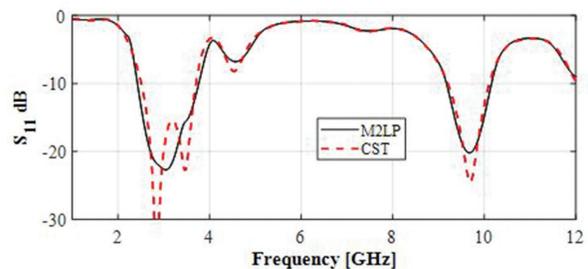


Fig. 4. Simulated results of multi-band antenna.

antennas [38]. The search protocol of the IWO algorithm is driven by cost function defined in the following equation:

$$\text{Cost} = \sum_{f_{\min_1}}^{f_{\max_1}} \frac{C_1}{|S_{11_i}(f)|} + \sum_{f_{\min_2}}^{f_{\max_2}} \frac{C_2}{|S_{11_i}(f)|}. \quad (2)$$

Here, C values are weighing coefficients of cost function sub-criteria. Since, in this work, the importance of each of the bands is equal, these coefficients are taken equally as $C_1 = C_2 = 1$. Here, the goal is to maximize both of the S_{11} values in the given frequency ranges. The aimed operation bands of the multi-band antenna are taken as: (1) 2.4–3.6 GHz for ISM, LTE, and 5G sub-frequencies; (2) 9–10 GHz for X-band applications.

In Table 3, the optimally selected design variables obtained from IWO algorithm are presented.

The results obtained using the proposed M2LP-based optimization technique had been compared with the simulated results of 3D full-wave EM simulator CST (Figure 4).

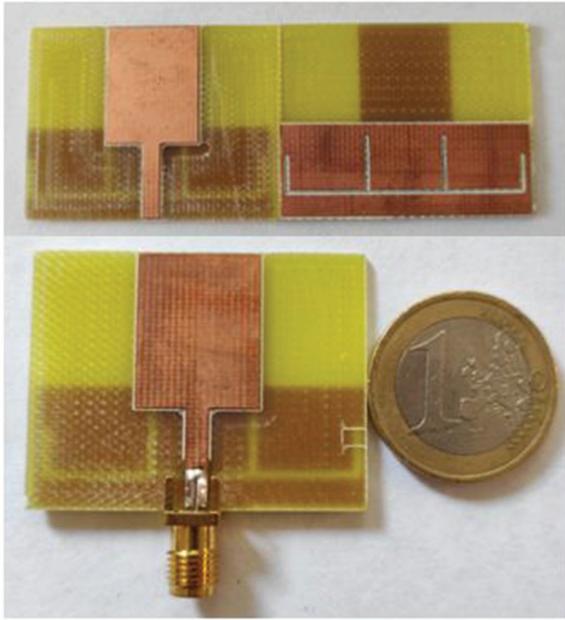


Fig. 5. The prototyped multi-band antenna.

IV. FABRICATION AND MEASUREMENT

For justification of the proposed designed methodology, the designed antenna in the previous section had been prototyped (Figure 5). The measurement devices (a network analyzer with a measurement bandwidth of 9 KHz to 13.5 GHz, and LB-8180-NF broadband horn antenna of 0.8–18 GHz as reference antenna) available in Microwave Laboratories of Yildiz Technical University had been used.

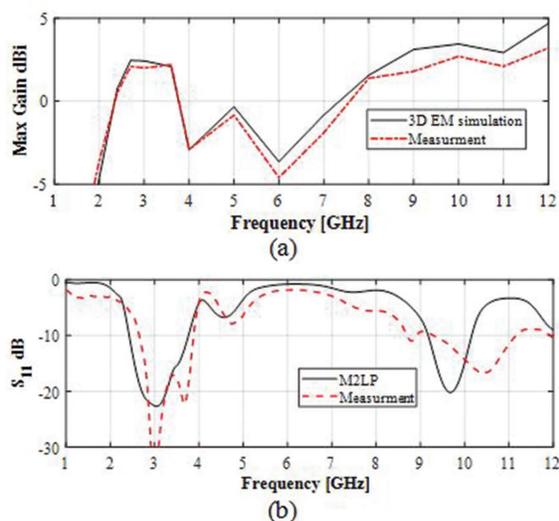


Fig. 6. Measured (a) maximum gain and (b) scattering parameters, over the operation band.

In Figure 6, the measured results of maximum gain over frequency and scattering parameter of prototyped antenna are presented. As it can be seen from the figure, the measured performances of the antenna are in agreement with the simulated results obtained in previous sections.

V. CONCLUSION

Herein, by using surrogate-based modeling technique, a computationally efficient design optimization of a multi-band microstrip antenna has been achieved. Toward this end, a M2LP regression model is used alongside of a meta-heuristic optimization algorithm IWO to determine the optimal design variables for selected operation bands of ISM, LTE, 5G sub-frequencies, and X-band applications. The obtained optimal design performance had been compared with both the simulated results from the 3D full-wave EM simulator tool and measured results of the prototyped antenna. Thus, in this work, computationally efficient design optimization process for having a multi-band microstrip antenna is achieved via the use of a novel regression model M2LP and a meta-heuristic optimization algorithm IWO.

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