Design Optimization of Ultra-Wideband Vivaldi Antenna using Artificial Intelligence

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Abstract – In this work, computationally efficient design optimization of frequency selective surface (FSS)-loaded ultra-wideband Vivaldi antenna via the use of data-driven surrogate model is studied. The proposed design methodology consists of a multi-layer FSS structure aimed for performance improvement of the Vivaldi design, which makes the design a multi-objective multi-dimensional optimization problem. For having a fast and accurate optimization process, a data-driven surrogate model alongside the metaheuristic optimizer honey-bee mating optimization (HBMO) had been used. The optimally designed antenna had been prototyped and its performance characteristics had been measured. The obtained experimental results are compared with the simulated results of the proposed method. Results show that the obtained FSS-loaded structure has enhanced directivity compared with the design without FSS structure, without any performance losses in the return loss characteristics. The FSS-loaded Vivaldi antenna operates at 2–12 GHz band with a maximum gain of 10 dBi at 10 GHz which makes the design a good solution for RADAR applications.

Index Terms – Frequency selective surface, optimization, surrogate modeling, ultra-wideband, Vivaldi antenna.

I. INTRODUCTION

Due to their high-performance characteristics Vivaldi antenna designs are being used in many communication applications such as microwave imaging and ground penetrating radar (GPR) [1], [2]. In order to analyze the composition of underground soil, GPR requires to propagate high-power EM wave to the ground. In order to have a wide range of characterization of soil the signals need to go deep into the ground and have high resolution. For such capability the GPR antenna requires to operate in low frequency, have ultra-wideband characteristics, and high gain performance [3]. There are different types of antennas suitable for GPR applications with respect to their characteristics such as o GPR antenna dipole [4], bowtie [5], [6], and Vivaldi antennas [7], [8]. Due to its high gain, ultra-wideband characteristic, Vivaldi antenna can be named as one of the most commonly used antenna design for GPR applications. It should be noted that such designs usually require a large design space or smaller size with lower performance measures. Usage of lens structures can be named as one of the methods for performance improvement of antenna designs [9], [10]. However, although the placement of dielectric lens structures can increase the gain performance of antenna but their improvements are limited [11].

Another well-known solution for performance enhancement of antenna designs is the placement of frequency selective surfaces (FSS) to the aperture of the antenna in an optimally determined configuration such as: antenna design with a multi-layer S-type resonator with zero index for gain enhancement [12], design with

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multi-layers [13], [14] for gain enhancement, and [15] for sidelobe suppression of the antenna design. Although the application of FSS can provide a significant performance improvement to the design, the placement and the geometrical design of FSS structures must be optimized to reach their full performance of improvement. Achieving such task requires a multi-objective multi-dimensional optimization process, which requires a considerable amount of trial and error. This process usually forces researchers to make a decision for their models. Either they should use a course model with low accuracy for achieving fast and computationally efficient design optimization or they must use fine meshed design with high accuracy at expanse of relatively long or infeasible design optimization process [16].

One of the most efficient solutions for having an accurate, reliable, and computationally efficient optimization process is the usage of data-driven surrogate models. Data-driven surrogate models had been used by many researches for applications such as parameter tuning [17], statistical analysis [18], [19], and multi-objective design [20]. In literature, there are many Artificial Intelligence (AI)-based methods for surrogate-based modeling of microwave structures such as polynomial regression [21], kriging interpolation [22], radial basis functions [23], support vector regression [24], polynomial chaos expansion [25], and artificial neural networks (ANN) [26].

In this work, for optimal determination of geometrical design variables of an FSS structure to be applied to an antipodal Vivaldi antenna (AVA) for performance improvements have been achieved via the use of data-driven surrogate modeling [27]. Firstly, an FSS-loaded Vivaldi antenna have been presented in Section II, alongside the design variables of FSS structure. By using Latin-hypercube sampling method, a data set generated with a 3D full-wave EM simulator is created to be used for data-driven surrogate model to create a mapping between geometrical design parameters of FSS structure and performance measures of scattering and maximum gain of the FSS-loaded Vivaldi antenna design. In Section III, some of the commonly used state of the art AI regression algorithms had been used and bench marked to obtain a model with best performance for creating a mapping between input and output of the data set. In Section IV, the optimal selected surrogate model will be used to drive the design optimization search alongside a meta-heuristic optimizer. Finally, the work ends with a brief conclusion in Section V.

II. FSS-LOADED VIVALDI ANTENNA

In Figure 1, a typical AVA design modeled in 3D CST MWS environment is presented. AVA is designed on a PLA Filament–Polar White RBX-PLA-WH002 (ε_r = 2.5) with two noncoplanar exponentially tapered edge arms on both top and ground plane (symmetrically) of the antenna. The exponentially tapered edges of the design are defined as exponential factor R, P1(x_1, y_1), and P_2(x_2, y_2), initial and final points of the exponential tapered shape respectively. Design equations are given below as eqn (1)–(3) [28, 29]:

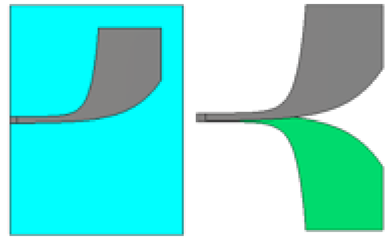


Fig. 1. A typical antipodal vivaldi antenna.

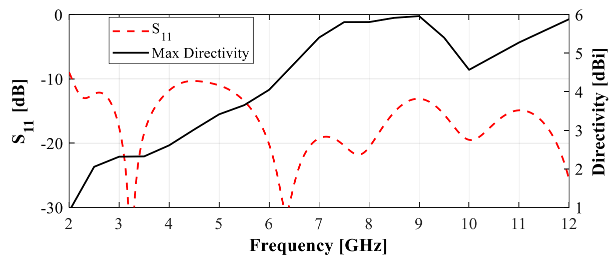


Fig. 2. Simulated performance of the vivaldi antenna.

$$y = C_1 e^{Rx} + C_2, \tag{1}$$

where

$$C_1 = \frac{y_2 - y_1}{e^{Rx_2} - e^{Rx_1}} \tag{2}$$

$$C_2 = \frac{y_1 e^{Rx_2} - y_2 e^{Rx_1}}{e^{Rx_2} - e^{Rx_1}} \tag{3}$$

C_1 = 5, C_2 = 0, R = 0.03; and C_1 = 15, C_2 = –8, R = 0.1, respectively. In Figure 2, the simulated performance of the Vivaldi antenna without FSS structure had been presented.

In Figure 3, the schematic of the proposed FSS structure to be placed in top and ground layer sides of Vivaldi antenna is presented. The variables of the FSS structure and their lower and upper limitations are presented in Table 1. For ease of modeling, L2 is taken as equal to L1. Here, for having computationally efficient modeling, the total number of training and test samples are taken as 600 where 500 of the samples are used for

Table 1: Design variables and their variation limits

Variable	Min	Max	Variable	Min	Max
W1	5	15	**L1**	2	8
S1	0.5	2	**H2**	2	6

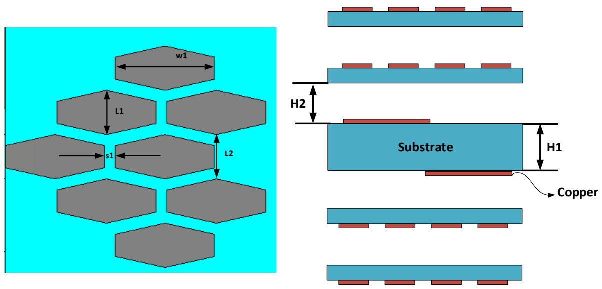


Fig. 3. Schematic of the proposed FSS-loaded Vivaldi antenna.

Table 2: Design variables and their variation limits

Model	HP	K-fold/Holdout
MLP	2 layers with 15 and 20 neurons, trained with "Levenberg–Marquardt"	9.1%/10.5%
SVRM	Epsilon SVR, Epsilon = 0.15, with radial basis kernel	7.9%/8.5%
Gradient boosted tree	Learning rate of 0.05 1500 number of estimators and depth of 7	10.6%/11.5%
Random forest	Max depth 10, 200 number of estimators, leaf size of 20	11.1%/11.9%
Gaussian process regression	Kernel function of "matern3/2," Prediction method of Block coordinate descent with block size of 2500	8.3%/9.0%

training and 100 are taken as "hold-out" data for evaluation of over-fitting performance of surrogate models. For sampling method, Latin-Hyper cube sampling (LHS) method is used. The frequency range is 1–12 GHz with a step size of 0.1 GHz.

III. SURROGATE MODELING

In this section, some of the commonly used AI regression algorithms have been used for creating a surrogate model for creating a mapping between design variables of FSS structure and the outputs of maximum gain and scattering parameters of the antenna design. For creating the surrogate model of the FSS-loaded Vivaldi antenna, the algorithms given in Table 2 are trained with K = 5 K-fold cross validation. Furthermore, a holdout data set with 100 samples is used for testing the over-fitting performance of the models. Relative Mean Error (RME) metric (Eqn (4)) have been used for performance study of models.

$$RME = \frac{1}{N}\sum_{i=1}^{N}\frac{|T_i - P_i|}{|T_i|}. \tag{4}$$

Here, T_i is the ith sample targeted value, P_i is the ith sample predicted value, N is the total number of tested samples over the given operation frequency. Here, the obtained RME values are combined values for both S_{11} and maximum gain at each frequency sample. With respect to the obtained results in Table 2, support vector regression machine (SVRM) had been taken as the best surrogate model to be used in the design optimization process due to having the lowest K-fold and hold out RME.

IV. DESIGN OPTIMIZATION

Herein, for determination of optimal design variables of the proposed antenna, a powerful population-based hybrid metaheuristic algorithm HBMO had been used [30, 31]. HBMO is an algorithm based on the mating habits of honey bees in which the new born members of the bee colony (usually assumed that all members are female) are ranked based on their fitness to be the new queen of the colony. The search for the new queen can be considered a global search strategy where there is no initial knowledge of the optimal solution [30]. When, the nurse bee finds a candidate with better fitness values than the current queen the candidate will be crowned as the queen. After the coronation, in order to enhance the development of the new queen and her breeding capabilities, the nurse bees start to feed the queen with "Royal Jelly," a nutrition that can significantly enhance the fitness of the new queen. This process can be considered as a local search where there is an initial knowledge about a global or local optimum which can be furthered enhanced [31]. It should be noted that, although there are many novel and recently published global search metaheuristic optimization algorithms in literature that might have better convergence speed than the used HBMO algorithm, the main concern of this work is not focused on the convergence performance nor the selection of optimal metaheuristic optimization algorithm. In this work, with the usage of the proposed data-driven surrogate modeling technique, the simulation time required for the prediction of scattering and directivity characteristics of the antenna would be much less than a second while single EM simulation for the selected antenna might take up to 5 minutes or more with respect to the mesh size and the used hard ware setup. Thus, in a case that hundreds of function evaluations would took less than a minute the convergence speed of the algorithm can be neglected. Thus, here HBMO algorithm is taken as an example of a metaheuristic optimization algorithm for the selected problem. The cost function that had been used for HBMO

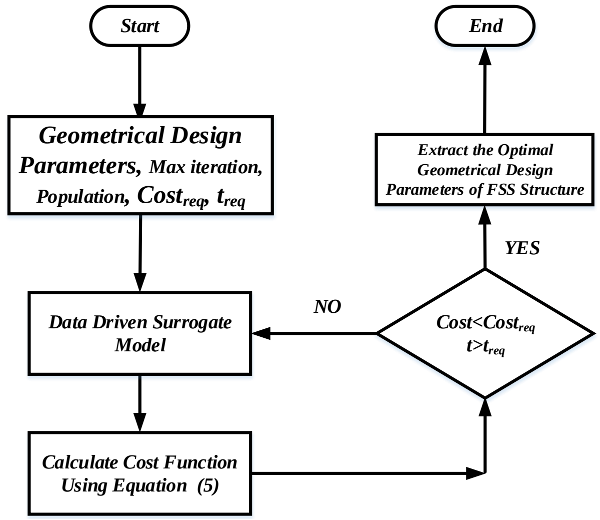


Fig. 4. Flow chart of the proposed optimization process.

search is presented in (5)–(7),

$$x^{*} = \underset{x}{\operatorname{argmin}}[w_1 C_1(x) + w_2 C_2(x)] \tag{5}$$

$$C_1(x) = \max\{f \in [f_{c1}, f_{c2}] : |S_{11}(x,f)|\} \tag{6}$$

$$C_2(x) = \max\{f \in [f_{c1}, f_{c2}] : Directivity(x,f)|\}, \tag{7}$$

where C is the cost function, x is the input vector of variables of $[W_1\ L_1\ S_1\ H_2]$, f_{c1} and f_{c2} denote the lower and upper frequency determining the target-operating band. The coefficients w_1 and w_2 are weighing of cost functions, these coefficients are taken as $w_1 = 0.7$ while $w_2 = 0.3$, due to the large possible difference between S_{11}, which can have low values such as –30 dB, and directivity for this design might be as high as 10 dBi. Here, the aimed operation bands of FSS-loaded Vivaldi antenna is to achieve an ultra-wideband operation frequency of 2–12 GHz which is an optimal operating range for RADAR applications. The flowchart of the proposed optimization algorithm is given in Figure 4. The optimally selected design variables of the design are as follows: W_1 = 8.75, L_1 = 4, S_1 = 1, H = 23.7 all in [mm]. These values are obtained after 15 iterations, 25 Drone bees, and Royal jelly step size of ±0.1 using HBMO optimization [30].

Furthermore, for justification of the proposed method, the obtained geometrical results are given to 3D EM model in CST and the performance measures of both CST and SVRM surrogate models are compared with each other. As it can be seen from Figure 5, the proposed method has the same performance characteristics as the 3D EM simulator tool.

V. FABRICATION AND MEASUREMENT

In this section, for further evaluation of accuracy and stability of the proposed design optimization method, the optimally designed antenna in section IV have been prototyped (Figure 6). The measurement devices (a Network Analyzer with a measurement bandwidth of 9 KHz–13.5 GHz, and LB-8180-NF Broadband Horn Antenna 0.8–18 GHz as reference antenna) available in Microwave Laboratories of Yildiz Technical University had been used.

In Figure 7, the measured experimental results of maximum gain, and scattering parameter of the optimally designed FSS-loaded Vivaldi antenna are

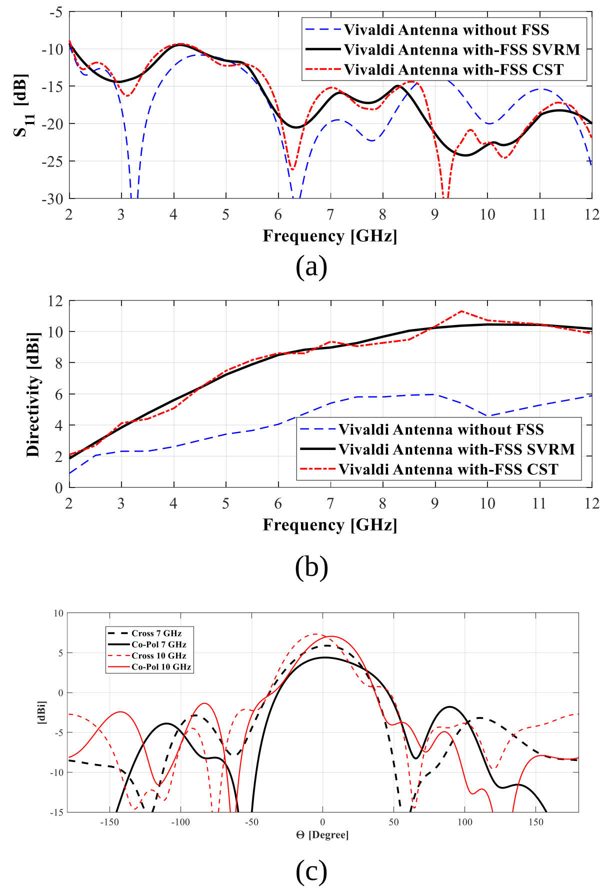


Fig. 5. Simulated (a) scattering, (b) directivity, (c) polarization of FSS loaded, antenna designs.

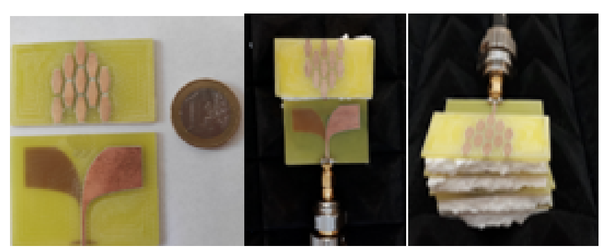
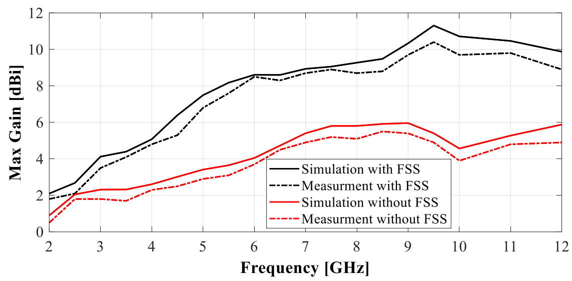
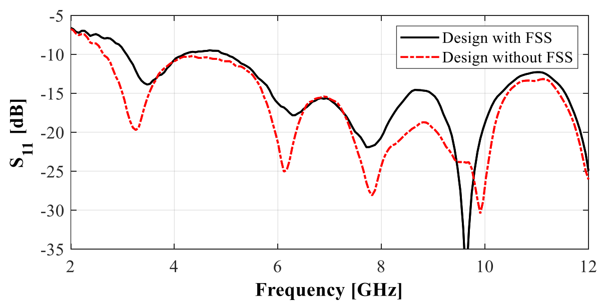


Fig. 6. The prototyped FSS-loaded Vivaldi antenna.

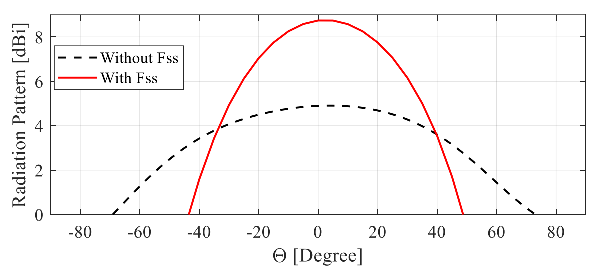


(a)

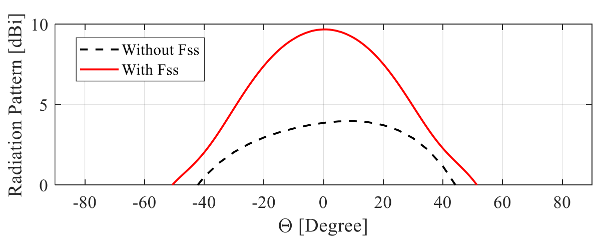


(b)

Fig. 7. Measured (a) maximum gain, (b) scattering parameters, over the operating band.



(a)



(b)

Fig. 8. Measured radiation pattern at (a) 7 GHz, (b) 10 GHz.

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. Furthermore, a performance comparison table of the proposed antenna design with the counterpart designs from the literature [32? –40] is presented in Table 3. As it can be deduced from the performance comparison table, the proposed antenna design achieves high gain, wide operation band performance compared to the counterpart designs in the literature with smaller size and lower cost material for substrate.

Table 3: RF performance comparison table

Work	***f* [GHz]**	**Gain [dBi]**	**Material**	**Size [mm]**
Here	2–12	2–11.8	FR4 Eps:4.4	50×58×1.8
32	3.5–16	3.5–12.5	RO4003C Eps: 3.38	80.5×52×14.5
33	1–12	1.5–5.1	FR4 Eps: 4.6	45×40×1.6
34	0.8–12	6.32	ARLON 600 Eps: 6.15	190×128×1.57
35	1.9–5.5	3.6–/4.6	FR4 Eps: 4.4	68.3×112.2×0.8
36	2–18	3/12.3	RO4003C Eps: 3.38	100×140×0.8
37	1.8/5.2	–/5.5	FR4 Eps: 4.3	80×60×1.6
38	2.9–11.6	–/3	Taconic RF-35 Eps: 3.5	26×26×0.76
39	2.4/5.2	3.6/2.5	FR4 Eps: 4.3	94.5×100×1.6
40	2.9–14.2	5–9	FR4 Eps: 4.3	40×50×1.6
41	0.8–3.4	2.4–8.1	FR4 Eps: 4.4	150×150×0508

*Most of the antenna designs have achieved similar S_{11} characteristics. Therefore, in this table S_{11} is not included.

VI. CONCLUSION

Herein, design optimization of an FSS-loaded Vivaldi antenna had been achieved using both SVRM-based surrogate model and a metaheuristic optimization algorithm HBMO. By using a multi-layer structured FSS design, the performance of a Vivaldi antenna has been increased without a distortion in the gain and scattering performance of the design. Furthermore, for justification of the proposed method the optimally designed antenna had been prototyped and its performance characteristics are measured. As a result, the measured characteristics are found to be in agreement with the simulated results of the proposed method. The proposed design achieves a maximum gain characteristic of 10 dBi with an operation bandwidth of 2–12 GHz which makes this design a suitable candidate for RADAR applications.

VII. ACKNOWLEDGMENT

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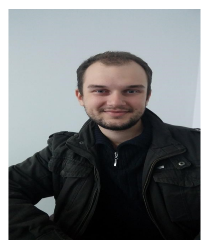

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