

Development of a High Gain FSS Reflector Backed Monopole Antenna Using Machine Learning for 5G Applications

Mohammed F. Nakmouche^{1, *}, Abdemegeed M. M. A. Allam²,
Diaa E. Fawzy¹, and Ding-Bing Lin³

Abstract—This work is devoted to the development of a high gain Frequency Selective Surface (FSS) reflector backed monopole antenna using Machine Learning (ML) techniques for 5G applications. It analyzes and solves the complexity of the determination of the optimum position of the FSS reflector and the ground dimension of the monopole in this composite antenna structure since there are no solid and standard formulations for the computation of these two parameters. ML modelling is involved in the development process for the sake of gain enhancement. It is applied to get the optimum position of the FSS reflector layer and the ground dimension of the monopole antenna. The proposed antenna structure is 50 mm × 50 mm, implemented on a Rogers 5880 substrate (thickness = 1.6 mm). Two different patch antenna structures, with and without FSS, are developed and considered in the current work. The antenna performance in terms of operating frequency, return loss, and gain is analysed using the finite element methods. The design is optimized for a targeting frequency band operating at 6 GHz (5.53 GHz to 6.36 GHz), which is suitable for 5G Sub-6 GHz applications. The obtained results show that the integration of the FSS layer below the antenna structure provides a simple and efficient method to obtain a low-profile and high-gain antenna. Finally, the proposed design is fabricated and measured, and a good agreement between the simulated and measured results is obtained. A comparison with similar studies in the literature is presented and shows that the current design is more compact in size, and the obtained radiation efficiency and gain are higher than other designs.

1. INTRODUCTION

Nowadays, mobile communication, Wi-Fi, and WiMAX applications are in need of low profile, low cost, and mechanically robust antennas mounted on rigid surfaces. Microstrip patch antennas are a very popular, attractive choice and widely used in such applications. For many years, many different design techniques for microstrip patch antennas have been addressed in the literature [1–8] with the aim of antenna overall performance enhancements such as bandwidth and gain. In spite of their many advantages, microstrip patch antennas suffer from some drawbacks, for example, low efficiency, low power, high Q, spurious feed radiation, and very narrow bandwidths [9–14]. On the other hand, larger gain plays a positive impact on communication systems. Thus, increasing the gain of microstrip patch antennas has been the goal of many researchers and antenna designers in the last decade. Many techniques have been developed and used for the enhancement of microwave components performance [15, 16]. The authors used metamaterials as defected ground structures for the design of dual bands with gain-enhanced patch antennas. Fishnet metamaterials as Defected Ground Structures (DGS) were used in [17] to increase the gain of a dual band PIFA antenna from 3 dB to 8 dB. Authors

Received 31 August 2021, Accepted 1 October 2021, Scheduled 8 November 2021

* Corresponding author: Mohammed Farouk Nakmouche (Nakmouche.MFarouk@gmail.com).

¹ Faculty of Engineering, Izmir University of Economics, Izmir, Turkey. ² Department of Communication Engineering, German University in Cairo, Cairo, Egypt. ³ Department of Electronic and Computer Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan.

in [18] presented a dual band patch antenna with good gain for Ku-band applications based on both substrate integrated waveguide and H-slotted DGS.

FSS is another attractive structure that plays an important role in the enhancement of the antenna gain. It was firstly developed to control the transmission and reflection characteristics of an incident radiation wave. It is a planar, infinite array of periodically arranged unit cells on a dielectric substrate [19, 20]. The unit cells are constructed from metallic patches or aperture elements that exhibit perfect reflection or transmission, respectively, in the neighbourhood of the resonant element [21]. Many antenna designs based on FSS have been proposed in the literature for the gain enhancement, such as holey superstrate-based antenna [22], a gain-enhanced printed slot antenna using an electric metasurface configuration in [23], and lastly a dual-band patch antenna with FSS reflector for radiation parameters enhancement in [24–27].

The above-mentioned solutions have greatly improved the antennas modelling process and radiation parameters; however, the design process has challenges in terms of computational time and energy usage.

The purpose of the current paper is to present a novel solution based on Artificial Neural Network (ANN) techniques to overcome the rigorous computational cost in terms of memory and CPU usage and the highly ownership cost of the electromagnetic (EM) simulation software [28–30]. Also, it helps on getting the optimum design configuration with no need for rigorous mathematical formulations for either the position of the FSS or the dimension of the ground of the monopole antenna as a function of the optimum performance parameters for the antenna quoted in this work. The proposed solution is applied to design a high gain monopole antenna backed by FSS reflector for 5G applications. The hybrid FSS layer is structured by combining rectangular and cross geometries. It is added below the microstrip patch antenna for the gain enhancement. The determination of the optimum position of FSS layer with respect to the antenna is not an easy task. For that, the performance of the antenna gain is analysed as a function of the FSS position at different heights along with the ground dimension of the monopole antenna using ANN. The ANN is modelled to get the optimum position of the FSS layer for maximum gain values.

This paper is organized as follows. Section 2 explains the machine learning methods used in the design of the proposed antenna. The FSS layer and antenna design methodologies are presented in Section 3 and Section 4, respectively. The simulated and measured results of the proposed antenna are described in Section 5. Finally, a conclusion is provided in Section 6.

2. MACHINE LEARNING

The use of machine learning techniques greatly enhances the computational efficiency in the antenna design process. Moreover, in some composite antenna structures, solid formulae for optimum designs do not exist. In the current work, a machine learning network based on back-propagation algorithms is used for antenna modelling and performance analysis in terms of FSS position at different positions along with ground layer length.

The procedure followed in the current work for the application of the ML techniques in antenna design is summarized in the following three steps:

- Multiple simulations are done using the CST electromagnetic simulator tool to extract the antenna fundamental radiation parameters for different combinations of geometrical parameters.
- These input and output parameters are organized in a database and used for the training of the machine learning network.
- Depending on the requirements of the designer, the antenna with the best results in terms of targeting resonance frequencies is predicted by the machine learning network.

The ANN model has the frequency, S_{11} , and gain as input parameters, a hidden layer of 100 neurons and an output layer consisting of the position of the FSS layer (H) and the antenna ground length (Wg). 75% of the extracted CST data set is used for the ANN training, 10% for the validation, and finally 15% for the testing. The proposed ANN network diagram and its parameters are illustrated in Figure 1 and Table 1, respectively.

Table 1. Artificial Neural Network (ANN) parameters.

Antenna Parameters	Parameters Value
Number of Input Layer Neurons	2
Number of Output Layer Neurons	4
Number of Hidden Layer Neurons	100
Learning Rate	0.09
Number of Epochs	1000
Training Algorithm	Training Algorithm Levenberg-Marquardt (LM)

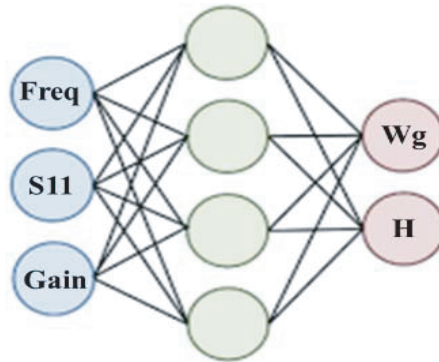


Figure 1. Proposed MLP-ANN architecture.

3. FSS SUPERSTRATE LAYER

A hybrid FSS layer with rectangular and cross geometries for the basic unit cell is proposed. Firstly, a microstrip patch antenna at operating frequency of 6 GHz for 5G Sub-6 GHz applications is designed and optimized using the finite element methods. Secondly, the FSS layer is added, and an optimization of the antenna gain performance analysis in terms of the FSS position at different heights along with ground layer length is conducted using both the finite element methods and ANN based methods. A comparative study is also conducted.

The main role of the FSS layer is that it acts as a conducting patch to transmit better radiating electromagnetic waves in order to achieve a desired antenna’s efficiency. The proposed FSS basic unit cell is based on a Roger 5880 dielectric substrate with a relative permittivity $\epsilon_r = 2.2$, a thickness $H_{Grid} = 1.6$ mm, and a metallization thickness of 0.035 mm as illustrated in Figure 2(a). The proposed FSS is a hybrid of two basic structures as sketched in Figure 2(b). The substrate and metallization thicknesses t and d along with the substrate permittivity ϵ_r of the unit cell directly impact the FSS electromagnetic properties.

Lastly, in order to satisfy the homogenization criterion, based on the antenna operating frequency (5.8 GHz) along with the corresponding wavelength in free space which is $\lambda = 52$ mm, the maximum dimension of the FSS unit cell must be less than $\lambda/10$ (5.2 mm). So, based on the homogenization

Table 2. Dimensions of the proposed antenna configuration and superstrate FSS layer.

Variables	A1	A2	A3	B1
Value (mm)	2.5	3.5	49	0.63
Variables	B2	B3	G1	G2
Value (mm)	0.25	49	0.5	0.5

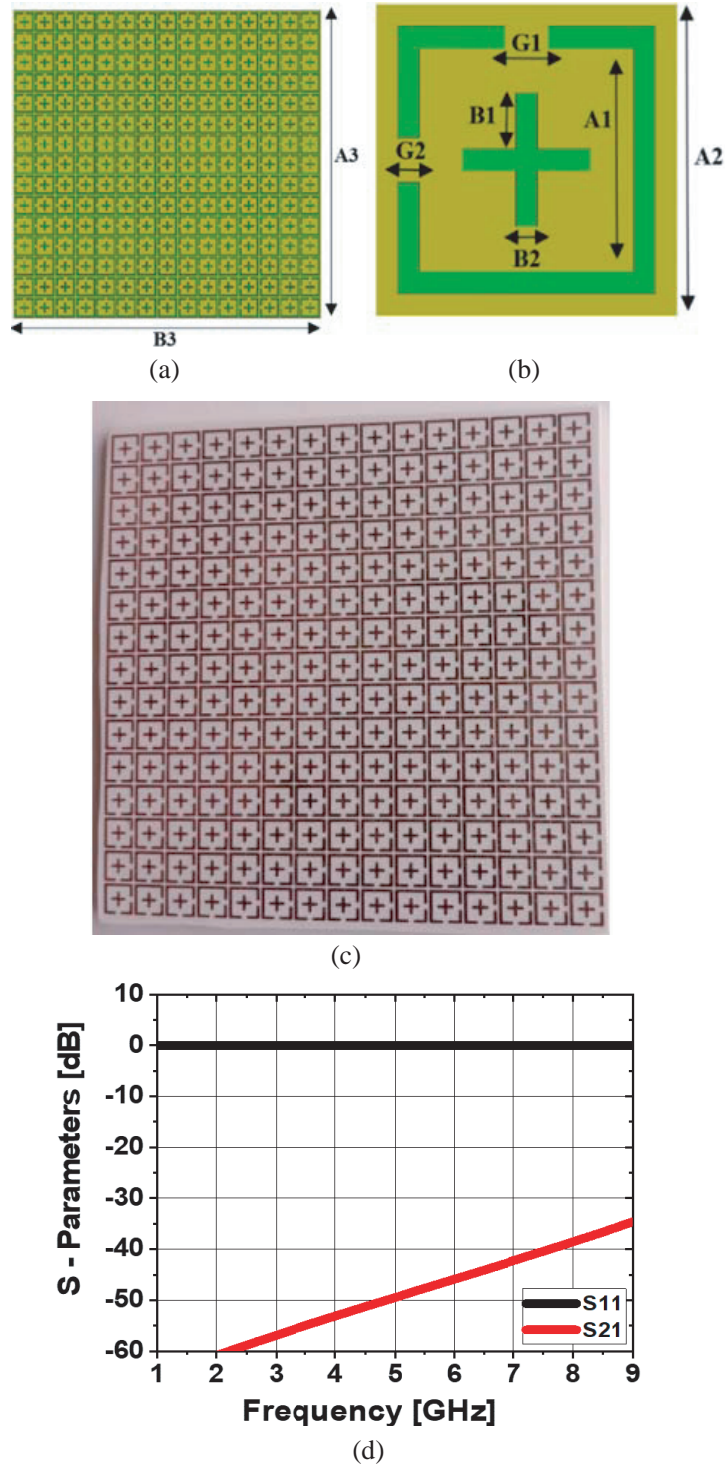


Figure 2. Proposed FSS. (a) FSS layer. (b) FSS unit cell. (c) Fabricated FSS. (d) FSS S -Parameters.

criterion, a parametric study is carried out to obtain the optimal dimensions of the FSS unit cell and the overall FSS structural dimensions as presented in Table 2.

The transmission and reflection characteristics of the proposed FSS reflector unit cell are shown in Figure 2(c). One can notice that the S -parameter S_{21} values are lower than -20 dB across the operating frequency band which means that we have a reflective behaviour.

4. ANTENNA DESIGN

The design geometry of the proposed basic patch antenna structure with FSS is shown in Figure 3. The proposed FSS based antenna incorporates a monopole antenna element with dimension $14.25 \text{ mm} \times 17.50 \text{ mm}$ and thickness of 0.035 mm on a Rogers 5880 substrate with thickness $H_{\text{sub}} = 1.508 \text{ mm}$. The FSS layer is positioned at $H = 6 \text{ mm}$ below the overall antenna structure as illustrated in Figure 3. The dimension parameters of the proposed patch antenna are presented in Table 3.

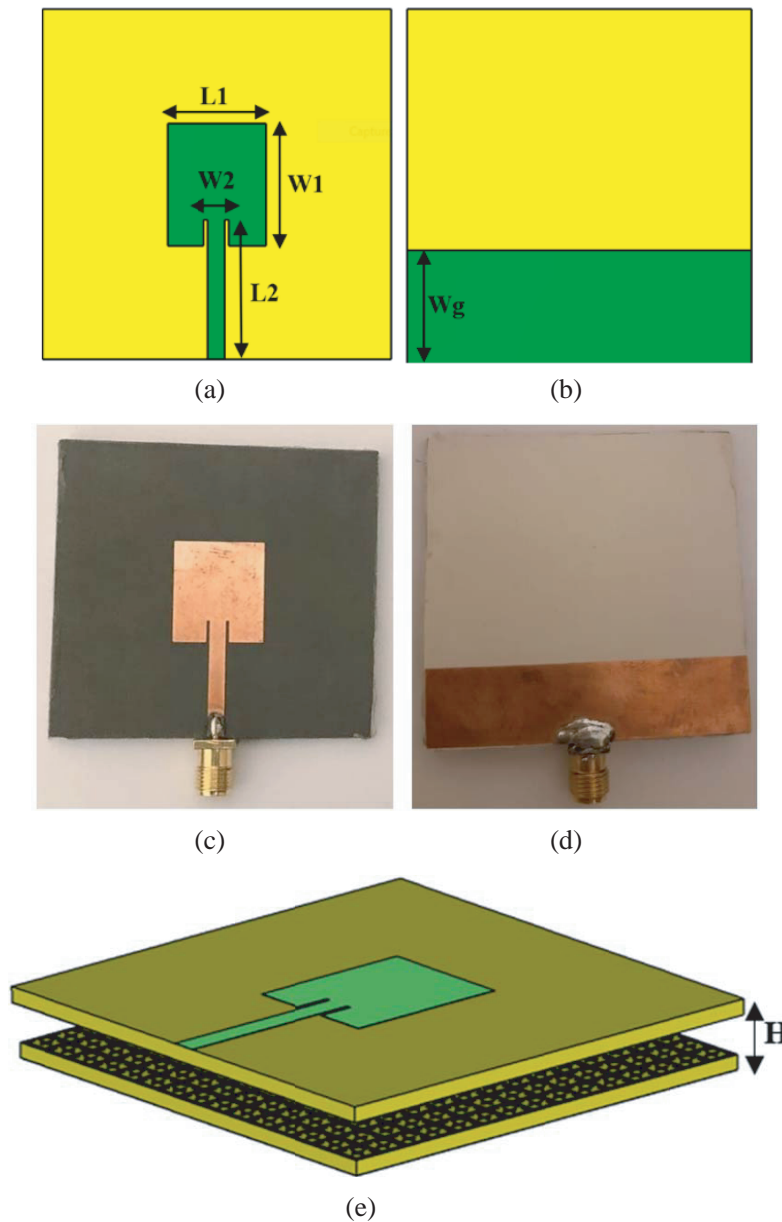


Figure 3. Proposed patch antenna configuration. (a) Top view. (b) Back view. (c) Fabricated top view. (d) Fabricated bottom view. (e) Side view with FSS layer.

Table 3. Dimension parameters of the proposed antenna configuration.

Variables	L1	W1	L2
Value (mm)	14.25	17.50	2.5
Variables	W2	L3	W3
Value (mm)	20	3.75	0.5
Variables	HGrid	Hsub	Wg
Value (mm)	1.6	1.508	12.3

5. SIMULATION RESULTS AND ANALYSIS

The CST Microwave Suite based simulations along with the ANN based design methods are used for the design of the proposed monopole antenna backed by an FSS reflector layer for 5G Sub 6 GHz application. The predicted ANN results were compared with the simulated CST results to observe the optimal performance of the proposed antenna in terms of the gain, return loss, and radiation efficiency.

Figure 4 depicts the return losses of the proposed antenna backed by an FSS layer for different FSS reflector layer positions (H) and ground dimensions of the monopole antenna (W_g). The position of the FSS is changed from 1 mm up to 8 mm, and the monopole's ground dimension is changed from 12.3 mm up to 20.3 mm. It can be seen that the H and W_g values are the key parameters in the antenna gain improvement. A comparison between CST and ANN simulation results in terms of frequency, S_{11} , and gain is illustrated in Table 4.

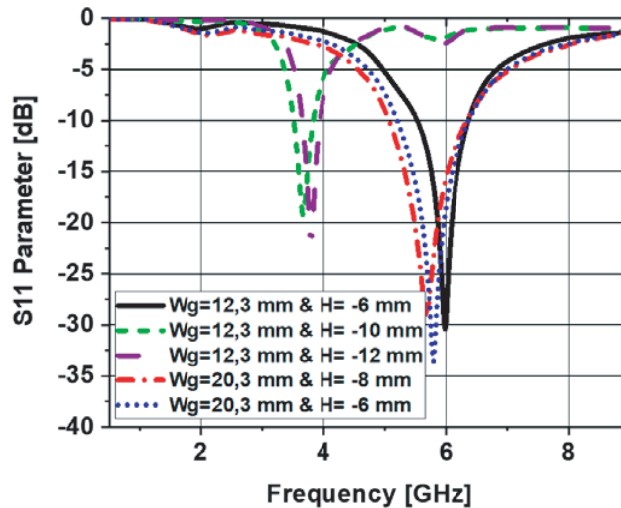
**Figure 4.** Simulated S_{11} parameters for different H & W_g values.

Figure 5 illustrates the return loss for the optimum H and W_g compared with those of the antenna without FSS. The optimization is carried out to obtain the optimal S_{11} and maximized antenna gain. The obtained results show that $H = 6$ mm and $W_g = 12.3$ mm are the optimum values at -10 dB S_{11} and maximized gain as shown in Figure 5. One can notice an improvement in S_{11} at the 6 GHz frequency band when using the FSS superstrate.

As seen from Table 4, a good agreement between the simulated CST results and predicted ANN results is obtained. Our proposed ANN based modelling design approach saves about 99% of the computational time while maintaining a prediction error below 5%.

The maximum realized gain of the proposed FSS based antenna is found to be 8.98 dB compared to 3.18 dB for that of the antenna configuration without FSS layer as shown in Figure 6. Lastly, the proposed antenna configuration shows a good radiation efficiency enhancement about 5% at the

Table 4. CST and ANN based simulation results for different antenna parameters.

		Input			Target Simulated by CST		Outputs Estimated by ANN	
		Freq (GHz)	S_{11} (dB)	Gain (dB)	Wg	H	Wg	H
Training Data	01	5.8	18	8.05	12.3	-4	12.29	-4.00
	02	5.7	28.57	8.46	12.3	-6	12.29	-6.00
	03	5.6	50	8.36	12.3	-8	12.29	-8.00

	73	4.54	19.63	3.81	14.3	-2	14.30	-1.99
	74	4.6	20.49	6.29	16.3	-2	16.30	-1.99
Validation Data	75	3.6	12.65	7.57	18.3	-8	18.30	-7.99
	76	3.5	20.16	7.48	18.3	-10	18.31	-9.97
	77	3.4	37.59	7.41	18.3	-12	18.29	-12
	78	5.36	15	6.32	20.3	-2	32.76	-3.75

	88	3.38	12	7.46	20.3	-10	20.06	-10.2
Testing Data	89	5.8	18	8.05	12.3	-4	12.29	-4.00
	90	5.7	28.57	8.46	12.3	-6	12.29	-6.00
	91	6	30.3	9	12.3	-6	12.3	-6
	92	5.6	50	8.36	12.3	-8	12.29	-8.00
	93	5.5	33.78	8.19	12.3	-10	12.30	-9.99

98	3.6	12.65	7.57	18.3	-8	18.30	-7.99	
99	3.5	20.16	7.48	18.3	-10	18.31	-9.97	
100	3.4	37.59	7.41	18.3	-12	18.29	-12	

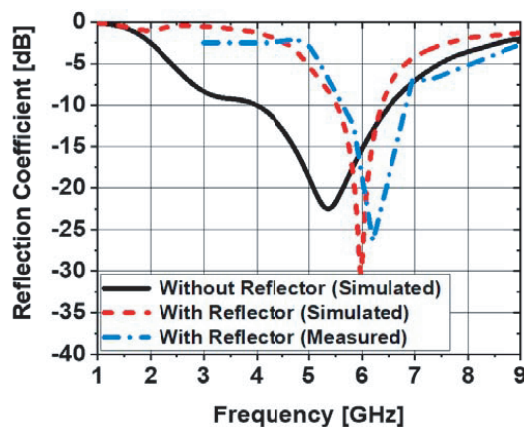


Figure 5. Simulated and measured S_{11} parameters of the proposed patch antenna.

dedicated operating frequency from 5.53 GHz to 6.36 GHz as shown in Figure 7. It is clearly noticeable from the simulation analysis that loading the monopole antenna with the proposed FSS has the following two advantages: i) Elimination of back propagation, ii) gain and antenna efficiency enhancement. One can say that the interaction of the Floquet' modes surrounding the two faces of the FSS and namely in between that layer and the patch antenna is the basis behind that optimum performance of the proposed composite structure.

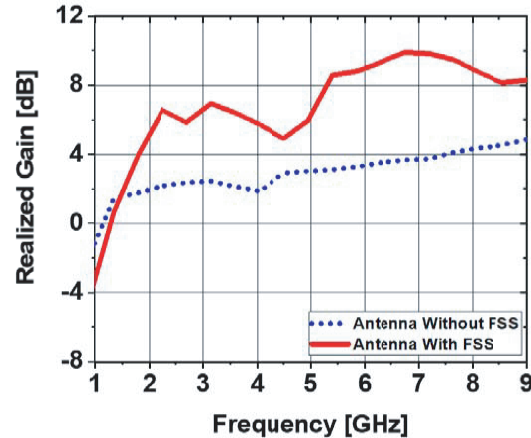


Figure 6. Realized gain of the proposed antenna (with/without FSS layer).

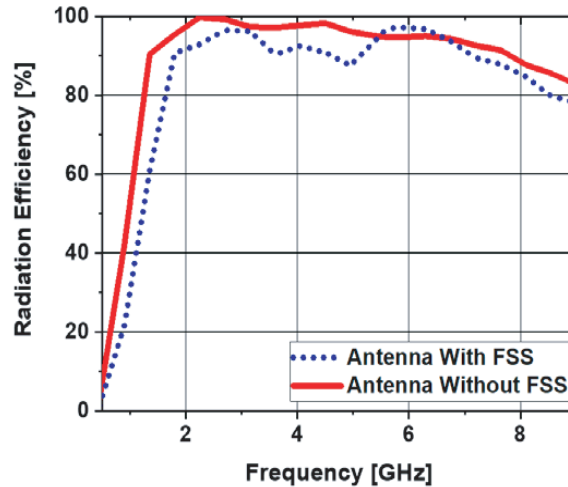


Figure 7. Simulated radiation efficiency of the proposed antenna (with/without FSS layer).

The gain improvement is considered as a significant feature for the antenna backed by FSS layer. Therefore, 2D and 3D radiation patterns showing this improvement are required in order to explain this point in more details. Figure 8 shows the difference in gain for the two cases, for configurations with and without FSS layer. By inspecting the 3D gain radiation pattern type as illustrated in Figure 8(a) and Figure 8(b), it is clearly seen that a gain enhancement about 5.8 dB is obtained. Furthermore, the antenna radiation pattern has changed from a monopole-like omnidirectional type to a directional one.

The current composite design is compared with other previous studies as presented in Table 5. It is clear that the proposed antenna obtains the highest gain and radiation efficiency. The proposed antenna size is somewhere smaller than some of other published works, and in other cases it is bigger but with high gain and radiation efficiency. According to Table 5, the proposed work shows a higher gain with a more compact size than the majority of the present studies in the literature [31–36]. Furthermore, its gain is greater than that of [37–39], without considering a reflector.

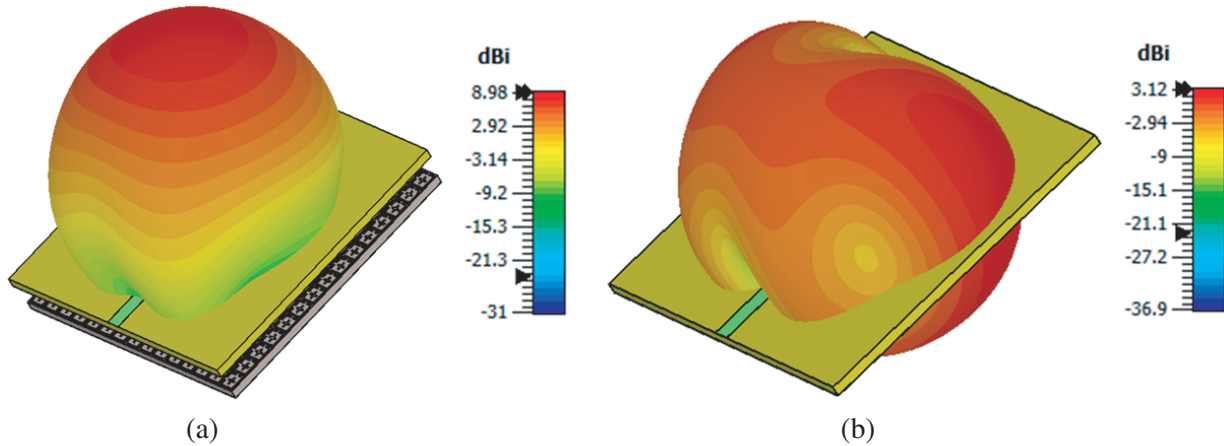


Figure 8. Simulated 2D and 3D Radiation Patterns of the proposed antenna with/without FSS Layer. (a) 3D radiation pattern with FSS layer. (b) 3D radiation pattern without FSS layer.

Table 5. Comparison of the proposed monopole antenna with previous work in terms of gain, radiation efficiency and dimension.

References	Antenna Type	Gain (dB)	Radiation Efficiency	Dimension (mm ²)
Ref. [31]	Monopole	8.4	71%	124 × 124
Ref. [32]	Monopole	5.1	79%	50 × 50
Ref. [33]	Monopole	6.88	< 80%	68 × 38
Ref. [34]	Monopole	6.2	Not evaluated	62 × 42
Ref. [35]	Monopole	4.8	Not evaluated	65.7 × 65.7
Ref. [36]	Monopole	6.2	Not evaluated	58 × 60
Ref. [37]	Patch	7.8	Not evaluated	46 × 46
Ref. [38]	Monopole (Without Reflector)	7.2	Not evaluated	61 × 80
Ref. [39]	Patch (Without Reflector)	4.53	< 80%	67 × 80
Current work	Monopole	8.89	> 95%	14.25 × 17.50

6. CONCLUSION

The determination of the optimum position of the FSS reflector and the ground dimension of the monopole in composite antennas structure requires rigorous mathematical formulations which are not available. The current study presents a novel approach based on ML techniques to simplify the computation of these two parameters in composite patch antenna design based on FSS with gain enhancement. The developed antenna resonates around the frequency band of 6 GHz (5.53 to 6.36 GHz), which is suitable for 5G Sub-6 GHz applications. The obtained results show a gain improvement about 5.8 dB (from 3.18 dB to 8.98 dB) with the integration of the FSS layer. The effect of integrating the FSS layer below the antenna provides a simple and efficient method for obtaining low-profile and high-gain antenna. The proposed antenna is fabricated, and the measured results are in good agreement with the simulated ones. Also, the comparison with related works in the literature shows a good validation for this approach. The basic behind the novelty of this approach is that there is no solid formulation for either the optimum position of the FSS reflector layer or the ground dimension of the monopole antenna to optimize the antenna performance. Moreover, up to our knowledge, it is the first time to use machine learning (ML) in the design of a composite monopole antenna backed by an FSS reflector for the purpose of gain enhancement. It is important to mention here that the currently developed approach saves up to 99% of the computational time compared with the traditional approaches.

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