Metasurface Antenna Circuitry for 5G Communication Networks

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Abstract—**In this article, the proposed antenna structure is designed for modern wireless communication systems. The antenna structure is consistent of twelve-unit metasurface (MTS) unit cells. Therefore, the antenna size is miniaturized effectively to 30×35mm^2 which is equivalently about 0.2λo, where λo is the free space wavelength at 3.5GHz. This is achieved by conducting the use of Hilbert shape MTS structure with T-resonator induction structure. The antenna structure is printed on a single side substrate to cover the frequency bands from 3.15GHz-3.63GHz and 4.8GHz-5.1GHz. Such antenna is found to provide a maximum gain of 3.5dBi and 4.8dBi at 3.5GHz and 5Ghz, respectively. Next, proposed antenna is found to be circularly polarized at 3.5GHz and 5GHz. The proposed antenna performance is simulated numerically using CST MWS software package with all design methodology that is chosen to arrive to the optimal performance. Then, the optimal antenna design is tested numerically using HFSS software package for validation. Finally, an excellent agreement is achieved between the two conducted software results.**

Index Terms—**MTS, circularly polarized, Hilbert.**

I. INTRODUCTION

Due to the recent growth in modern communication systems, several requirements are demanded to satisfy the current state of the arts in the antenna design [1]. The emergence and development of the concept of artificial materials throughout years led to a revolution microwave researches [1]. So, an antenna is an element of a cellular transmission line and is one of the most critical components of wireless communications systems. Dipoles/monopoles, slot/horn antennas, loop antennas, microstrip antennas, reflector antennas, helical antennas, dielectric/lens antennas, log periodic antennas, and frequency-independent antennas are nine different kinds of antennas that have been developed in the last fifty years for both communication and navigation systems. Each type is better suited to a specific application than the others. Because of its low cost, light weight, and ease of fabrication, microstrip antennas are the most commonly used in reconfigurable antenna designs [2].

The idea of reconfigurable antennas can be traced back to a D. Schubert patent from 1983 [2]. In 1999, the United State Defense Advanced Research Projects Agency (DARPA) funded a project called "Reconfigurable Aperture Program (RECAP)" to look into the subject in applications of reconfigurable antennas [3]. Reconfigurable antennas have also been used in applications such as broadband networking, cognitive radio, MIMO systems, and others.

So, changing the frequency, polarization, or radiation characteristics of an antenna may be used to reconfigure it. The majority of antenna reconfigurability techniques redistribute antenna currents, changing the electromagnetic fields of the antenna's efficient aperture [4]. Recently, reconfigurable patch antennas are the most commonly produced reconfigurable style antennas due to the ease of fabrication and incorporation into small electronic devices such as mobile phones and laptops. A standard reconfigurable patch antenna is made up of several separate metalized regions that are carried out on a plane and connected through switches or tuning components [4]. Different metalized parts can be brought in contact with each other by dynamically regulating the state of the switches, thus altering the overall antenna's radiation efficiency [5].

However, antennas with Multiple Inputs and Multiple Outputs (MIMO) are used to improve wireless channel capacity [5]. For spatial diversity characteristics, the adopted MIMO technology provides an efficient, high data rate that is split into multiple lower-rate streams. Many wire-free communication technologies, such as WLAN, 3G, LTE, and WiMAX (4G), depend on MIMO antennas where many researchers developed with various shapes to cover a wide range of frequency bands [6].

Moreover, a MIMO antenna with a small size, high gain and performance, and CP radiation, as well as a large impedance bandwidth, is needed for many wireless communication systems [7]. Additionally, MIMO systems have been proposed to mitigate multipath fading effects [8], however adjacent antennas coupling within a short separation distance may be the most significant drawback, especially in portable recent MIMO devices and systems [9].

In MIMO systems, this coupling must be reduced to improve antenna impedance matching and radiation properties [10], where mutual coupling refers to electromagnetic losses caused by surface wave interactions between antenna elements [11]. Mutual coupling can be thought of as surface wave leakage in this case; however, it is highly dependent on antenna geometry, array structure, and separation distances [12].

II. ANTENNA GEOMETRICAL DETAILS

The proposed antenna, see Fig. 1, is constructed from circular patch geometry mounted on a Techtronic FR4 substrate. The antenna patch is fed with a coplanar waveguide (CPW) microstrip line printed on the same panel with the patch from the antenna substrate. The transmission line is designed as a triangular coplanar waveguide to maintain high coupling efficiency between the patch structure and the source over a wide frequency range [4].

For the proposed MTS structure, the array is oriented around the patch edges to suppress the surface waves in which

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an excellent enhancement can be achieved in terms of the antenna gain-bandwidth product [10]. The proposed array is constructed from twelve-unit cell that are distributed with a certain separation distance to achieve capacitive coupling effects that magnifies the electrical field fringing and return reduces the antenna size [4]. The individual unit cell is constructed from Hilbert curve fractal geometry to maintain high surface current density within a limited area [3]. The frequency resonance of the individual unit cell can be tuned with a T-resonator structure through controlling the total impedance with a variable capacitor [9].

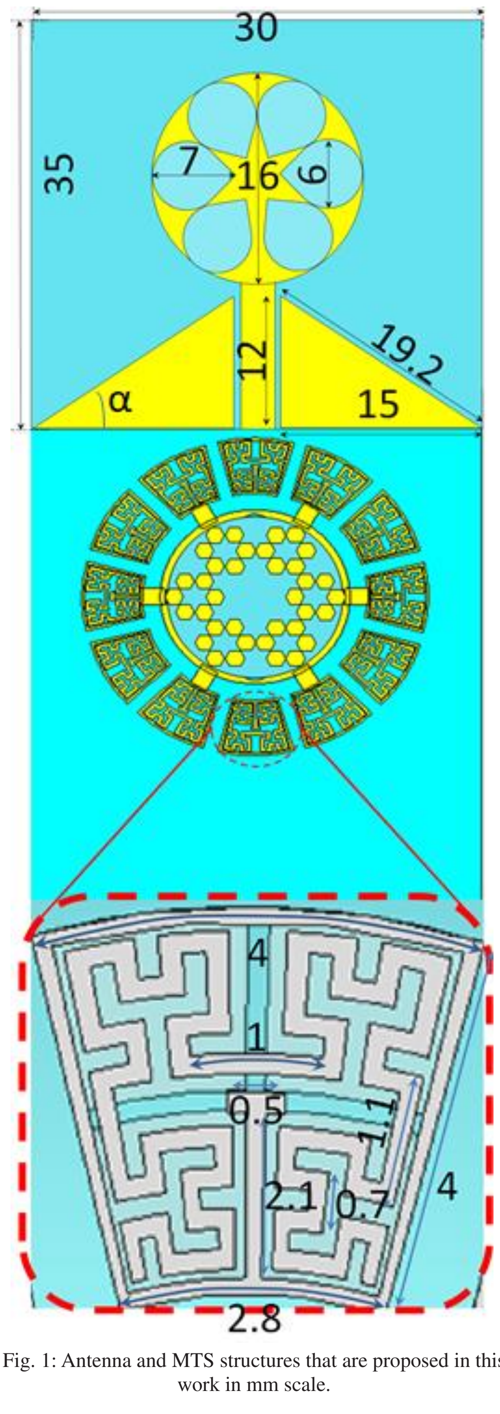

Fig. 1: Antenna and MTS structures that are proposed in this work in mm scale.

III. MTS CHARACTERIZATIONS

Now, to realize the performance of the proposed MTS unit cell, a numerical analysis is conducted based on CST MWS of a finite integral technique. The authors evaluated the proposed MTS unit cell S_{11} spectra using HFSS software package to be compared to their relative results from CST MWS. For this, a comparison study in terms of S-parameters spectra are presented in Fig. 2. First of all, we found that the obtained results from both software packages agree very well to each other. Also, the frequency resonance is found to be very close to the frequency band of interest. This motivated the authors to consider this unit cell to be an excellent intimate to the proposed design that realizes an excellent reduction in the antenna surface waves from the patch edges [7]. The surface wave reduction is achieved by the effects of the proposed unit cell which suppresses the surface wave significantly at the frequency band of interest [9].

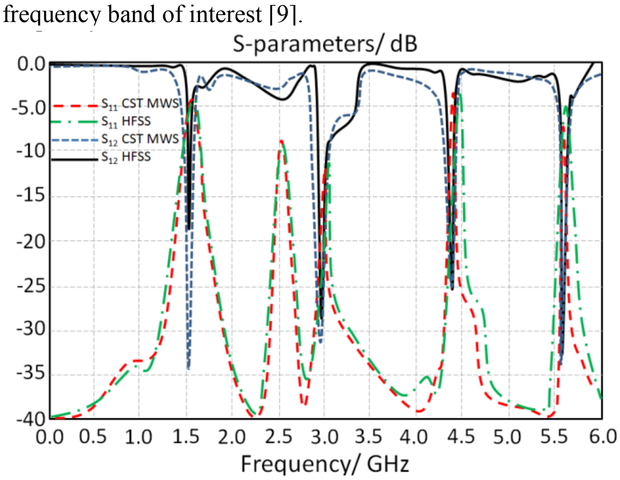

Fig. 2: Evaluated S-parameters spectra from both considered software packages.

IV. TRIANGULAR CPW DETAILS

The triangular CPW is designed to the proposed antenna to ensure bandwidth enhancement with maximum coupling. Moreover, the proposed CPW is structured with a triangular ground plane of certain slop angle (α). Therefore, the authors, partially, studied the effects of changing the goun plane slop angle by varying α from 36° to 40° with a step of 2° as seen in Fig. 3. It is observed that increasing the number of stages realizes a significant enhancement on the antenna bandwidth. This technique is invoked to maintain the antenna gain-bandwidth enchantments as shown in Fig. 4. This is in fact is achieved by eliminating the accumulated surface charges on the proposed CPW edges [8]. The slope of the suggested land causes the charge accumulation to increase up [5]. Consensually, tripping the electromagnetic energy within the substrate layer [6], that refer band with decrease by lowering the patch's surface resistance to actualize inconsistency between the load and the source's input impedance [2]. The authors did this because the suggested CPW has a substantial impact on the antenna bandwidth and gain by placing the SMA port in a specific orientation. The reverse side of the hypothesized CPW impact on discharging the accumulated surface charge is used in this approach, and it does actually deliver these improvements [7].

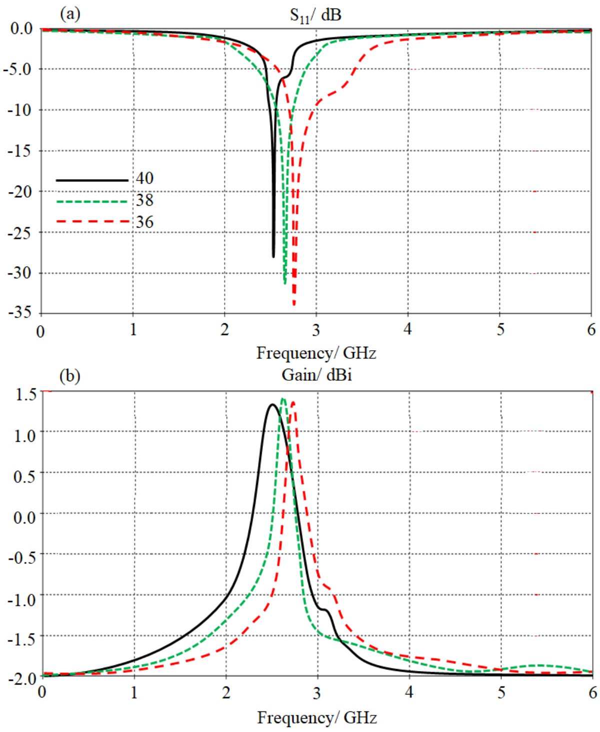

Fig. 3; Evaluated S_{11} and gain spectra based on the parametric study: (a) S_{11} and (b) Gain.

V. Design Methodology

The proposed antenna design methodology is presented in Fig 4 by considering a parametric-study based on flowchart. The optimal antenna performance of the proposed system is characterized according to S-parameters and gain spectra.

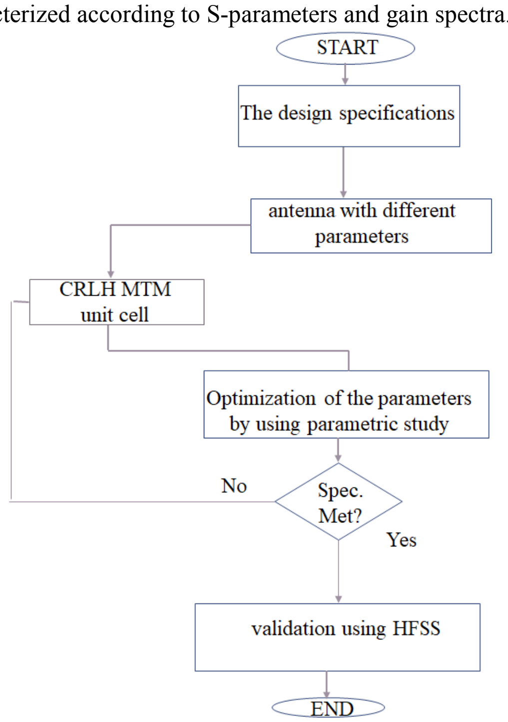

Fig. 4; The considered design methodology flowchart.

For this, the parametric study is invoked to change the substrate height (h), outer radius (R) of the main antenna patch, separation distance (G) between the antenna patch and MTS layer, and the spacing between the proposed CRLH with respect to the antenna middle ring (w). These antenna parameters are studied as following:

A. *Basic Antenna Design (h and R)*

The main basic parameters are considered because they have significant effects on the antenna matching bandwidth and gain. As seen in Fig. 5, the proposed antenna performances variations with respect to h and R. It is found that the antenna frequency resonance is slightly shifted without significant variation in the antenna gain relative to varying the antenna substrate height (h) from 1mm to 3mm as seen in Fig. 5(a). However, the antenna frequency and gain spectra are affected with changing the main patch radius (R) from 15mm to 17mm as shown in Fig. 5(b).

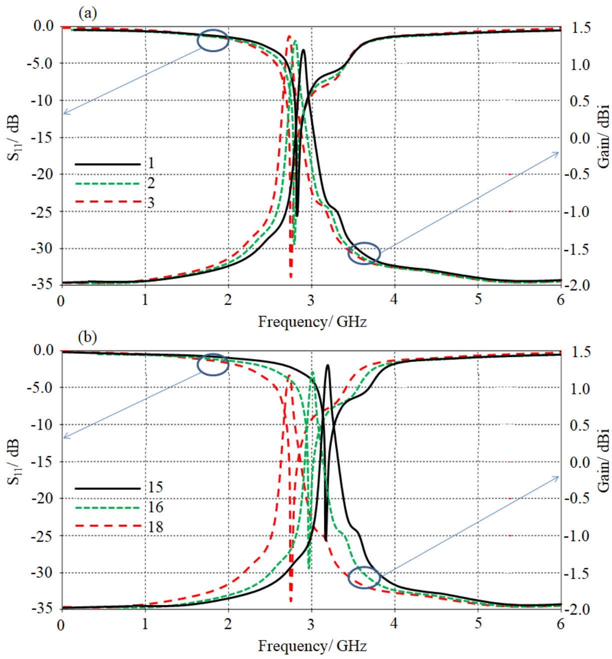

Fig. 5; Evaluated S11 and gain spectra based on the parametric study with varying: (a) h and (b) R.

B. *MTS Effects*

From the evaluated results in terms of S_{11} and gain spectra, see Fig. 5, we found that the proposed antenna provides a resonance mode around 3.5GHz with another band at 5GHz. These two frequency bands are very suitable for modern applications including 5G networks. Nevertheless, the antenna gain is found to be in the range of 3.2dBi and 4.8dBi, respectively.

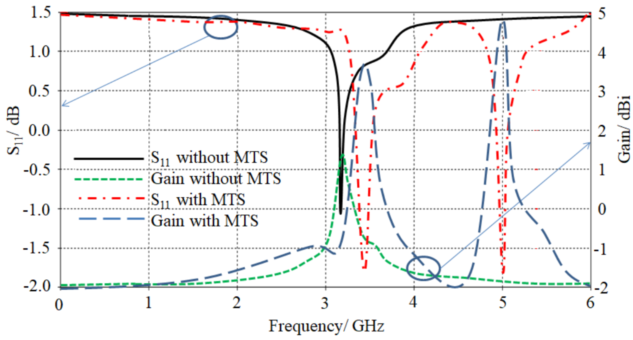

Fig. 6; Evaluated antenna performance in terms of S11 and gain spectra.

C. *Optimization Process based Convolution Neural Network*

Now, the design methodology is invoked to be *studied* parametrically using neural network architecture. For this network, convolution neural network model is designed for the proposed antenna structure to suite sub-6GHz bands. In Fig. 7, a synthesis model is defined as to obtain dimensions (G, w, h) of the antenna while providing the resonant frequency (f_r), gain (G_o), bandwidth (B.W), Quality factor (Q), and return loss spectra (S_{11}) at the input of the proposed model.

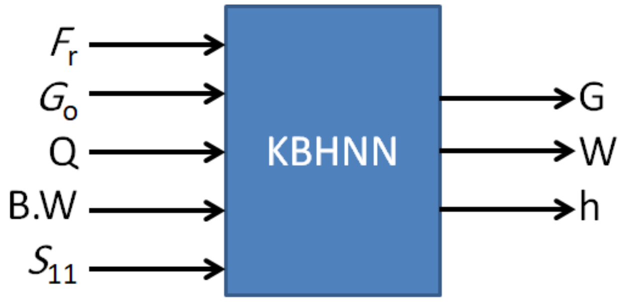

Fig. 7; The synthesis of proposed antenna using neural network.

Artificial neural networks are commonly employed to solve problems that include a lot of nonlinearity and many variables. They are also used to empower sensors for the more complex sensing applications [7]. Because the developing system of linear equations by using curve fitting for calculating the effective permittivity of the microwave resonators ambient is extremely difficult, because it depends on multi-variable multi-resonances, and depends on many parameters such as the shape of the field, the container, the overall mixture permittivity [9]. In order to solve these problems that were mentioned above by using feedforward multi-layer could be a good alternative. As training data for the proposed neural network, about 200 samples are collected by varying the dimensions of the proposed microstrip patch antenna using the numerical results from CST MWS software package. To classify the input data from regression, the results from the Matlab code is involved to show the classification of the input data according to their category. In this category, the input data is classification by the neural network to three intervals mainly a cording to the regression rate. In this classification, the first third of the input values are determent as low gain. The second interval is considered the intermediate gain level. The last interval is considered for the high gain. From Fig. 8, the data regression is found to be excellently fitting to the output data. Also, it is very ovals the regression subject, the proposed sensor best on the neural network realizes excellent matching with the classifications at low and high gain. However, this observation is limited to intermediate values, which could be realized high error. To realize an effective solution, more points are required to recognize the best fitting for this interval. It is good to mention, such discrepancy in the intermediate interval is observed in the Fig. 8 that shows a break point in the middle of the values from the simulation that agrees with measured data. Table I lists the best values obtained for the most commonly used neural parameters.

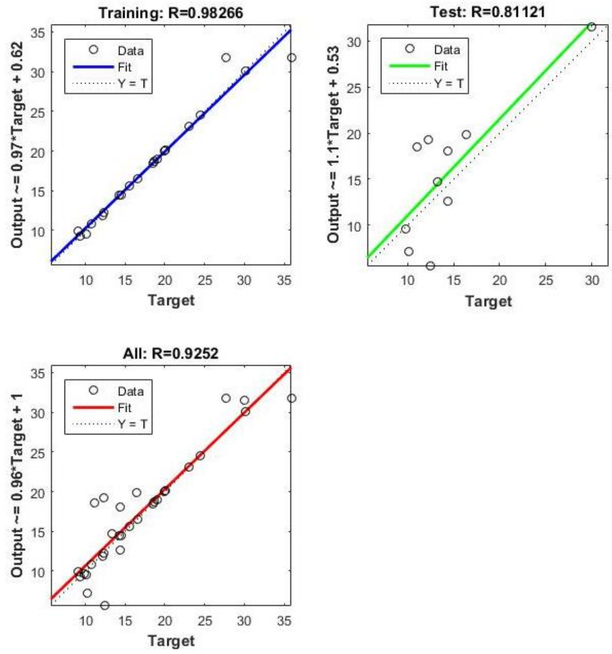

Fig. 8 Findings from the regression analysis.

TABLE I
THE NEURAL NETWORK PARAMETERS.

Neural Network parameters	Neural Network for simulation
Number of Input layer nodes	5
Number of Hidden layer nodes	3
Number of Output Layer nodes	1
Transfer function	logsig
Training function	pureline
Learning rate	0.001
Maximum number of Epochs	88

VI. RESULTS VALIDATION AND DISCUSSIONS

The obtained results from CST are compared to those obtained from HFSS for validation. The comparison reviles an excellent agreement between the considered software packages as seen in Fig. 9. The antenna performance, in terms of S_{11} and gain spectra with radiation patterns are tested numerically. The simulated S_{11} and gain spectra of the proposed antenna from both software packages are compared to the each other. The obtained results are found to agree to each other excellently. It is found that the proposed antenna provides a bandwidth from 3.15GHz to 3.63GHz and 4.8GHz to 5.1GHz with gain of 3.5dBi and 4.8dBi, respectively.

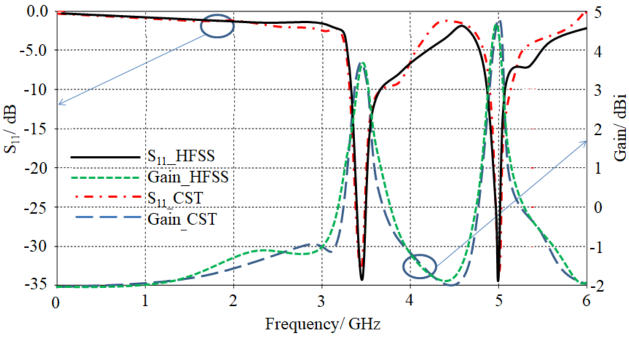

Fig. 9; Antenna performance validation.

The antenna radiation patterns at 3.5GHz and 5GHz are presented in Fig. 10(a). We found the antenna radiation patterns are almost Omni-directional around the antenna transmission line. This due to the fact of the proposed antenna structure is designed without back panel ground plane [3]. Therefore, the surface current distribution on the antenna patch is distributed symmetrically as seen in Fig. 10(b).

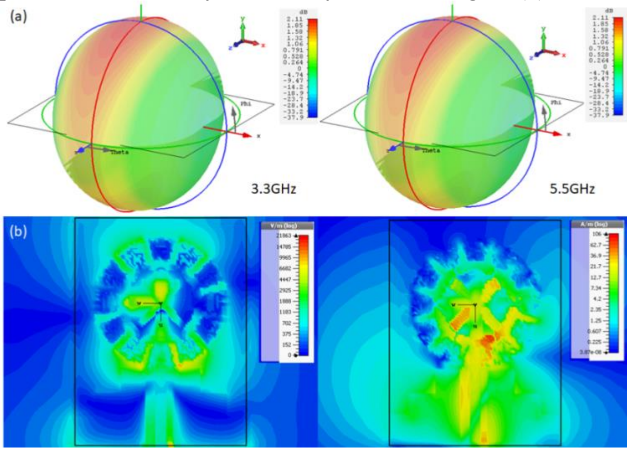

Fig. 10; Antenna field distribution: (a) Radiation patters and (b) surface current.

The proposed antenna is designed to realize a circular polarization feature at 3.5GHz and 5GHz as seen from the axial ratio (AR) in Fig. 11. The evaluated results from both CST MWS and HFSS are compared to each other. It is found that the evaluated results agree very well to each other.

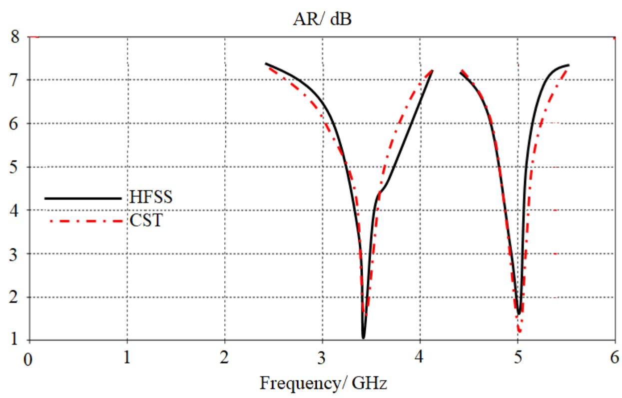

Fig. 11; Antenna AR spectra validation.

Finally, the proposed antenna performance is compared to other published results in the literature as listed in Table II. It is found from such comparison, that the proposed antenna system maintains an excellent gain-bandwidth product over other published results with small size. Nevertheless, the antenna shows an excellent AR in comparison to other listed antennas.

TABLE II
A COMPARISON BETWEEN THE PROPOSED ANTENNA PERFORMANCE AND OTHER PUBLISHED DESIGNS.

Ref.	Freq./GHz	Gain/dBi	Size(mm^2)	AR
[13]	3.4-3.7	8.3	15×440	×
[14]	2.49/3.45	4, 6	80×80	×
[15]	3.9	8	170.8×40	×
[16]	3.3-4.2/4.8-5.9	7.24, 3.74	40×204	×
This work	3.15-3.63, 4.8-5.1	3.5, 4.8	30×35	√

VII. CONCLUSION

The proposed antenna performance is numerically validated with respect to different software packages. It is found that the proposed antenna realizes a significant enhancement in the antenna matching impedance bandwidth. Such enhancement is achieved by introducing the proposed MTS unit cells. We found that the proposed antenna provides a bandwidth at two frequency bands 3.15GHz-3.63GHz and 4.8GHz-5.1GHz with gain of 3.5dBi and 4.8dBi, respectively. This is in fact attributed to the surface plasmon current motion on the antenna patch with a significant reduction in the surface waves. This is achieved when; the proposed antenna structure is fetched to the patch structure. Therefore, the charge accumulation on the substrate is converted as plasmonic current on the patch surface. For this, the antenna bandwidth is improved through the proposed MTS introduction. Finally, it is found that the proposed antenna is an excellent candidate for the modern wireless communication networks.

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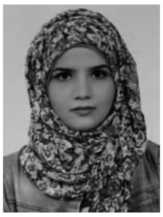

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