Design and optimization of pi-slotted dual-band rectangular microstrip patch antenna using surface response methodology for 5G applications

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**ABSTRACT**

Modern wireless network antenna technologies are designed to meet the ever-increasing needs of emerging applications. Hence this paper investigates potential antenna impedance bandwidth performance enhancement techniques based on optimizing independent geometrical parameters of pi-shaped slotted dual-band rectangular microstrip patch antenna (DBRMSPA). The antenna considered in the optimization process is with a slotted patch which improves impedance bandwidth of the antenna. And independent factors are geometrical parameters that influence the antenna’s impedance bandwidth (BW) and operating frequency (\(F_r\)). The factors are substrate height (\(H_s\)), patch length (\(l_1\)), and slot (\(s_2\)) length (\(L_s\)). And the experiment is designed using Computer Simulation Technology (CST) suite 2019 to generate a dataset by varying these parameters in a specific range. Then based on the dataset, response surface methodology (RSM) is applied to develop mathematical models that relate the responses \(F_r\) and BW with independent variables. Using analysis of variance (ANOVA), the effects of varying independent factors on both responses and model validation were investigated. Then constrained numerical optimization is applied to determine optimum design parameters. The optimized parameters, substrate height, patch length, and slot (\(s_2\)) length (\(L_s\)) are 0.648 mm, 3.048 mm, and 1.325 mm, respectively. The optimized dual-band antenna, designed with optimized parameters, achieved a target impedance bandwidth (\(\geq 4\) GHz), 7.2 GHz and 4.17 GHz at 28 GHz and 38 GHz, respectively. Similarly, the antenna’s radiation efficiency at 28 GHz and 38 GHz is 75.457% and 88.6237%, respectively. The proposed antenna also gives a gain of 6 dBi at 28 GHz and 4.15 dBi at 38 GHz. And VSWR is less than 2 throughout its impedance bandwidth. All of these results were generated using the CST EM solver and validated using the Ansys High Frequency Simulation Software (HFSS) with good agreement. As a result, the proposed potential performance enhancement techniques provide an antenna with a wide impedance bandwidth suitable for 5G mobile communication applications.

**1. Introduction**

Antenna technologies for recent wireless networks, such as 5th generation mobile networks, are being developed to meet the ever-increasing demands of emerging applications. 5G is a high-frequency technology, and mmWave communication is important to 5G radio networks due to limited inter-cell interference, low transmission latency, and enhanced security [1]. The millimeter-wave (mmWave) and terahertz (THz) bands are new wireless communications technology frontiers that are expected to enable seamless interconnection between ultra high speed wired networks (fiber optic links) and personal wireless devices, achieving full transparency and rate convergence between wireless and wired links. Traditional antenna technology faces several severe constraints in meeting the requirements of millimeter-wave (mmWave) and terahertz (THz) communication applications. As a result, the ultimate challenge is to design a compact antenna that meets the requirements of mmWave communication [2, 3]. According to the International Mobile Telecommunications 2020 (IMT2020), mmW frequency bands between 24 and 71 GHz with a spectrum bandwidth of 17.25 GHz are allocated to implement 5G. mmWave frequencies are attenuated during propagation due to atmospheric gases, water vapors, rainfall, trees, building materials, and structures [4]. This attenuation has resulted in smaller wavelengths and caused material absorption and diffraction at these frequencies. The attenuation of mmWave frequencies due to atmospheric conditions is depicted in Fig. 1. 28 GHz and 38 GHz have been identified as ideal operation frequencies for implementing 5G cellular communication networks as attenuation due to

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atmospheric conditions is relatively lesser at these frequencies. With the advancement of electronic technology, the size miniaturization and performance enhancement of communication systems are key requirements [5]. That is why several researchers are drawn to microstrip patch antennas’ compact size and thin profile. Despite the disadvantage of a narrow impedance bandwidth, microstrip patch antennas have numerous advantages, including low profile, small dimensions, lightweight, easy conformability, easy portability, planar structures, and ease of manufacture using printed circuit technology [6].

Several researchers have been reporting on maximizing the performance of microstrip patch antennas. Broadband antenna technologies with small physical size, ease of fabrication using traditional fabrication technologies, high gain, and omnidirectional radiation, in particular, have piqued the interest of wireless application developers. This is due to its benefits of high data rate, low power consumption, high capacity, low cost, reliable, and simplicity [7]. Most recently, metamaterial (MTM), metasurface (MTS), substrate integrated waveguides (SIW), slotted patches, thick substrates, multiple radiating elements, multiple feeding, proximity coupling, and optimizing impedance matching are technologies used to improve the performance of compact-sized antennas for millimeter-wave (mmWave) applications. For example, antenna impedance bandwidth has been increased by introducing slots on the antenna patch and a defected ground structure (DGS) [2, 3, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17].

Gains of 9.24 dB and 10.29 dB were achieved by designing and simulating 2x1 and 4x1 rectangular microstrip antenna arrays, respectively [18]. Similarly, metamaterials (MTMs) have been extensively demonstrated in the design of compact antennas and microwave devices [19, 20].

Optimization algorithms and computer-aided tools are also used to optimize antenna designs and achieve desired results. In [21], the effects of varying conductor thickness on the performance of a microstrip patch antenna were mathematically modeled and optimized, yielding an impedance bandwidth of 1.72 GHz. The artificial neural networks (ANNs) toolbox in MATLAB was used to train a model and generate the necessary data for model creation. The Grey Wolf Optimization Algorithm (GWOA) is used to solve the optimization problem. Similarly, in [6], a dual-band compact coplanar waveguide (CPW)-fed microstrip patch antenna with defected ground structure is optimized and proposed for covering upper C band and lower X band applications. A constrained adaptive bacterial foraging optimization (ABFO) algorithm is used to optimize the antenna, and curve-fitting is used for mathematical modeling. The proposed structure results in a maximum bandwidth of 2.84 GHz. Particle swarm optimization is also used in [8, 10] to improve the performance of a microstrip patch antenna. Traditional optimization methods are used in such works with the initial solution and progress to the optimal solution with each iteration. In addition, if adaptive meshing is used, it increases the number of simulations required for high-quality output and increases computational costs. On the other hand, global optimization algorithms, such as particle swarm optimization and genetic algorithms, require many iterations to optimize the structure’s geometries. A statistical approach like Response Surface Methodology (RSM) reduces the number of iterations [22].

RSM is an optimization method that uses statistical techniques to determine optimum conditions from a small number of experiments. It is based on factorial designs of central composite design. This method enables us to model and analyze problems in which several independent factors influence a response. RSM is now used in many areas where simulation optimization is required [23, 24, 25, 26, 27]. According to the literature in this domain, there are no research findings on the applicability of RSM on geometrical parameter modeling and optimization of patch antennae. Furthermore, no research findings are available on assessing the combined effects of substrate height, patch length, and slot length on the performance of 5G antennae. As a result, the main contributions of this work are:

- assessment of the combined effects of the substrate height, patch length, and slot length on the antenna’s performance.
- development of regression models that relate the effects of substrate height, patch length, and slot length on the operating frequency and impedance bandwidth of a pi-shaped slotted dual-band rectangular microstrip patch antenna using RSM.
- model validation and optimization of the dual-band slotted rectangular microstrip patch antenna structure using numerical optimization.

Once the optimal parameters have been determined, the proposed antenna is modeled and simulated on EM simulator softwares to evaluate and validate its performance. Furthermore, the optimized antenna resonates at 28 GHz and 38 GHz, making it suitable for 5G wireless communication applications.

2. Designed and configuration of DBRMSPA

Fig. 2 shows the geometric configuration of the dual-band rectangular microstrip patch antenna with an inset-quarter-wave transformer feed line. The rectangular radiating patch element with a pi-shaped slot, ground plane, substrate, and feeding component constitutes the proposed antenna. The radiating element and ground plane, perfect electric conductors (PECs), are located on the top and bottom sides of the substrate, respectively. The substrate is Rogers RT6002 with a dielectric constant of 2.94 and dimensions of 7.91 x 7.85 mm. RT6002 is a low-loss material with excellent mechanical and electrical properties that perform well at high frequencies. The radiating patch is fed with a microstrip line feed along its radiating edge with a quarter-wave transformer. A finite integration technique (FIT)-based electromagnetic solver, Computer simulation technology Microwave Studio (CST MWS) solver 2019, is used to prepare dataset, model, analyze, and simulate this design. This is because simulation in CST takes less time. Finally, the outcomes are validated with HFSS software.

The shape of the initially designed radiating element is a rectangular patch where its physical dimensions (length and width) are determined using transmission-line model antenna design equations below. Where c is the free-space velocity of light, fᵣ is the resonant frequency, and εᵣ is the dielectric constant of the substrate, the patch width (W) of an efficient radiator is given by [28]:

\[
W = \frac{c}{2fᵣ} \sqrt{\varepsilonᵣ}
\]
The fields at the patch’s edges fringe as the patch’s dimensions are finite. Because of this fringing effect, the microstrip antenna patch appears larger than its physical dimensions. The effective length of the patch \(L_{eff}\), that accounts for length extension \(\Delta L\) on each end and actual physical patch length \(L\), is related as in Eq. (2). The effective patch length and length extension are both functions of the effective dielectric constant \(\varepsilon_{reff}\), which is introduced to account for fringing and wave propagation in the line [29].

\[
L_{eff} = L + 2 \Delta L = \frac{c}{2f_{r} \sqrt{\varepsilon_{reff}}}
\]

(1)

where the effective dielectric constant, and length extension are given by:

\[
\varepsilon_{reff} = \frac{\varepsilon_{r} + 1}{2} + \frac{\varepsilon_{r} - 1}{2} \left[ 1 + \frac{12 \varepsilon_{r} H_s}{W} \right]^{-1/2}
\]

(2)

\[
\Delta L = 0.412 H_s \left[ \varepsilon_{reff} + 0.3 \left( \frac{W}{W_{g}} + 0.264 \right) \right] \left( \varepsilon_{reff} - 0.258 \left( \frac{W}{W_{g}} + 0.8 \right) \right)
\]

(3)

Once the dielectric constant, substrate height \(H_s\), and operating frequency are determined, the patch width, effective dielectric constant, an extension of the length, and finally, the actual length of the patch are determined using Eq. (1) to Eq. (4). The inset-feed and quarter-wave transformer considered in the design are intended to achieve perfect impedance matching between the patch and the feed. Inset feed is achieved by recessing a distance \(F_i\) from the radiating edge and the value of \(F_i\) is determined using the equation in [30]. Where \(k = \lambda_s / \varepsilon_{reff}\) is the guided wavelength, the length of the quarter-wave transformer \(L_{T}\) is given as in Eq. (5) [31].

\[
L_{T} = \frac{\lambda_s}{4}
\]

(4)

The width and length of the microstrip feed line are calculated using the formula in [29]. The original rectangular patch is modified by inserting a pi-shaped slot and two additional slots on the non-radiating edges. These slots are etched for impedance matching, bandwidth enhancement, and antenna radiation characteristics improvement. The pi-shaped slot, which is a modified inverted U-shaped slot, is well-known for its relatively large impedance bandwidth. Hence, the dimensions of the pi-slot are adjusted to achieve the lowest possible input reflection coefficient of the antenna around the resonant frequencies, and their position is chosen so that the radiating structure can produce a wider bandwidth while also providing proper impedance matching.

### Table 1. Geometrical dimensions of antenna design.

| Design parameters | Dimensions (mm) |
|--------------------|-----------------|
| Ground plane width \((W_{g}\)) | 7.91 |
| Ground plane length \((L_{g}\)) | 7.2 |
| Substrate width \((W_{s}\)) | 7.91 |
| Substrate length \((L_{s}\)) | 7.85 |
| Patch width \((W)\) | 4.73 |
| Patch length \((L)\) | 3.055 |
| Transformer width \((W_{T})\) | 0.7 |
| Transformer length \((L_{T})\) | 2.4 |
| Feedline width \((W_{f})\) | 2.5 |
| Feedline length \((L_{f})\) | 1.2 |
| Slot \((s_1)\) | 3.17 x 0.175 |
| Slot \((s_2)\) | 0.2 x 1.6 |
| Slot \((s_3)\) | 0.15 x 0.325 |
| Slot \((s_4)\) | 0.5455 x 0.35 |

Fig. 2 (a) and (b) depict the proposed antenna’s dimensions, which include ground plane width \((W_{g})\), ground plane length \((L_{g})\), patch width \((W)\), patch length \((L)\), quarter-wave transformer width and length \((W_{T} \text{ and } L_{T})\), and feedline width and length \((W_{f} \text{ and } L_{f})\). Fig. 2 (c) also shows the initial 3D model of the antenna created with the parameters in Table 1, substrate height \((H_s) = 0.32\) mm and patch thickness \((H_f) = 0.05\) mm. Furthermore, as shown in the model, a waveguide port is used for excitation. Input reflection coefficient at 28 GHz and 38 GHz for this design are -39.635 dB and -15.017 dB, respectively, as shown in Fig. 3. The minimum input reflection coefficient is achieved at 28 GHz; thus, this resonating frequency is considered for additional parametric study and optimization to improve the antenna’s impedance-bandwidth performance.

To meet the demand for data-intensive applications, the fifth generation of wireless communication networks includes millimeter-wave frequencies, massive antenna arrays, beamforming, dense cells, and other features [32]. Hence, the optimized antenna with high bandwidth shown below is an excellent candidate as an element antenna in massive antenna arrays or beamforming technologies for 5G wireless communication systems.

### 3. Designed antenna optimization

The general conceptual framework for optimizing a pi-slotted dual-band rectangular microstrip patch antenna with inset feed and quarter-wave transformer is depicted in Fig. 4. From the antenna designed in the previous section, three design parameters, namely substrate height \((H_s)\), slot \((s_2)\) length \((L_s)\), and patch length \((L)\), are selected for optimization as a variation of these parameters has a significant effect on antenna performance. These parameters are varied and simulated.
Fig. 3. Input reflection coefficient plot for initial antenna configuration in the CST working environment.

Table 2. Simulation results with the variation of antenna parameters.

| Parameter | Value | Signal Bandwidth (GHz) | Reflection Coefficient (dB) |
|-----------|-------|-------------------------|----------------------------|
| $H_s$ (mm) | 0.24  | 28.014                  | −21.503                    |
| $W$ (mm)  | 4.73  | 28.014                  | −23.507                    |
| $L_s$ (mm) | 3.055 | 27.996                  | −25.306                    |
| $L_t$ (mm) | 1.6   | 27.978                  | −26.397                    |
| $F_r$ (GHz) | 3.055 | 27.978                  | −28.397                    |

Fig. 4. Methodology for antenna design performance optimization.

repeatedly to generate the subsequent experiment and mathematical modeling dataset. Then, the three input factors and two responses are carried out using the factorial design experiments. In this regard, the Design of Experiments (DoE) method is used to perform statistical analysis to obtain the response-surface model, which relates coded variables and can be used experimentally to obtain the responses. The model’s fitness is then assessed using ANOVA and residual analysis results. To improve convergence speed and accuracy, model treatments are applied based on the ANOVA and residual analysis results. After developing a well-fitted model, parameters are optimized using constrained numerical algorithm for desired performance. Finally, the results of the optimized antenna are validated using simulation with the electromagnetic solvers CST MWS 2019 and Ansys HFSS 2019. The steps followed are explained in detail in the following subsections.

3.1. Parameter variation and antenna performance

Numerous variables influence the response in any system, and it is impractical to find and control each one [22]. As a result, a small number of significant parameters are chosen from a large list and used as input variables. Antenna design considerations, including slotted patches, thick substrates, and other geometrical parameter variations, affect the impedance bandwidth of antennas. Following the design of...
the required antenna dimensions using design formulae discussed in section 2, the proposed antenna configuration with the defected ground structure shown in Fig. 2 is designed. The substrate height (Hs), slot (sL) length (Ls), and patch length (L) are considered for optimization. These optimization parameters are varied and simulated for creating the dataset that can be used for further analytical modeling. To be specific, substrate height (Hs) is varied from 0.24 mm to 0.64 mm with an interval of 0.02, slot (sL) length (Ls) is varied randomly from 1.32 mm to 1.6 mm. The variation of other parameters can be seen in Table 2. As a result, 21 antenna designs are simulated and analyzed to generate the dataset for all parameter variations, as shown in Table 2. As seen from the dataset, increasing the substrate height (Hs) increases the bandwidth of the proposed antenna.

3.2. Mathematical modeling using response surface methodology

The dataset shown in Table 2 is statistically analyzed using Design Expert 13.0 Software. Design-Expert software’s response surface methodology (RSM) relates design parameters to resonant frequency and bandwidth. Response surface methodology is a statistical, theoretical, and mathematical technique for constructing a model or function that best represents the relationship between factors and response values. Depending on the significance of the selection variables, models such as quadratic, cubic, and quartic are used. Individual variables, as well as their interactions, help to improve the prediction of the response values. To select the best fitting polynomial, statistical parameters such as lack-of-fit, predicted and adjusted multiple correlation coefficients, and coefficient of variation of different polynomial models were compared [22]. Moreover, a third-order model with interaction and polynomial terms is created for both response variables. Mathematical equations are fitted to describe the response behavior of the dataset shown in Table 2. Generally, third-order polynomial response surface models are mathematically represented as in Eq. (6).

\[ Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} X_i X_j + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} X_i X_j + \epsilon \]

(6)

where Y represents the fitted responses, \( \beta_0 \) is the intercept coefficient, \( \beta_i \) is the ith linear coefficient, \( \beta_{ii} \) is the quadratic coefficient, \( \beta_{ij} \), \( \beta_{ij} \), and \( \beta_{ij} \) are the cubic term coefficients, \( \epsilon \) is the error, and \( X_i \) and \( X_j \) represent independent factors. Third ordered polynomial equations for both response variables obtained applying response surface methodology are given by Eqs. (7) and (8). Model treatment is used because the model contained insignificant terms. These equations relate independent variables to the responses (resonant frequency \( F_r \) and bandwidth \( BW \)).

\[ F_r = 28.48 - 2.62H_s + 0.155L_s - 2.63L_p - 0.6414H_s L_p + 4.57H_s L_p - 0.6671L_p + 1.46H_s^2 + 0.1962L_p + 2.45L_p^2 + 0.5045H_s^3 + 0.38L_s^3 \]  

(7)

\[ BW = 0.6871 + 0.9039H_s - 0.8684L_p + 2.02L_p + 1.73H_s - 7.15H_s L_p - 1.48H_s^2 + 0.8937L_p^2 - 4.01L_p^3 + 2.13H_s^3 + 6.23H_s L_p^2 + 2.82L_s^3 \]  

(8)

3.3. Model fitness validation

The analysis of variance (ANOVA), and residual analysis are used to check the adequacy of the response surface models. The ANOVA results for both \( F_r \) and \( BW \) are shown in Table 3. The results from the table revealed that the experimental dataset could be represented well with a cubic polynomial model with coefficients of determination (\( R^2 \)) values of 0.996 and 0.9999 for resonating frequency (\( F_r \)) and bandwidth (\( BW \)), respectively. Here coefficient of determination (\( R^2 \)) is a metric to signify the model’s accuracy in predicting future outputs. The model fits the data better if the \( R^2 \) value is closer to unity. As a result, the proposed models’ results show that they can accurately predict future responses. In the proposed models, parameters with a \( p < 0.05 \) are considered, which are significant terms. Thus the effective terms that influence resonating frequency (\( F_r \)) are substrate height (\( L_p \)), slot (\( sL \)) length (\( L_s \)), the interaction between substrate height and slot (\( sL \)) length (\( H_s L_s \)), patch length and slot (\( sL \)) length (\( L_s L_p \)), substrate height squared (\( L_s^2 \)), slot (\( sL \)) length squared (\( L_s^2 \)) and substrate height cube (\( H_s^3 \)) are significant model terms. Similarly, patch length (\( L_p \)), slot (\( sL \)) length (\( L_s \)), the interaction between substrate height and patch length (\( H_s L_p \)), substrate height and slot (\( sL \)) length (\( H_s L_s \)), substrate height squared (\( H_s^2 \)), patch length squared (\( L_p^2 \)), slot (\( sL \)) length squared (\( L_s^2 \)), slot (\( sL \)) length cube (\( H_s^3 \)) and other more terms are significant model terms which influence the bandwidth (\( BW \)) of the proposed antenna.

Fig. 5(a) and (b) show the typical plots of the residuals used for the residual analysis. The residuals are the difference between the responses and the predicted values. Moreover, it is assumed that these deviations are normally distributed. This assumption holds for both plots in Fig. 5, where residuals portray a normal distribution because virtually all the points follow a straight line. The other plot which gives information about the fitness of the models is the residual vs. no. of the run plot. The model will fit the best if the residuals bounce randomly about the residual = 0 line. Moreover, as shown from Fig. 6 (a) and (b), residual vs. no. of iteration plots of \( F_r \) and \( BW \), both responses are distributed well about residual = 0 line, which signifies the models are suitable.

The response surface and contour plot due to the interaction between variables on resonating frequency (\( F_r \)) are shown in Fig. 7. If the
response surface plots are reasonably flat curvature, it indicates the effectiveness of the models [22]. Fig. 7 shows that 3D response surface plots for resonating frequency ($F_r$) are close to flat curvature. Similarly, the response surface plots for impedance bandwidth (BW) are checked to be reasonably flat curvature. These characteristics of the response plots revealed that the proposed models are suitable. Fig. 7 (a) shows the effect of interaction between substrate height ($H_s$) and patch length ($L$) on resonating frequency ($F_r$). The other plot in Fig. 7 (b) shows the effect of interaction variable $H_s L_s$ on resonating frequency.

3.4. Model optimization

The regression models produced are used to optimize the dual-band slotted rectangular microstrip patch antenna structure by setting certain constraints. The optimal values within the constraints are searched
to improve input variables’ values. After constructing models by importing the dataset, numerical optimization of the models is performed using the Design-Expert software to determine the target responses. This optimization requires goals to be set for the responses as minimize, maximize or target value. The constraint summary is shown in Table 4. The two responses, $F_r$ and $BW$, are set as a target of $28\, \text{GHz}$ and $4\,\text{GHz}$, respectively. Thus, the main goal is to achieve a DBRMSPA with wider bandwidth for a 5G application. Design-Expert software generates a list of factor solutions with unity desirability based on the criteria. Again, the top candidate is marked as selected of all feasible solutions. From list of optimum factor solutions the DBRMSPA structures with desirability one and selected are: substrate height ($H_s$) = 0.648 mm, patch length ($L$) = 3.048 mm, and slot ($s_2$) length ($L_s$) = 1.325 mm.

### 3.5. Optimized antenna results

Table 2 in the previous section shows the combined effect of parameter variation on impedance bandwidth and antenna operating frequency. In this section, sample manual optimizations from the table are simulated using CST software, along with the optimized antenna, for further analysis. Then the simulated results of the optimized antenna further validated using another EM solver. Fig. 8 shows the optimized antenna’s input reflection coefficient versus frequency variation compared to three other manually optimized structures. The plot shows that the combined variation (increase in $H_s$, decrease in $L_s$, and slight change in $L$) improves the antenna’s impedance bandwidth. The change in these geometric parameters also affects the location of input reflection coefficient minima. Although the impedance bandwidth performance achieved through manual optimization is good, the wide frequency range remains unsuitable. As a result, constrained numerical optimization is applied to the selected antenna structure parameters. Based on the geometrical dimensions in Table 1 and Table 5, the optimized antenna structure is redesigned on a CST MWS EM solver 2019 software. Furthermore, the proposed dual-band antenna structure achieves broadband performance with a minimum input reflection coefficient of $-51.174\,\text{dB}$ at $28\,\text{GHz}$ and $-16.548\,\text{dB}$ at $38\,\text{GHz}$. Again this antenna provides a maximum impedance bandwidth of $7.2\,\text{GHz}$ and $4.17\,\text{GHz}$ at $28\,\text{GHz}$ and $38\,\text{GHz}$, respectively.

Ansly High Frequency Simulation Software (HFSS) 2019, another EM solver based on the finite element method (FEM), is also used to verify the optimized antenna characteristics. A waveguide port, similar to the CST, is used in the HFSS simulation process. The minimum input reflection coefficient of the optimized antenna generated by HFSS at $28.14\,\text{GHz}$ and $38\,\text{GHz}$ is $-47.729\,\text{dB}$ and $-15.65\,\text{dB}$, respectively. At $28\,\text{GHz}$ and $38\,\text{GHz}$, the antenna has an impedance bandwidth of $6.87\,\text{GHz}$ and $3.6\,\text{GHz}$, respectively. Fig. 9 depicts a comparison of the simulation results of $S_{11}$ obtained from HFSS and CST. It can be seen that the input reflection coefficient and impedance bandwidth results obtained by both softwares are in reasonable agreement. At both resonant frequencies, there is a slight difference in the level of the input reflection coefficient and impedance bandwidth as the two softwares used two different methods for the substrate losses at high frequencies, and meshing techniques [33, 34].

The VSWR of the optimized antenna and the three other manually optimized designs, simulated using CST, are depicted in Fig. 10. The VSWR is an antenna performance indicator that reflects how effectively an antenna is matched at the feed point. The ideal absolute value of VSWR is 1, but it could lie below 2 or 3 [12]. As shown in Fig. 10, the simulated VSWR for optimized design is less than 2 throughout its impedance bandwidth. Again the VSWR of manually optimized antenna with $H_s = 0.54\,\text{mm}$, $L = 3.005\,\text{mm}$, and $L_s = 1.44\,\text{mm}$ remains within the optimal range. In contrast, the VSWR of the other two manually optimized antennas is outside the optimal range for a wider frequency range. Fig. 11 shows a comparison of the VSWR simulation results obtained with the CST and HFSS EM solvers. Furthermore, the VSWR results of the two simulators show good agreement. As a result, the VSWR results demonstrate the effectiveness of the model developed for optimizing the antenna’s geometrical parameters.

Fig. 12 and Fig. 13 show the optimized antenna’s 2D and 3D radiation patterns as simulated by CST, respectively. The radiation pattern is a graphical representation of the antenna’s radiation characteristics that describes how the antenna radiates and receives energy into and

![Fig. 7. 3D response surface and contour plot of (a) $F_r$ vs. $H_sL$ and (b) $F_r$ vs. $H_sL_s$.](image)
Fig. 8. Comparison of the input reflection coefficient of the optimized antenna with manually optimized antennas.

Fig. 9. Comparison of the input reflection coefficient of the optimized antenna using HFSS and CST.

Fig. 10. Comparison of the VSWR of the optimized antenna with manually optimized antennas.
Fig. 11. Comparison of the VSWR of the optimized antenna using CST and HFSS.

Fig. 12. 2D Radiation patterns of the proposed antenna: (a) Absolute (28 GHz), (b) Absolute (38 GHz), (c) Co-polar and Cross-polar (28 GHz) and (d) Co-polar and Cross-polar (38 GHz).

from space. Fig. 12 (a) and (b) show the 2D absolute radiation pattern at 28 GHz and 38 GHz respectively. The peak directivity of the antenna is 7.26 dBi at 28 GHz and 5.33 dBi at 38 GHz. The main beam has an angular width of 92.6° at 28 GHz and 105.8° at 38 GHz. The copolarization and cross-polarization radiation patterns simulated in CST are also shown for the two different frequencies in Fig. 12 (c) and (d). For the copolarization plot φ = 0° and θ changes between 0° and 180°. Again for cross-polarization φ = 90° and θ changes between 0° and 180°. The proposed antenna’s 3D radiation patterns at 28 GHz and 38 GHz are also shown in Fig. 13 (a) and (b), respectively. As shown in Fig. 14 (a) and (b), the radiation patterns generated by CST at both operating frequencies are compared to those generated by HFSS. The radiation patterns obtained by the two different softwares are in good agreement.

Fig. 15 (a - f) depict the surface current distribution simulated in CST at 28 GHz. As shown in Fig. 15 (c - f) for power sources with 60°, 90°, 120°, and 150° phase angles, the maximum current intensity on the radiating patch is focused around the center. As indicated in the plots, the maximum current intensity of 74.7 A/m is observed on the patch. Similarly, the surface current distribution simulated in CST at 38 GHz is shown in Fig. 16 (a - f). The current distributions in the feed line and patch edges are observed at 38 GHz when the phase is 60°, 90°, and 120°, as illustrated in Fig. 16 (c - e). It can be seen that the surface current distribution is much stronger in lower band resonant frequencies than in upper band resonant frequencies, which validates gain [35].

Fig. 17 depicts the realized gain versus frequency curves of proposed and manually optimized antennas as simulated by CST. The proposed
antenna has a gain of 6 dBi at 28 GHz and 4.15 dBi at 38 GHz. The gain increases and then decreases at lower frequencies, whereas at higher frequencies, it gradually increases. As shown in Fig. 18, the gain of the optimized antenna over the frequency band generated by CST is compared to the simulated gain in HFSS EM solver. This figure shows that the optimized antenna’s gain profile in the CST and HFSS has a reasonable agreement. Furthermore, the antenna in the HFSS achieves a maximum gain of 5.7 dBi and 4.9 dBi at 28 GHz and 38 GHz, respectively.

Fig. 19 compares the radiation efficiency of the proposed dual-band antenna and manually optimized antennas as simulated by CST. From the plot, it can be seen that the radiation efficiencies for the optimized antenna are $-1.2256 \text{ dB (75.412\%)}$ and $-0.54319 \text{ dB (88.24\%)}$ at 28 GHz and 38 GHz, respectively. In the impedance bandwidth range of the antenna, the maximum radiation efficiency is $-0.364 \text{ dB (91.96\%)}$ at 35.8 GHz. The plot shows that the optimized antenna outperforms manually optimized antennas. The radiation efficiency achieved using CST simulator is compared with HFSS simulation result and the results of the two different EM solvers are within a reasonable agreement. At 28 GHz and 38 GHz, the radiation efficiencies achieved using HFSS are 72.1\% and 85.08\%, respectively. The simulated curve of front-to-back ratio in dB versus frequency for both optimized and manually optimized antennas is presented in Fig. 20. The front-to-back ratio increases and decreases gradually at lower frequency ranges then increases again as frequency increases. At higher frequencies, the optimized antenna’s front-to-back ratio reaches a maximum of 20 dB. The proposed antenna’s front-to-back ratio using the two simulators shows the same plot profile with a slight variation. Table 6 summarizes the optimized antenna results obtained from the two EM solvers. As shown in the table, there is a reasonable agreement between the results obtained by both softwares.

The optimized antenna results are compared to previously published works to assess the proposed model equation’s effectiveness. In [28], a 20 mm $\times$ 20 mm microstrip patch antenna was designed on a 1.575 mm thick Duroid 5870 substrate for Ku and K-band applications. This antenna’s reported performance shows impedance bandwidths of 1.07 GHz and 0.94 GHz in the first and second resonances, respectively. Another paper in [36] described a small dual-band microstrip patch antenna for 5G mobile phones that operate at 38 GHz and 60 GHz. This work achieved impedance bandwidths of about 2 GHz and 3.2 GHz for 38 GHz and 60 GHz, respectively. The input reflection coefficient, which is $-42 \text{ dB}$ for the 38 GHz and $-47 \text{ dB}$ for the 60 GHz, is another performance metric reported in this work. Table 7 compares the proposed antenna to other references in terms of overall size, resonant frequencies, input reflection coefficient, bandwidth, and gain. As can be seen from the table, the proposed antenna improves bandwidth performance at both operating frequencies while meeting the optimization goal (≥4 GHz) in CST EM solver. The impedance bandwidth of the antenna in HFSS is close to the target in the second operating frequency. The antenna is also compact, making it ideal for situations where space is limited. At 28 GHz, the proposed antenna has a much lower input reflection coefficient than others. Furthermore, the proposed antenna provides a VSWR of 1.0154 and 1.35 at 28 GHz and 38 GHz, respec-

Fig. 13. The 3D radiation pattern of the proposed antenna: (a) 28 GHz and (b) 38 GHz.

Fig. 14. Comparison of the radiation pattern of the optimized antenna with CST and HFSS: (a) 28 GHz and (b) 38 GHz.
Fig. 15. Surface current distribution of the optimized antenna with CST with different phase angles at 28 GHz (a) 0°, (b) 30°, (c) 60°, (d) 90°, (e) 120° and (f) 150°.

Fig. 16. Surface current distribution of the optimized antenna with CST with different phase angles at 38 GHz (a) 0°, (b) 30°, (c) 60°, (d) 90°, (e) 120° and (f) 150°.
Fig. 17. Comparison of realized gain of the optimized antenna with manually optimized antennas.

Fig. 18. Comparison of realized gain of the optimized antenna with CST and HFSS.

Fig. 19. Comparison of radiation efficiency of the optimized antenna with manually optimized antennas.

Table 6. Comparison of the results of the optimized antenna obtained with HFSS and CST.

| EM Solver | Operating Frequency (GHz) | Gain (dB) | Bandwidth (GHz) | S_{11} (dB) | VSWR | Efficiency (η) |
|-----------|--------------------------|-----------|-----------------|------------|------|----------------|
| CST       | 28, 38                   | 6.0, 4.15 | 7.2, 4.17       | −50.97, −16.65 | 1.0154, 1.35 | 75.46%, 88.62% |
| HFSS      | 28, 38                   | 5.7, 4.9  | 6.87, 3.6       | −47.729, −15.65 | 1.017, 1.395 | 72.1%, 85.08%  |
Fig. 20. The simulated curves of FTBR versus frequency with antenna dimensions variation.

**Table 7. Summary of comparison between the proposed antenna with previous antenna designs.**

| References | Operating Frequency (GHz) | Size (mm²) | Gain (dBi) | Bandwidth (GHz) | S11 (dB) | Efficiency (η) |
|------------|---------------------------|------------|------------|-----------------|----------|----------------|
| [6]        | 7.3, 9.4                  | 26.5 × 38  | NS*        | 2.836           | −48.728  | NS*            |
| [21]       | 28                        | 5.34 × 4.54| 9.55       | 1.72            | −39.49   | 90.1%          |
| [28]       | 15.46, 20.41              | 20 × 20    | NS*        | 1.07, 0.94      | −32.56, 31.13 | 82.80%          |
| [36]       | 28, 60                    | 15 × 25    | 6.5, 5.5   | 2.32            | −42, −47 | 99.57%, 99.87% |
| [37]       | 28, 38                    | 20 × 20    | 5.75, 7.23 | 4.864, 3.602    | −40.64, −32.66 | NS*           |
| [38]       | 28, 36                    | 8 × 7.5    | 4.2, 6.9   | 4.9, 7          | NS*      | NS*            |
| [39]       | 33.5, 60.8                | 2.28 × 3.06| 6.64, 7.13 | 1.20, 1.16      | −11.82, −13.89 | 95.7%, 96.5% |
| [40]       | 26, 28                    | 20.27 × 9.5| 5.4, 5.5   | 2.4, 2.1        | NS*      | 60%            |
| This work  | 28, 38                    | 7.91 × 7.85| 6.0, 4.15  | 7.2, 4.17       | −50.97, −16.65 | 75.46%, 88.62% |
| NS*        | Not Specified in          |            |            |                 |          |                |

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4. Conclusions

The proposed antenna structure results from EM simulations are recorded as a dataset by varying geometric parameters of the proposed antenna structure. Then, this dataset uses response surface methodology to model resonating frequency and bandwidth of the DBRMSPA structure. In the process constrained numerical optimization is applied to achieve the desired impedance bandwidth (BW). The optimized antenna results are validated by comparing the results of two different EM solvers. The bandwidth performance of the proposed DBRMSPA is enhanced to broadband performance in a frequency range of 27.214 GHz to 34.445 GHz and 34.816 GHz to 38.99 GHz. The antenna also gives suitable gain and radiation efficiency performance at both operating bands of the antenna. The VSWR of the antenna is less than 2 throughout its operating range. Thus, response surface methodology (RSM) based modeling and constrained numerical optimization using Design Expert is a competent approach for enhancing the performance of high-frequency antennas. The proposed antenna is suitable for high-bandwidth 5G mobile communication systems, the Internet of things (IoT) and other intelligent automations applications.

**Declarations**

**Author contribution statement**

Lijaddis Getnet Ayalew, MSc; Fanuel Melak Asmare, MSc: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
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