SEMARAK ILMU
PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage:
https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

Design and Fabrication of Compact MIMO Array Antenna with Tapered Feed Line for 5G Applications

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ARTICLE INFO

Article history:
Received 12 October 2023
Received in revised form 22 January 2024
Accepted 28 April 2024
Available online 22 May 2024

Keywords:
Microstrip antenna; MIMO antenna; 5G application; mm-wave band; Tapered Feed Line

ABSTRACT

This paper presents the design, fabrication, measurement, and evaluation of two multiple input multiple output antenna elements (MIMOs) optimized for performance in the 5G frequency band. The MIMO antennas are integrated onto Roger/Druoid 5880 substrates with a dielectric constant of 2.2, housed within a compact volume measuring $20 \times 24.14 \times 0.79 mm^3$. Initially, a thorough parametric study is conducted using the CST Electromagnetic (EM) Simulator to analyze and optimize the antenna's performance according to 5G application requirements. Subsequently, in the antenna design phase, calculations are made for the envelope correlation coefficient (ECC > 0.01dB) and diversity gain (DG > 9.9dB), yielding favorable outcomes. Fabrication and measurement procedures are carried out to verify the antenna's performance, demonstrating good agreement between simulation and experimental results. Additionally, a tapered feed structure with inset feed is employed to minimize mutual coupling and ensure matching along two transmission lines with various impedances, achieving high compactness within the antenna structure. Furthermore, the paper reports that the proposed antenna structure attains a gain of 8 dBi (dB) within the relevant operating frequency band (24.25 GHz)

1. Introduction

The primary requirements for the 5G current communication systems are the high data rate, flexible applications, and services. Since antennas are the fundamental component of communication systems, the antenna sector needs to develop new types of antennas for 5G applications [1-3]. Current studies on 5G antennas mostly focus on the millimetre wave (mm-Wave)

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https://doi.org/10.37934/araset.46.1.146156

frequency range [4]. MIMO-based systems are utilized in 5G communication systems [5,6] to address multipath fading, improve channel capacity, and deliver a high data rate while maintaining low power consumption and steady communication quality [7]. Multiple antennas are used by MIMO systems for both transmission and reception.

A further prerequisite for 5G systems is hardware miniaturisation. We have a limited amount of space set aside for the MIMO antenna configuration, therefore as the antenna is the primary component of communication systems, its overall structure miniaturization should be taken into account during the construction process. In addition, the MIMO antenna itself needs larger distance between antennas in order to achieve strong isolation between its antenna elements [7, 8]. For academics and antenna designers working on 5G communication systems and specialized antennas in miniaturization and high isolation, this final need poses a difficulty [8].

The literature on antennas for 5G applications has a variety of designs available, as reported in [9–23]. According to [24], an inset-feed two-element patch antenna with good isolation and an overall dimension of 55.0 x 110.0 mm2 operates at the 28 GHz and 38 GHz frequency bands, respectively. A dual-band circular patch antenna is shown in [25] with realized gains of 7.6 dB and 7.21 dB at 28 GHz and 45 GHz, respectively. The dimensions of the suggested antenna are 55.0 x 110.0 mm^2. A broadband magneto-electric dipole based on feeding strips with a Γ form is built in [26], as described in [27]. The suggested antenna exhibits a 25 dB better level of isolation.

An additional dipole antenna with a gain and total radiation efficiency of 6.81 dBi and 98.82%, respectively, covering a frequency range from 24.3 GHz to 41.95 GHz and from 49.91 GHz to 52.15 GHz, is based on a unique ground plane, as demonstrated in [28]. In [29], a coplanar waveguide (CPW)-feed for mm-wave 5G mobile terminal with a wideband antenna that operates at 28 GHz and a 9 dB gain is introduced. A slot-based antenna array for 5G applications with a gain and total radiation efficiency of 8 dB and 80.0%, respectively, is presented in [31] and another work in [32]. A 4-port based MIMO antenna operating at 26.0 – 31.0 GHz band frequency with a higher gain of 10 dB is designed and presented in [30]. As demonstrated in [33], where a monopole antenna array operating at 28 GHz and with a gain of 8 dB is built, monopole antennas were considered as a potential for 5G communication systems. Recently, researchers and antenna designers have employed many technologies, including Defected Ground Structures (DGS), Frequency Selective Surfaces, and EBG as given in [34–42], to increase overall performance enhancement, miniaturization, and multi-band microwave and mm-Wave component design.

In order to achieve high data rate transmission, a wideband 2-port MIMO antenna working from 24.25 GHz to 25.75 GHz is constructed and researched in this publication. It uses a modified feeding line. High gain, isolation, total radiation efficiency, and MIMO features (ECC and DG) are all demonstrated by the suggested antenna, which qualifies it for use in 5G millimeter-wave applications.

2. Methodology

2.1 MIMO Antenna Design Procedures

The following is a summary of the step-by-step process for designing MIMO antennas:

i. Single patch antenna element calculations, which include reference element design and optimisation of the first fundamental parameter values.

ii. Feeding network optimisation and fundamental parameter calculations.

iii. Optimising and designing array antennas with 0.3λ reference element separation.

iv. Combining DGS with circuit design.

2.1.1 Reference antenna element design and analysis

As shown in Figure 1, the first step in creating a MIMO antenna is to create a rectangular patch antenna. The antenna is mounted on a Roger/Druoid 5880 substrate, which has an overall structural volume of 20 × 24.14 × 0.79 mm3 and a dielectric constant of ∈r = 2.2. Since the Roger/Druoid 5880 substrate has a loss tangent of 0.0009, compared to other dielectric materials, it indicates a low dielectric loss in the high-frequency range. The values of the initial parameters are determined using equations (1), (2), (3), and (4):

$$W = \frac{C}{2\pi f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{1}$$

$$L = \frac{C}{2f_r\sqrt{E_{eff} + 1}} - 2\Delta L \tag{2}$$

$$\Delta L = 0.412h\frac{E_{eff} + 0.3}{E_{eff} - 0.258}\left[\frac{\frac{w}{h} + 0.264}{\frac{w}{h} + 0.8}\right] \tag{3}$$

$$E_{eff} = \frac{\varepsilon_r + 1}{2} - \frac{\varepsilon_r + 1}{2}\left[1 + 12\frac{h}{w}\right]^{-\frac{1}{2}} \tag{4}$$

The main feed line parameter values of 50-ohm is calculated using the equation (5):

$$\mathrm{Z} = \frac{120\pi}{\sqrt{E_{eff}}\left[\frac{W_0}{h} + 1.393 + 0.667ln\left(\frac{W_0}{h} + 1.444\right)\right]} \tag{5}$$

To improve matching, the feed line is tapered and the inset dimension is optimized. The purpose of the tapered feed line structure is to increase the impedance bandwidth and smooth the course of the current. Table 1 provides the overall optimized reference element design values.

(a) (b)

Fig. 1. Single antenna element design (a) CST Model (b) Fabricated antenna

Table 1
Reconfigurable-Pin Diode Switches

Variables	F1	F2	F3	F4	F5
Values (mm)	1.42	0.25	2.82	3	2.73

As shown in Fig. 2, both the simulated and the measured reflection coefficient are consistent within the bandwidth of 23.9 GHz-28.93 GHz, with the central frequency being 25 GHz. Several factors contributed to additional resonances at lower frequencies, such as the compactness of substrate and patch, SMA connectors and cables, and fact that measurements were not performed in isolated laboratories. The optimal simulated gain and overall radiation efficiency (8 dBi) is 92.5% as shown in Fig. 3. Fig. 4 shows the simulated radiation patterns for the E and H plane for the operating frequency 25 GHz.

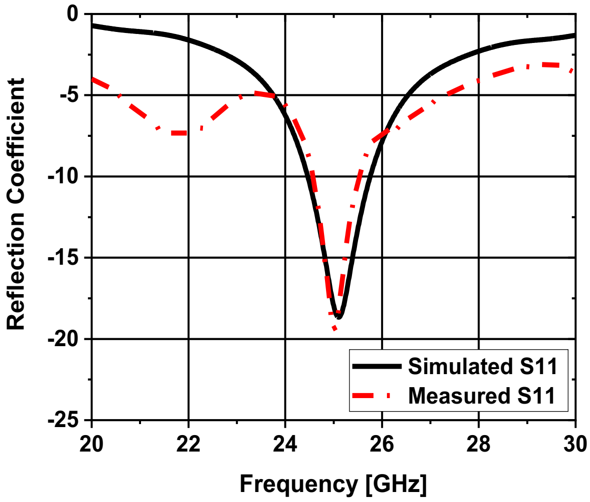


Fig. 2. Simulated and Measured Reflection coefficient of the reference antenna element

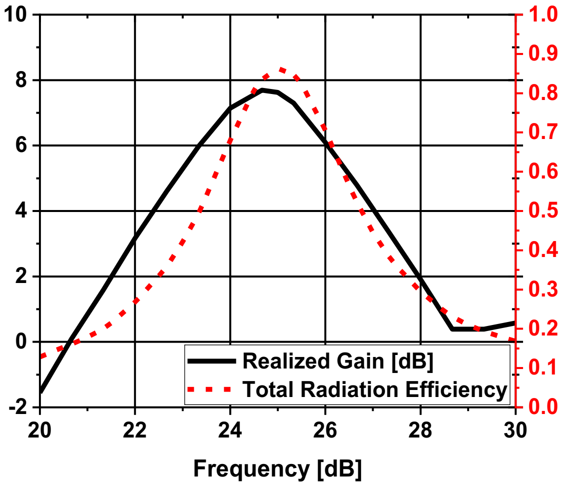


Fig. 3. Simulated realized gain and total radiation efficiency of the reference antenna element

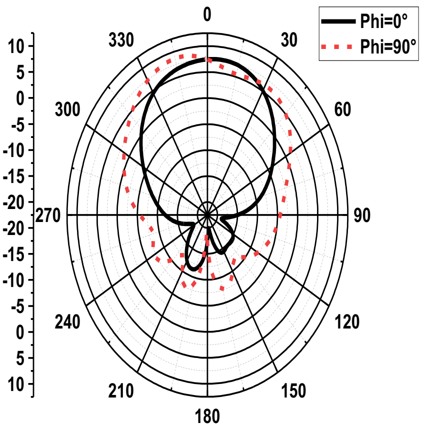
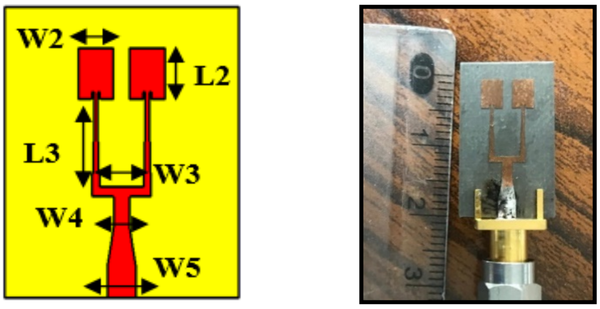


Fig. 4. Simulated radiation patterns of MIMO antenna at Phi=0° and Phi=90°

2.1.2 Antenna array design and analysis

Once the single element design has been validated for basic antenna performances such as S11, gain and overall radiation efficiency, the next step is to design an array antenna according to the following procedure: Figure 5(a) is an example of an antenna array configuration. It consists of two identical one element antennas. Its feeding network is shown in Fig. 5(b). Table II shows the optimized dimensions of the array antenna. Note that the slot dimensions of the array configuration are different from the ones of the single element. This means that the coupling of the array elements will be compensated.

Since the feeder width is larger than the patch width in the single and array configuration, conventional feed methods cannot be used. To enhance the impedance matching of both elements while keeping the compactness, the antenna is fabricated using tapered feed line and inset feed, reducing the mutual coupling between the two array's elements. The antenna is fabricated as shown in Fig. 5(b). The reflection coefficient is simulated and measured in Fig. 6. Good agreement is achieved. As shown in Fig. 7, the array configuration has increased the total realized gain by about 9.25 dB, with the total radiation efficiency being 92.5% (compared to 7.9% for the single element antenna) while maintaining the higher compactness.



(a) (b)

Fig. 5. Array antenna element: (a) CST Model (b) Fabricated antenna

Table 2
Optimized dimension of array antenna (Unit cell of the MIMO)

Variables	L2	L3	W2	F1 (Array)	Variables
Values (mm)	3.58	6.19	3	0.48	3.58
Variables	W3	W4	W5	F2 (Array)	W3
Values (mm)	3.73	1.36	2.45	0.19	3.73

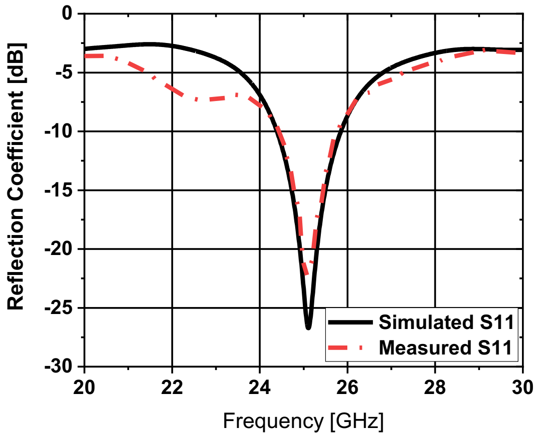


Fig. 6. Simulated and Measured Reflection coefficient of the antenna array

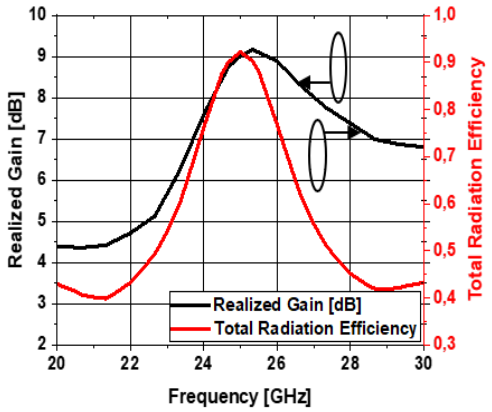


Fig. 7. Simulated realized gain and total radiation efficiency of the array antenna

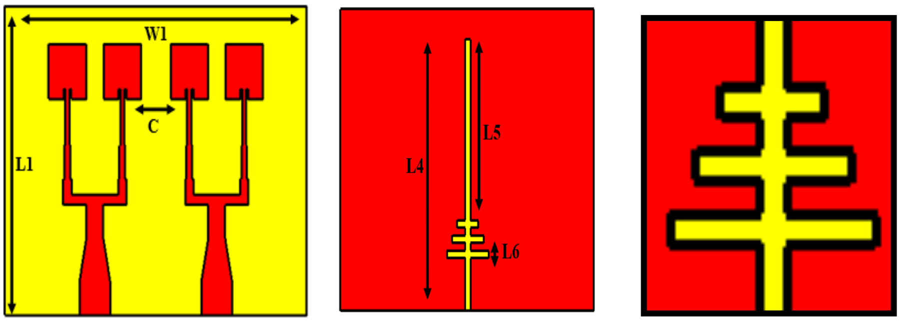
2.1.3 MIMO antenna design and analysis

Last but not least, based on our previous design of the array antenna, CST EM software is used to design and simulate a MIMo antenna. As you can see in Figure 8 (a), C is the space between the antenna edges. For good isolation between antenna elements, C1 is between λ / 4 and λ / 2. In our proposed design, C = 0.3 λ. A proposed DGS is etched into the ground plane in order to minimize mutual coupling. In Figure 8 (b), our proposed DGS minimizes mutual coupling by minimizing C. By minimizing mutual coupling, our proposed DGS achieves a compact dimension. This is achieved by discontinuing the surface current distribution introduced into the ground plane. Our proposed DGS has two main control structures:

i. What is a vertical line slot? Vertical line slots consist of a single vertical line, optimized for length and width that splits the ground under an MIMO field antenna into two equal sections.
ii. Horizontal line slot the horizontal line slot is a series of three vertical lines engraved between feed lines where the coupling concentration is maximal.

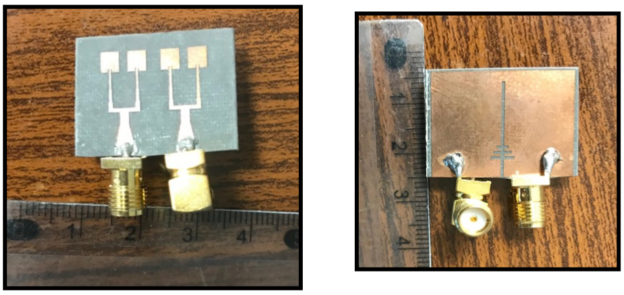
Simulated and measured S- parameters of the optimized antenna design with or without DGS covering the band of frequencies 24.25-25.75 GHz are shown in Fig. 10. Improved isolation due to introduction of DGS in ground plane.

Reduced distance of MIMO antenna element. Note that DGS only improves MIMO antenna performance, not unit cell array antenna performance. Total realized gain is 9 dB at 25 GHz as shown in Fig. 11. Small reduction in realized gain (≥ 0.25dB) due to mutual coupling of the two array cells as compared to array configuration. Optimized design parameters of our proposed overall MIMO configuration Table 3



(a) (b) (c)

Fig. 8. MIMO Antenna in CST: (a) Top Layer (b) Bottom Layer



(a) (b)

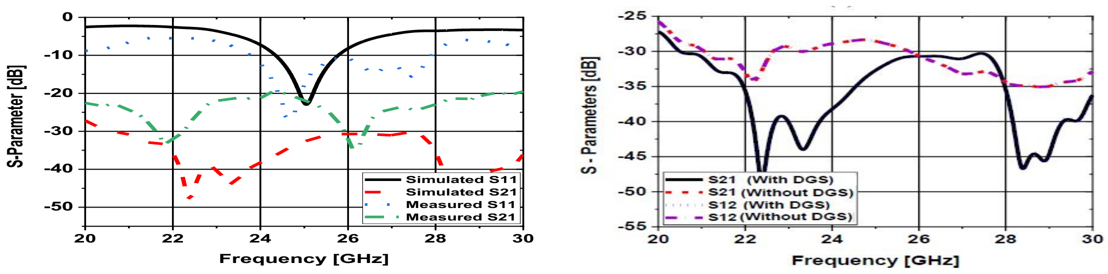
Fig. 9. Fabricated MIMO Antenna: (a) Top Layer (b) Bottom Layer

Table 3
Parameters of the designed MIMO antenna

Variables	L1	L4	L5
Values (mm)	20	18	12
Variables	L6	W1	W6
Values (mm)	0.5	24.14	4

Figure 12 This figure shows the radiation pattern of the proposed antenna with the E plane at 0° and the H plane at 90°. The maximum radiation at the E and H planes is shown at 0° and 90° degrees, respectively. In addition to the main antenna parameters, such as S parameters, Gain, total radiation efficiency, and the objective to design an antenna for MIMO, the ECC and Diversity gain of the proposed antenna are calculated and shown in Figure 13.

Using the ECC, MIMO antenna designers can better understand the level of coupling between the different antennas in the MIMO system. Minimization of the mutual coupling would reduce the correlation coefficient to the lowest possible between the two ports. ECC can be calculated from



(a) (b)

Fig. 10. Simulated and Measured S-Parameters of the MIMO Antenna (a) S-Parameters with DGS (b) S-Parameter’s comparison with & without DGS

both far-field or S-parameter using equation (7), according to [43]. Using both simulated s-parameters and far-field, ECC is calculated, and good and suitable results are observed, as shown in Figure 12 (a). To validate the designed MIMO antenna's good operation, the ECC value should be < 0.05 to ensure good isolation between the different antennas in the MIMO system.

Our proposed designed MIMO antenna ECC value is <0.01. Based on the ECC value and using equation (8) [41], the DG is calculated and sketched in Figure 12 (b).

$$\mathrm{ECC} = \frac{\left|\int (XPR.E_{\theta 1}(\Omega)E_{\theta 2}{}^{*}(\Omega) + E_{\varphi 1}(\Omega)E_{\varphi 2}{}^{*}(\Omega)d\Omega\right|^{2}}{\int (XPR.G_{\theta 1}(\Omega)E_{\varphi 1}{}^{*}(\Omega))d\Omega\,.\int (XPR.G_{\theta 2}(\Omega)E_{\varphi 2}{}^{*}(\Omega))d\Omega} \quad (7)$$

$$DG = 10\sqrt{1 - ECC} \qquad (8)$$

The envelope correlation coefficient is close to zero at the target frequency band, and the diversity gain exceeds 9.8 (near the maximum), indicating good isolation between these two elements.

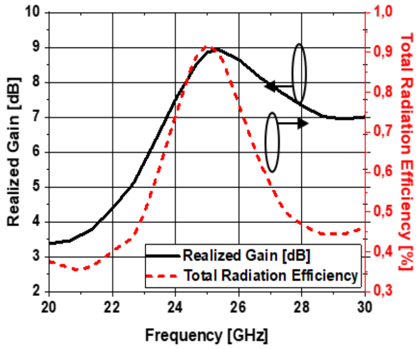


Fig. 11. Simulated realized gain and total radiation efficiency of MIMO Antenna

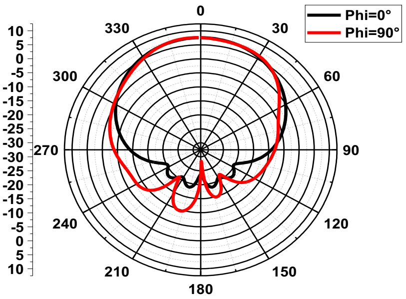
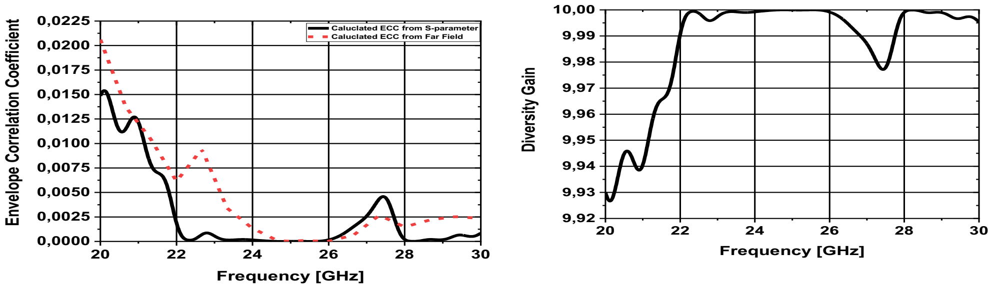


Fig. 12. Simulated radiation patterns of MIMO antenna at Phi=0° and Phi=90°



(a) (b)

Fig. 13. Calculated ECC and DG (a) ECC (b) DG

3. Results

3.1 Comparison with other related works

A comparison of our proposed antenna with related literature is done and presented in Table 4. The comparison is made in terms of total antenna performance as well as MIMO related performance (ECC and DG). From our comparative study, we can conclude that our proposed design has a good gain (ECC & DG) compared to the other literature reported. Furthermore, the suggested MIMO configuration has a small overall dimension compared to the other works.

Table 4
Comparison with other related works

Ref.	Freq. (GHz)	Overall Dimension (λ3)	Gain (dB)	Decoupling Method	ECC & DG (dB)
[44]	25	2.75×1.73×0.02	7.37	Isolation by Separation	NA
[45]	28	2.5×2.9×0.06	8.3	N/A	0.01 & 9.96
[46]	28	1.65×1.65× 0.02	8	Microstrip Feed slots	0.13 & 9.9
[47]	27.5	2.72 × 3.18 × 0.07	8.3	DGS	<0.01, >9.96
[48]	24	1.2 × 1.52 × 0.02	6	EBG	0.24, 9.7
Proposed Work	25	1.38 × 1.675 × 0.05	8	DGS	0.01 & 9.9

4. Conclusions

A new compact MIMO antenna design with high performance two elements mounted on Roger / Druoid 5058 is designed, studied, and presented. This MIMO structure shows a gain of 8 DBi at the relevant operating band of frequencies 24.25 GHz-25.75 GHz. The design uses a tapered feed structure with inset feed to minimize mutual coupling and achieve matching along 2 transmission lines with various impedances. The previous conventional designs with this substrate and this frequency range are very limited in comparison with the proposed design. The proposed antenna configuration is also validated with Envelope correlation coefficient and Diversity gain, with good results. Fabrication and measurement were performed, and very good correlation with simulation is observed.

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