Research

Compact eight-element MIMO antenna array for sub 6 GHz Mobile applications

Mohamed M. Morsy[1]

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Abstract
A compact eight-element multiple-input multiple-output (MIMO) antenna array operating at the sub-6-GHz (LTE band 52) for the 5G handheld applications is proposed. The antenna array is realized by employing eight couple-fed slots etched on the ground plane of the MIMO antenna system. The size of the slot radiators excites the required operating bandwidth. A parametric analysis study of the effect of varying the size of the slot radiators on the ground plane is provided to give some insight into the operation of the proposed antenna system. The radiators are excited by 50-Ω strip lines. Rectangular-shaped slits are used as isolation structures to mitigate the mutual coupling effect between elements, resulting in a low Envelope Correlation Coefficient (ECC) of less than 0.1 at the operating bandwidth. The proposed MIMO antenna was fabricated and experimentally validated. The measured and simulated results are in good agreement. Other MIMO performance indicators, such as radiation patterns, Mean Effective Gain (MEG), and the proposed MIMO antenna system's total efficiencies, are being analyzed. Measurements and simulation results are consistent, which shows that the proposed antenna is a good candidate for 5G applications in the LTE band 52.

Article Highlights

- A compact MIMO antenna array is being developed for integration into 5G handheld devices.
- Design features reduce element coupling, enhancing MIMO system performance.
- Extensive validation affirms the antenna's effectiveness for 5G applications.

Keywords MIMO antenna · Sub 6 GHz · LTE · 5G · Mobile applications

1 Introduction

In today's Internet of Things (IoT) era, the demand for wireless devices with broad bandwidth, fast data rate, and wireless reliability through multi-path communications encouraged the rapid development of 5G communications. MIMO systems that were employed in 4G applications continued to be employed in 5G frequency bands [1]. The sub-6-GHz band is a promising frequency band for 5-G applications as it overcomes several limitations of the mm-wave bands, such as link budget, path, and propagation losses [2, 3]. However, mm-wave antennas feature a compact design and wide bandwidth. MIMO systems for 5G applications face many challenges primarily

✉ Mohamed M. Morsy, mmorsy@tamut.edu | [1]Engineering and Physics Department, Texas A&M University-Texarkana, Texarkana, TX 75503, USA.

because of the confined space allocated for antennas in wireless handheld devices. For 5G applications, the number of antenna elements needs to be at least six to eight elements for most applications [4].

Aggregating that number of antenna elements in a limited space requires optimization of isolation, antenna size, and innovative isolation techniques. Several techniques are being used to mitigate the mutual coupling effect of MIMO antenna systems. Such as bandgap structures[5, 6], parasitic elements [7–9], decoupling structures [10, 11], polarization diversity [12, 13], and defective ground planes [14]. In [10], lumped elements are used as a decoupling structure which achieves plausible isolation but also complicates the design structure with a total size of 150×75 mm^2. In [11], open-ended slots were used to achieve sound isolation. Polarization diversity has also proven to be very successful in achieving high isolation performance. In [12], T-shaped slot linearly polarized elements were positioned such that polarization diversity is attained. While two orthogonally polarized square-ring elements were used at the four corners of a PCB substrate to achieve a highly isolated eight-element MIMO antenna system, as shown in [13]. However, the total size of the antenna proposed in [13] can be further optimized.

This paper presents a compact eight-element MIMO antenna for 5G applications. The proposed antenna configuration consists of slot radiators etched on the ground plane and fed by rectangular microstrip lines. A rectangular slit was used to mitigate mutual coupling. The essential characteristics of the MIMO systems are investigated in the following subsections, including a parametric study that shows the effect of varying the size of slot radiations on the s-parameters. Moreover, the radiation characteristics of the MIMO system are also investigated. The proposed MIMO antenna system exhibits good ECC and MEG values. Total efficiency is also calculated. All simulated and measured characteristics show that the proposed antenna system is suitable for 5G communications.

The paper is organized as follows: Sect. 2 details the design and construction of the proposed eight-element MIMO antenna. This includes an analysis of the effect of varying the size of the slot radiators and the optimization process of the antenna dimensions. Section 3 presents a comparison between simulated and measured s-parameters, reflection coefficients, and transmission coefficients. Section 4 presents the radiation characteristics of the proposed antenna design, including radiation patterns and key performance indicators such as the envelope correlation coefficient (ECC) and mean effective gain (MEG). Finally, the "Conclusion" section summarizes the study's findings, the suitability of the proposed antenna for 5G applications, and the advancements made in MIMO antenna design.

2 Proposed antenna array

Figure 1 illustrates the configuration and measurements of the eight-element antenna array that has been proposed, including its geometry and dimensions. In Fig. 1, the eight antenna elements are labeled Ant. 1–8 are formed along two sides of an FR4 substrate (dielectric constant = 4.4 and tangent = 0.02). The substrate size is $105 \times 60 \times 1.6$ mm, which is suitable for most handheld devices such as smartphones and laptops. In this design, each antenna covers the entire LTE band 52 (3300–3400 MHz). Figure 1 shows the effect of varying the slot radiator length(L1) on the reflection coefficient (S11) and the transmission coefficient (S21) when considering only two elements. It is also noticed that as the slot length (L1) gets wider, the resonance shifts towards a lower frequency, as shown in Fig. 2a, while mutual coupling increases as the distance between radiating slots is reduced (Fig. 2b)

To gain more insight into the operation of the antenna array, the current distribution at 3.4 GHz, when Ant. 1 is excited while a 50Ω waveport terminates the remaining elements, is shown in Fig. 3. The scale used for the current distribution density is 0–42 A/m. It is seen that the couplings between Ant. 1 and other antennas are relatively weak. However, due to spatial proximity, the most mutual coupling effect is shown between Antennas 1,2 and antennas 1,8.

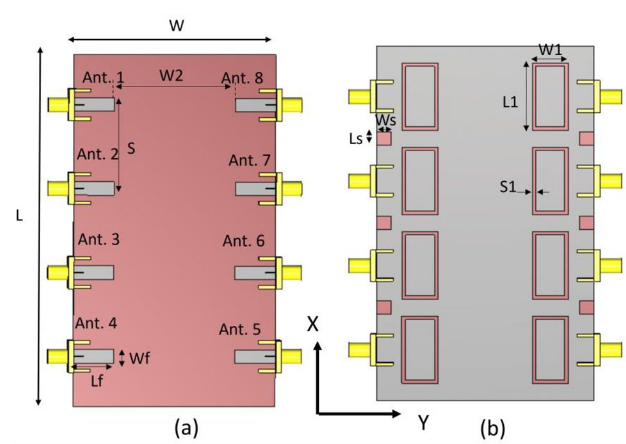

Fig. 1 Antenna geometry **a** front view and **b** back view (ground plane)

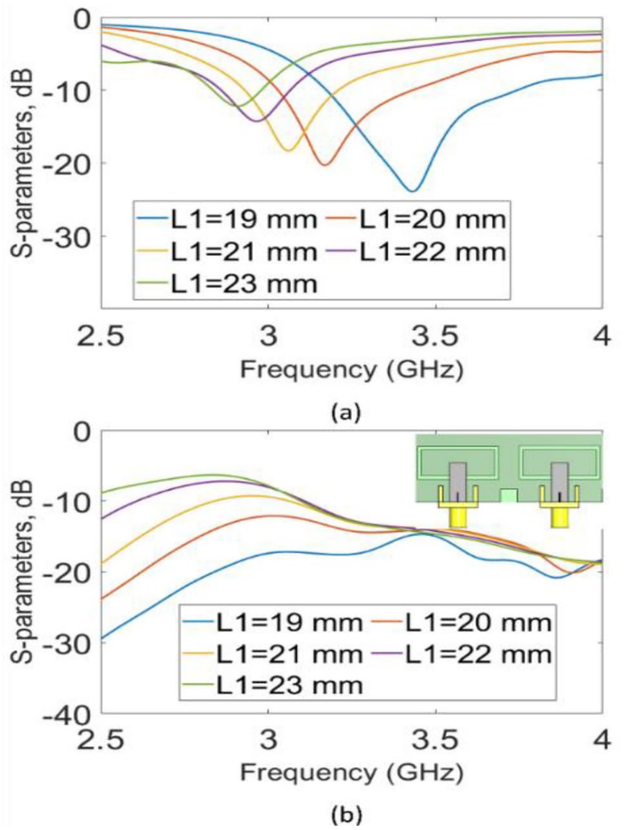

Fig. 2 Effect of varying the slot length(L1) on the S-parameters **a** reflection coefficient, **b** transmission coefficient

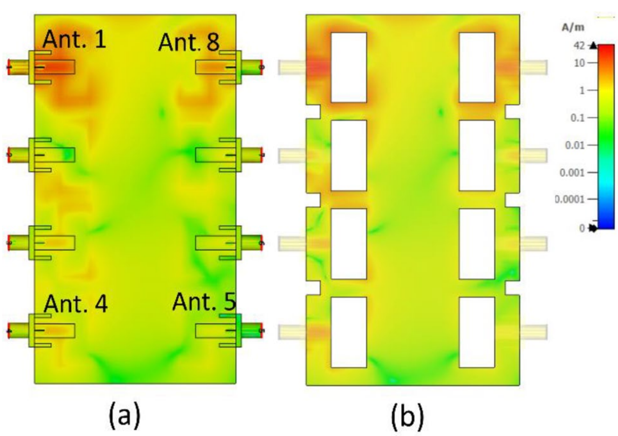

Fig. 3 The Current distribution at 3.4 GHz when Ant.1 is excited **a** front view, **b** back view

3 Results and discussion

Based on the optimized dimensions listed in Table 1, a prototype was fabricated on an RF4 substrate with relative permittivity of 4.4 and an overall dimension of 105×60 mm^2. The feeding striplines are soldered to 50-Ω SMA connectors. The radiating slots are etched on two opposite sides of the ground plane with a size of 20×10 mm^2. Figure 4 shows a picture of the fabricated prototype.

Both simulation and measurements have verified antenna performance. Simulation is performed using 3D electromagnetics software, CST Microwave Studio 2023 [15]. Figures 5 and 6 show the simulated and measured s-parameters of the MIMO proposed antenna system,

Table 1 Design parameters of the proposed MIMO antenna system

Parameters	Value (mm)	Parameters	Value (mm)
L	105	Ws	4
W	60	Ls	4
S	25	S1	1
L1	20	Lf	12
W1	10	Wf	4
W2	36		

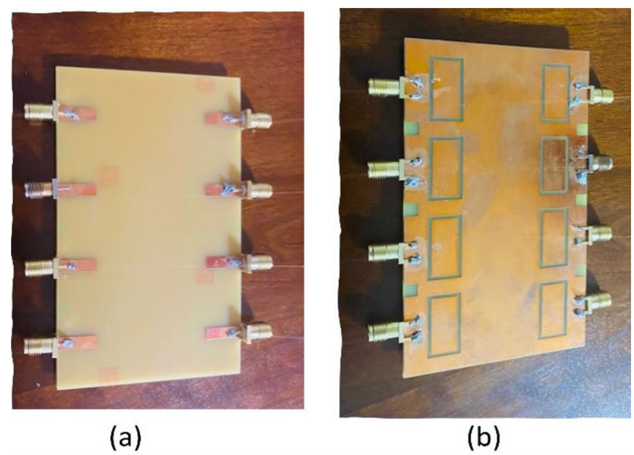

Fig. 4 Fabricated MIMO antenna system, **a** front view **b** back view

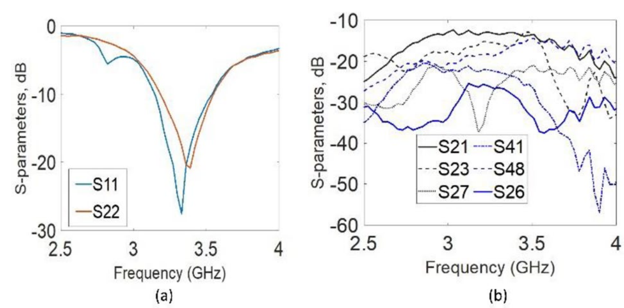

Fig. 5 Measured s-parameters, **a** magnitude of the reflection coefficients (dB) **b** Magnitude of transmission coefficient (dB)

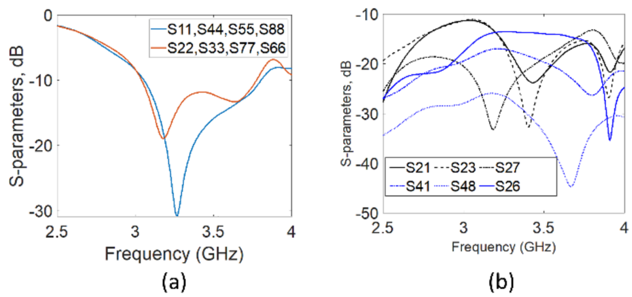

Fig. 6 Simulated s-parameters, **a** magnitude of the reflection coefficients (dB) **b** Magnitude of transmission coefficient (dB)

respectively. As the design is symmetrical, only distinct s-parameter values are presented. Due to the symmetrical structure of the antenna system, it can be noticed that the reflection coefficient of antennas 1, 4, 5, and 8 are identical.

Similarly, the reflection coefficient of antennas 2, 3, 6, and 7 are also identical. Figure 5a presents the measured reflection coefficients of the proposed antenna array. The corresponding 10-dB impedance bandwidth is 3.2–3.55 GHz.

Figure 5b shows the measured magnitude of the transmission coefficients of the antenna system in dB. The isolation of the antenna systems ranges between – 12 and – 26 dB. As expected, the strongest coupling is between antennas 1 and 2; however, the isolation value is still acceptable for 5G applications.

4 Radiation and MIMO performance

To better understand the radiation characteristics of the proposed design, the 2D (theta and phi components) radiation patterns were simulated and measured, as shown in Fig. 7. The far-field measurements were performed for antennas 1, 2, 3, and 4 in the XY plane. Due to the symmetrical structure, the radiation patterns of antennas 5 through 8 are mirror

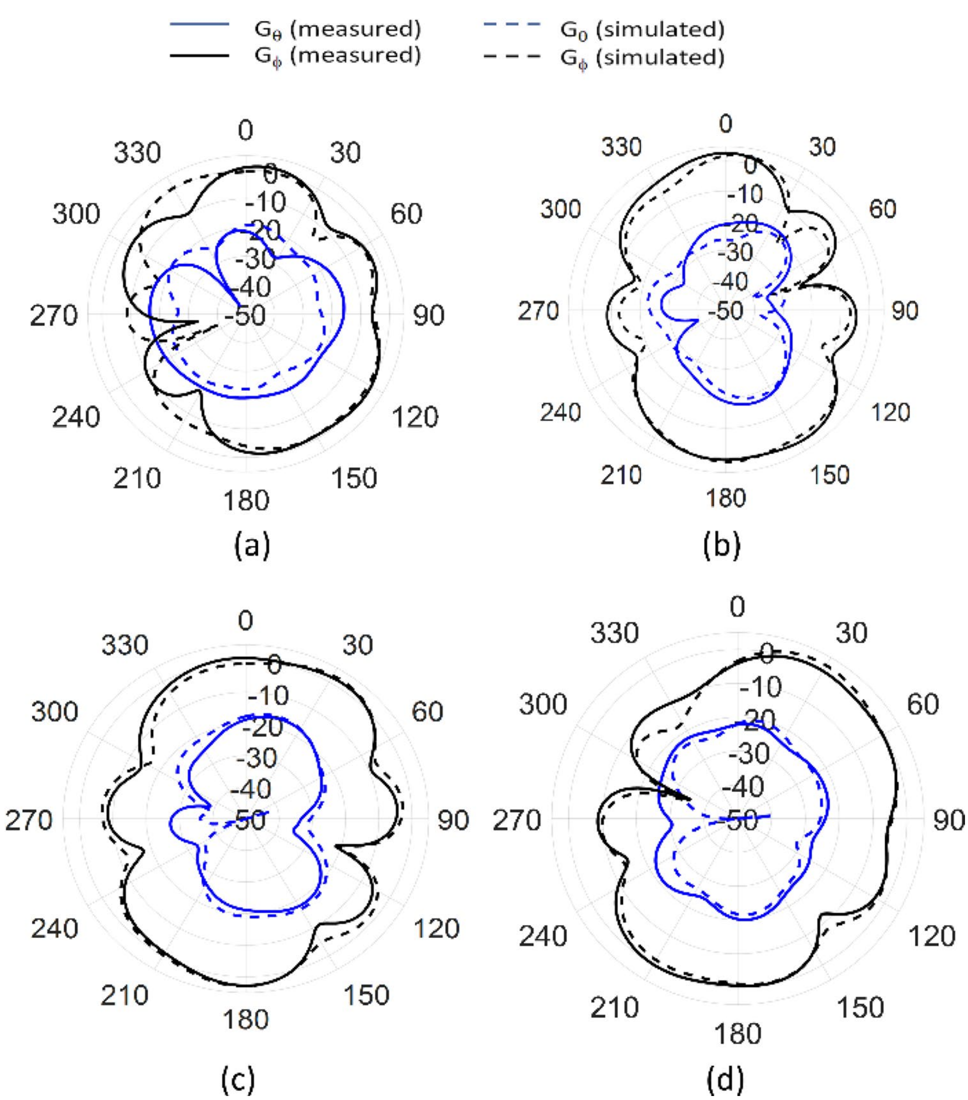

Fig. 7 Measured and simulated radiation patterns in the XY plane, **a** Ant. 1 **b** Ant. 2, **c** Ant. 3, **d** Ant. 4

images of antennas 1 through 4. The antenna mainly exhibits a linear performance as the cross-polarization components (Gain-theta) are at least 10 dB less than the co-polarization components (Gain-phi) around the main lobe directions.

The envelope Correlation Coefficient (ECC) is a key performance indicator for MIMO performance and is calculated using the radiation characteristics of the MIMO elements, as in [16].

$$ECC_{ij} = \frac{\int_{4\pi} E_i(\theta,\varnothing)E_j^*(\theta,\varnothing)d\Omega}{\sqrt{\int_{4\pi} E_i(\theta,\varnothing)E_i^*(\theta,\varnothing)d\Omega \int_{4\pi} E_j(\theta,\varnothing)E_j^*(\theta,\varnothing)d\Omega}}, \quad (1)$$

where E_i and E_j are the far-field radiation patterns from antennas *i* and *j*. The analysis is done assuming that incoming signals are isotropically distributed. The calculated ECC values of the proposed antenna systems are shown in Fig. 8. For brevity, and because of the symmetrical design, only necessary ECC curves are shown. All ECC values are well below 0.1 in the operating frequency band. This result indicates good isolation between antenna elements, an essential characteristic of MIMO operation.

Mean effective gain (MEG) is an essential characteristic of MIMO systems in a fading environment. It is a measure of the average power received by a MIMO antenna relative to the power received by an isotropic antenna [17]. It is calculated using the measured s-parameters data, as shown in [17].

$$MEG_i = 0.5\left(1 - \sum_{j=1}^{N} \left|S_{ij}\right|^2\right) \quad (2)$$

where *N* is the number of antenna elements, and *i* is the antenna under observation. MEG values should typically be within – 12 to – 3 dB [14], which is in agreement with the obtained calculated MEG values for the proposed antenna. Figure 9.

The difference between MEG values is recommended to be less than 3 dB so that

$$\left|MEG_i\right| - \left|MEG_j\right| \leq 3dB \quad (3)$$

The total efficiency of the proposed antenna array is shown in Fig. 10. As illustrated, the antenna elements show high total efficiencies around the LTE 52 band (3.4–3.5 GHz), which is more than 70%.

Table 2 compares the key characteristics of the proposed antenna to other MIMO systems. It can be seen that the proposed antenna has a good performance in terms of size, efficiency, and ECC.

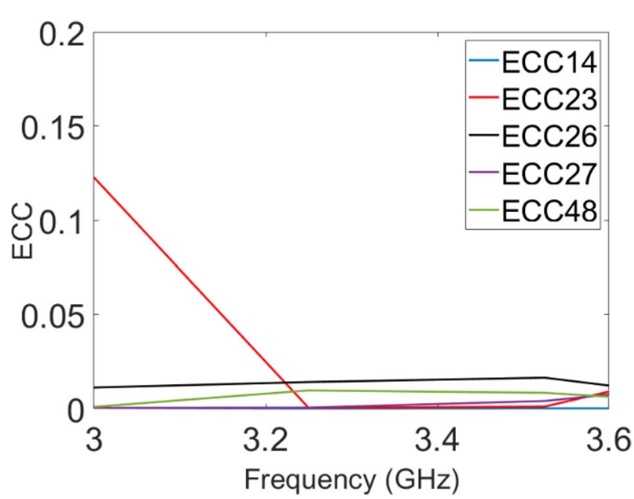

Fig. 8 Calculated envelope correlation coefficients (ECC) of the proposed antenna system

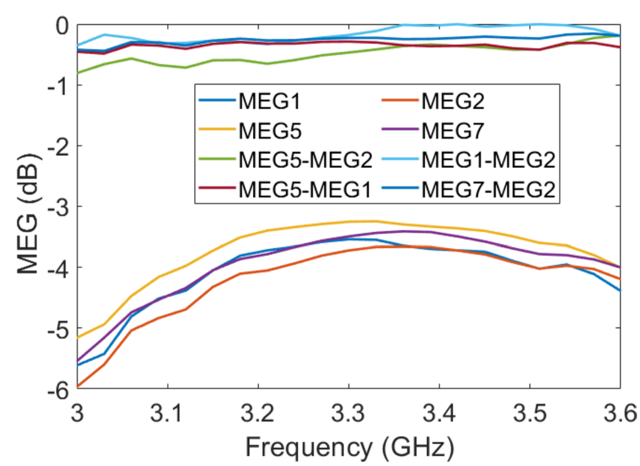

Fig. 9 Calculated mean effective gain of the proposed antenna

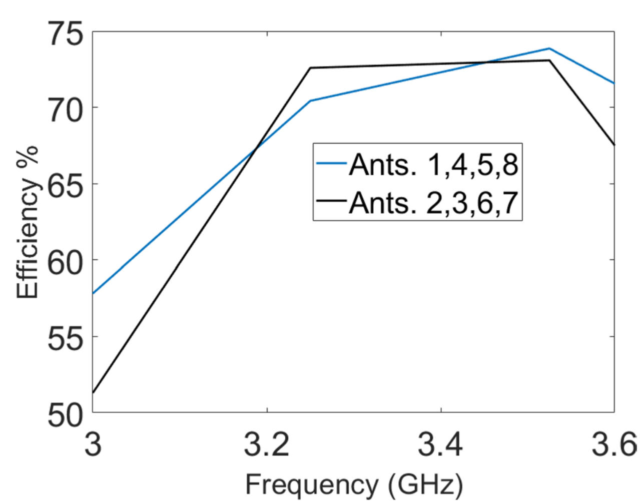

Fig. 10 Total efficiencies of antenna elements

Table 2 Performance comparison between the proposed MIMO antenna and other work

References	No. of Elements	Dimensions (mm^2)	Sub-6-GHz Bandwidth Range (GHz)	Efficiency (%)	ECC
[4]	2	60 × 100	1.87–2.53	83	0.1815
[7]	4	60 × 70	2.38–2.42	72	0.02
[9]	2	50 × 80	5–5.8	95	0.02
[10]	8	150 × 75	3.4–3.6	62	–
[13]	8	150 × 75	3.4–3.8	60	0.005
Proposed MIMO antenna	8	105 × 60	3,2–3.55	70	0.03

5 Conclusions

This article introduces a novel MIMO antenna design that is well-suited for 5G applications. The proposed design utilizes slots that are etched in the ground conductor of the antenna to function as radiators. These slots are fed by 50-Ω striplines located on opposite sides of a rectangular FR4 substrate. To address the issue of mutual coupling between the antenna elements, a square slit has been etched between the slot radiators on the ground plane of the proposed MIMO antenna system. The performance of the MIMO antenna was verified through fabrication and testing, with simulation and testing results indicating excellent agreement. Additionally, the radiation patterns, ECC, MEG, and total efficiency of the antenna were calculated and found to fall within acceptable values for MIMO operation.

Author contributions The paper has a sole author who is responsible for all work.

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Data availability All data generated or analyzed during this study are included in this article.

Declarations

Competing interest The authors declare no competing interests.

Ethical approval Not applicable.

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