High-isolation Quad-port MIMO Antenna for 5G Applications

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Abstract — This paper presents a compact, high-isolation MIMO antenna with physical dimensions of 68 × 68 × 0.8 mm, designed for use in 5G applications. The antenna's bandwidth ranges from 3.25 GHz to 4.34 GHz and it offers a gain of 4.3 dBi, making it suitable for applications relying on 5G technology. Several improvements have been introduced to improve its overall efficiency, such as adjustments to the ground plane and integrating apertures in the radiating patch. The alterations referred to above were optimized using the sweep parameter method to ensure that their best configurations are achieved. Furthermore, much attention has been paid to enhance isolation by ensuring all terminals are positioned precisely at 90° angles. The CST Studio Suite was utilized to design and thoroughly simulate the proposed MIMO antenna.

Keywords — 5G, compact antenna, high-isolation, MIMO antenna, sub-6 GHz

1. Introduction

The inherent advantages of 5G wireless communication systems, including higher transmission rates, low latency, and improved spectral efficiency, have attracted increasing academia and industry interest [1], [2]. The frequency ranges employed in 5G communication can be categorized into two main groups: sub-6 GHz, which includes the spectrum below 6 GHz, and the 5G millimeter wave spectrum, above 24 GHz [3]. Although the 5G millimeter wave spectrum offers higher data transfer rates than sub-6 GHz, its widespread adoption could be improved due to its limited coverage range. The inclination towards sub-6 GHz frequencies has increased demand in many countries with well-developed wireless communication industries. Therefore, the frequency range of 3.4 to 3.8 GHz inside the sub-6 GHz spectrum has attracted significant interest recently [4].

To enhance channel capacity and spectral efficiency without using extra bandwidth or transmission power, 5G mobile devices use MIMO antennas [5] to achieve spatial diversity, i.e. transmit data across many antennas and facilitate propagation along spatial pathways that are not coupled. This approach enhances the dependability and robustness of systems in multipath fading scenarios.

The spatial multiplexing technique used in MIMO involves dividing the data stream into segments, each delivered along a distinct propagation path. This improves data transfer rates without requiring more bandwidth or transmission power [6]. The choice between these two methods depends on the prevailing wireless fading conditions. A MIMO system with spatial multiplexing is best suited for multipath wireless channels with a high signal-to-noise ratio (SNR), while spatial diversity is better for multipath wireless channels with a low SNR [7], [8].

However, increasing the number of antennas in MIMO might lead to problems with isolation. Consequently, this phenomenon can degrade antenna performance [8]. Hence, it is of crucial importance to attain superior performance of MIMO antenna systems, defined by the achievement of low envelope correlation coefficients (ECCs) and high isolation, while simultaneously maintaining compact antenna sizes [9]–[14].

Many research projects have been conducted to improve the isolation of MIMO antennas systems and boost their performance. A study described in [15] introduced a decoupling structure for MIMO antennas, aiming to enhance isolation by leveraging magnetic and electric coupling. This approach yielded isolation values below 20 dB in the 2.3–2.9 GHz frequency range. The authors of [22] present a dual-band, four-element MIMO system designed specifically for 5G mobile terminals. This system contains antenna pairs that are self-decoupled, resulting in enhanced isolation. The achieved isolation values surpass –17.5 dB and –20 dB in the 3.5 and 4.9 GHz frequency bands, respectively. In [17], a novel eight-port MIMO antenna array was developed specifically for 5G smartphones and a frequency of 2.6 GHz. This array has orthogonal polarization and strategically positioned elements, improving isolation between the antenna ports.

The study presented in [18] introduces an eight-element MIMO array developed specifically for 5G smartphones that operate inside the 3.45 GHz frequency band. This array utilizes U-shaped and L-shaped antenna arrays, relying on inverted-I ground slots and NL structure to achieve a 15 dB increased isolation. Moreover, in the study described in [19], an eight-port antenna array is proposed for 5G MIMO systems used in mobile devices. This antenna array operates in the 3.5 and 5 GHz frequency bands and includes a neutralized line to address the coupling issue.

The project described in [20] offers an additional contribution, as it discusses the integration of self-isolated antennas in a 5G MIMO system for mobile terminals. This integration achieves isolation levels above 20 dB without additional decoupling devices.

In conclusion, the study described in [21] presents a compact MIMO antenna array design for 5G mobile devices. This design comprises eight elements and achieves a remarkable isolation performance of over 12.2 dB without additional elements or decoupling techniques. The MIMO antennas' mutual coupling is another important problem, since antenna components are located close to each other [22].

The main objective of this article is to propose and evaluate a compact MIMO antenna array designed specifically for 5G applications. The design has been optimized to ensure efficiency at a frequency of 3.6 GHz, employing a cost-effective FR-4 substrate material. The proposed antenna exhibits decent performance, confirmed by S-parameters, radiation patterns, gain characteristics, and envelope correlation coefficients. The tiny dimensions make it well-suited for easy integration into modern communication equipment.

The proposed design is unique due to the smaller dimensions of the antennas (measuring only 12 × 24 mm^2) compared to the solutions proposed in previous studies focusing on this particular area. Furthermore, it offers dual-band functionality, increased bandwidth, high isolation, and better gain.

The paper is organized as follows. Section 2 defines the geometry of the antenna system. Results of simulations concerning the proposed antenna (return loss, performance, and radiation pattern) are presented in Section 3. Section 4 compares the proposal with other research projects, with conclusions presented in Section 5.

2. Antenna Geometry

The process of designing an antenna may be divided into two distinct operational phases. First, an individual antenna element is developed. The second phase consists in integrating four individual aerials into a MIMO configuration. The geometry of the intended MIMO antennas was selected and CST software was used for simulation purposes. Through CST optimization, the values of specific parameters were fine-tuned to obtain the best possible results meeting the required specifications.

2.1. Single Antenna Structure

The primary element of the proposed antenna is the patch (radiating component, i.e. emitter). The remaining components include the ground plane, the dielectric substrate, and the input port. The patch has the form of a narrow strip of copper foil mounted on one side of the insulating substrate. The ground plane, made of the same metal as the patch, is placed on the opposite side of the substrate. In order to create some space between the patch and the ground plane, a dielectric substrate is used. Figure 1 shows the front and back of the proposed antenna, illustrating its components.

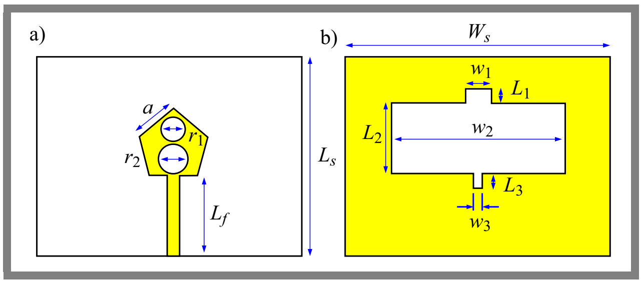

Fig. 1. Front a) and back b) view of the designed antenna.

2.2. MIMO Antenna Design

Figure 2 shows the proposed MIMO antenna configuration and a fabricated prototype comprising four ports. Each of these ports is positioned at a distance of less than one-third of the wavelength, on a 68 × 68 mm^2 FR-4 substrate with a dielectric constant of 4.3 and thickness of 0.8 mm. The detailed dimensions are provided in Tab. 1. The design incorporates symmetrical radiating elements, with optimized dimensions and suitable placement of the feed points ensuring that the most favorable impedance matching may be achieved.

Various techniques exist for feeding microstrip patch antennas, including microstrip aperture coupling, line feed, coaxial probe feed, electromagnetic coupling, and coplanar waveguide. In this case, a microstrip patch feed line with a characteristic impedance of 50 Ω is employed. The dimensions of the feed line, i.e. width W_f and length L_f, are fixed to ensure a 50 Ω impedance match. Figure 2a presents the configuration of such a feed line.

3. Results and Discussions

3.1. Single Antenna

The main parameter of the antenna is the maximum transfer of power, achieved by matching the feed line with input impedance. This relationship is typically represented by S_{11}

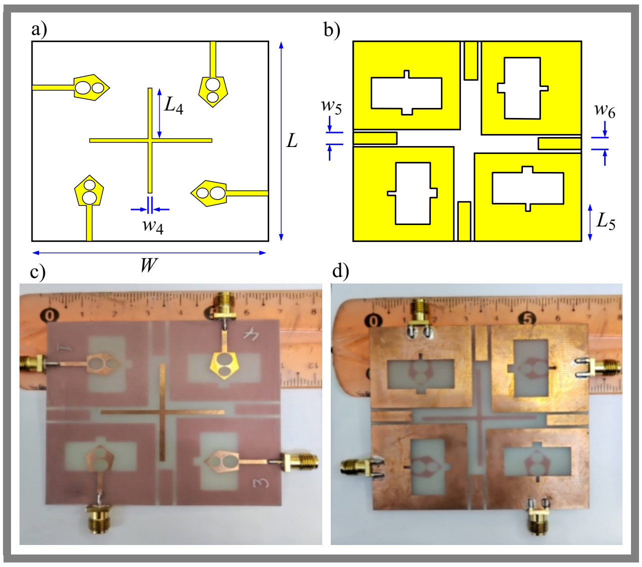

Fig. 2. Configuration of the proposed MIMO antenna: a) front view, b) back view, and c-d) both sides of the fabricated prototype.

Tab. 1. MIMO antenna dimensions.

Parameter	Value [mm]	Parameter	Value [mm]
W_s	32	w_1	3
L_s	30	L_1	2
W_f	1.5	w_2	20.8
L_f	12	L_2	10.65
a	6	w_3	1
L	12.3	L_3	2.35
r_1	2	L_4	17.25
r_2	2.4	w_4	1.5
h	0.8	w_5	6
L_5	13	w_6	4
L	68	W	68

quantifying the ratio between the amount of energy sent and reflected. Figure 3 shows S_{11} of an antenna as a function of frequency, known as its input reflection coefficient curve.

The antenna S-parameters are influenced by altering the radius of the circular slots on the patch. Various values specified by the sweep parameters are used. The return loss value must be minimized to less than –10 dB to ensure optimal antenna performance. By comparing different radius values, it was observed that with $r_1 = 2$ mm and $r_2 = 2.4$ mm, the antenna achieved a minimum return loss of –30 dB at a frequency of 3.6 GHz.

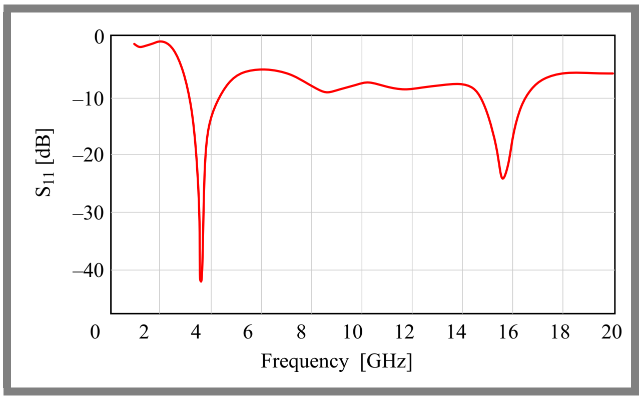

Fig. 3. Reflection coefficient of a single antenna.

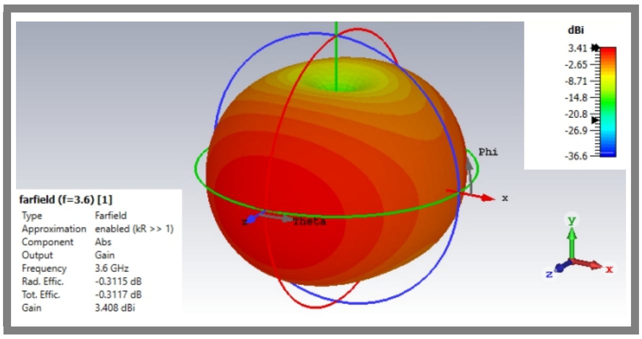

Fig. 4. Gain of single antenna.

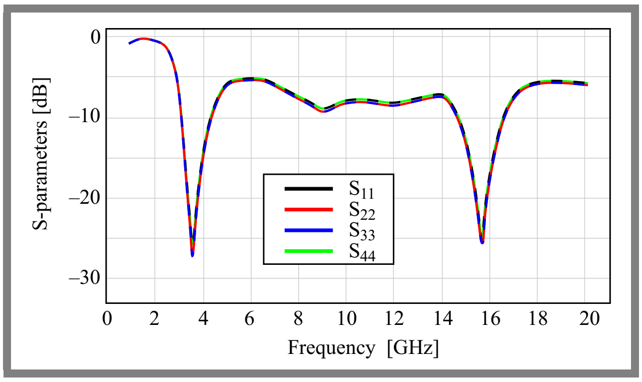

Fig. 5. Reflection coefficients of a MIMO antenna system.

The gain of an antenna refers to its capacity to focus radiated power in a specific direction, or to efficiently absorb incoming power from that direction. For a single patch antenna, this gain is approximately 3.4 dBi.

The simulated results demonstrate that the radiation patterns at far-field distance of the designed antenna are characterized by omnidirectional properties within the full bandwidth. Figure 4 illustrates gain characteristics of a single antenna.

3.2. MIMO Antenna

As the array technique enhances the behavior of a microstrip patch antenna, four array elements are used to show how the extra aerials improve the overall performance. The layout of the four components must be compact due to requirements prevailing in 5G mobile connectivity applications. To keep the proposed MIMO antenna compact and in to mitigate interference and fading caused by the larger number of antennas needed to achieve higher gains and wider bandwidths, an aerial spacing of 25 mm is recommended.

The reflection coefficient serves as a critical parameter for identifying the antenna's operating bands. Figure 5 shows the return loss simulation results (S_{11}–S_{44}). One may notice that the proposed MIMO antenna system achieves a bandwidth spanning from 3.25 to 4.34) GHz, as illustrated in the figure.

S_{12}, S_{13}, and S_{14} parameters play a significant role in characterizing mutual coupling within a MIMO system. As shown in Fig. 6, across the operational frequency spectrum, all these parameters remain below 25 dB. Due to the symmetrical structure of the MIMO design, S_{12} and S_{14} exhibit close similarity.

3.3. MIMO Antenna System Performance

The graphical representation of the simulated performance of the MIMO system is shown in Fig. 7.

One may notice that the gain and efficiency of the four antenna elements behave consistently throughout the operational frequency range. Specifically, gain remains constant at 4.3 dBi, while efficiency hovers at approximately 90%.

The two-dimensional electric field radiation patterns depicted in Fig. 8 provide a visual insight into the radiation characteristics of each antenna within the MIMO system. These patterns vividly illustrate the emission directions of the an-

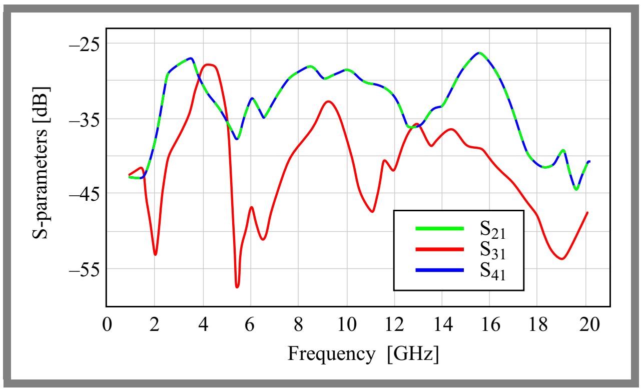

Fig. 6. Transmission coefficients of a MIMO system.

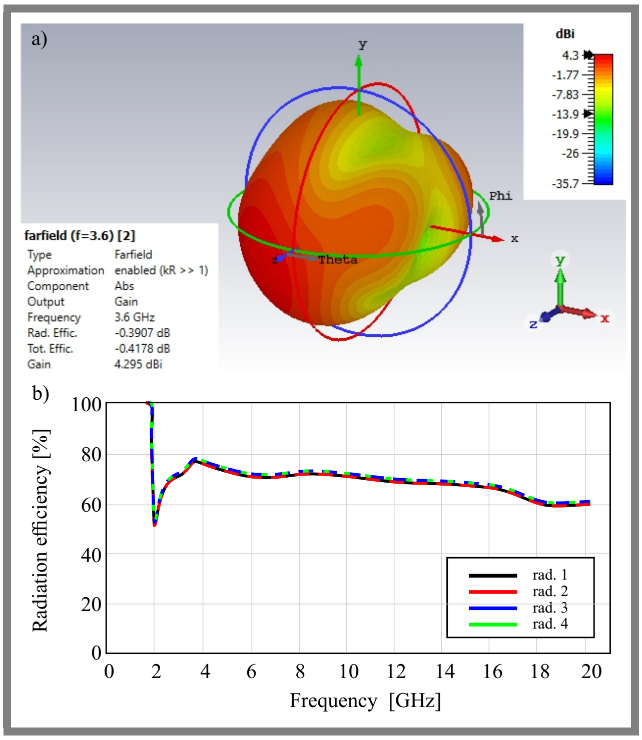

Fig. 7. Simulated MIMO antenna: a) gain and b) radiation efficiency.

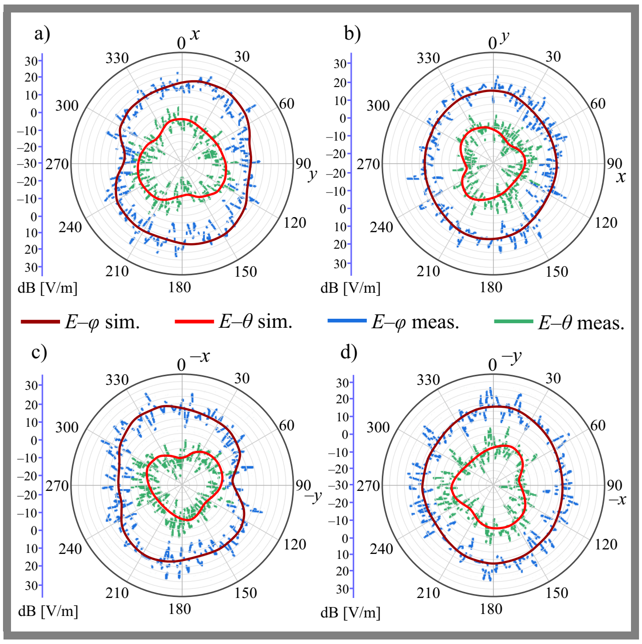

Fig. 8. Radiation pattern at 3.6 GHz for a) antenna 1, b) antenna 2, c) antenna 3, and d) antenna 4.

tennas at the frequency of 3.6 GHz. These observations show that the proposed MIMO system effectively radiates in various directions, underscoring its capability to transmit signals across a broad angular spectrum.

The envelope correlation coefficient (ECC) is the most important metric used for assessing the correlation between different antenna elements within a MIMO system. ECC is utilized to evaluate the diversity performance of MIMO system configurations, where individual radiating elements can simultaneously and independently transmit data streams. As such, the radiators of antenna elements must exhibit low ECC values, ideally below 0.5, to ensure robust isolation between MIMO components. Correlation ϱ_e between two antenna elements i and j in an N port MIMO system can be calculated using the relationship provided in [23], [24].

$$|\varrho_{(ij)}|^2 = \varrho_{(eij)} = \left| \frac{|S_{ii}^* S_{ij} + S_{ji}^* S_{jj}|}{\left|(1-|S_{ii}|^2-|S_{ji}|^2)(1-|S_{jj}|^2-|S_{ij}|^2)\eta_{rad\,i}\,\eta_{rad\,j}\right|^{\frac{1}{2}}} \right|^2 \tag{1}$$

Figure 9 illustrates the ECC for four elements, consistently remaining below 0.05 across the entire frequency band. This signifies strong isolation between the emitters, indicating that the designed MIMO system is characterized by good diversity performance.

The diversity gain (DG) of a MIMO antenna system is an important parameter in the context of various strategies of enhancing the signal-to-interference ratio [25]. It can be expressed as:

$$DG = 10\sqrt{1-|\varrho_{(eij)}|}\,. \tag{2}$$

Correlation coefficient ϱ_e predominantly influences diversity gain. The highest attainable diversity gain value of 10 is achieved when ϱ_e equals zero, signifying an optimal diversity scenario. Higher diversity gain values are achieved as ECC values decrease.

As shown in Fig. 10, DG approaches nearly 10 dB for the antenna's operating band. This underscores the considerable enhancement in diversity gain achieved within these frequency ranges.

4. Comparison with Previous Works

The quad-port MIMO antenna system introduced in this research is compared with other recent studies. As illustrated in Tab. 2, the proposed MIMO system is characterized a relatively small physical dimensions, despite consisting of four radiating elements. In contrast to the cited literature, the ar-

Tab. 2. Comparison with recent works dealing with 4-element MIMO antennas.

Reference	PCB size [mm^2]	Bandwidth [GHz]	Isolation [dB]	Efficiency [%]	ECC
[9]	130 × 74	3.3–3.6, 4.8–5 (–6 dB)	>12	>50	<0.1
[10]	120 × 65	3.3–4.2, 4.4–5	>18.8	—	<0.018
[11]	150 × 75	3.4–3.6	>16.3	>64	
[12]	115 × 65	3.5–5.9	>20	—	<0.005
[13]	150 × 75	3.21–3.81	>10	>70	<0.02
[14]	150 × 82	3.3–6.6	>23	—	<0.005
Proposed	68 × 68	3.25–4.32	>25	>88	≈0

chitecture described in this study features a wide operational bandwidth.

Furthermore, the proposed compact design demonstrates decent isolation and high gain due to the orthogonal alignment of the radiating antennas. Such an alignment facilitates the introduction of diverse patterns. It achieves isolation levels of more than 23 dB between radiators, without the need to use complex decoupling components.

5. Conclusion

This paper presents an efficient and compact quad-element MIMO antenna system designed for 5G applications, specifically focusing on the 3.25 to 4.32 GHz frequency range. The design incorporates four patch antennas carefully placed in the corners of FR-4 substrate, with the overall dimensions of the substrate equaling 68 × 68 × 0.8 mm^3. The shape of each antenna includes a polygonal patch element connected to a microstrip feed line. This specific layout improves isolation by guaranteeing that all antenna ports are oriented orthogonally at an angle of 90°. With isolation levels above 25 dB, radiation efficiency above 85%, and an ECC approximation close to zero, the proposed design is well-suited for use in 5G mobile terminals.

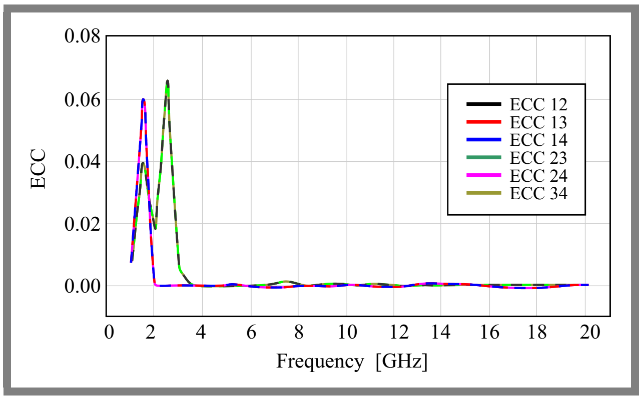

Fig. 9. ECC of the proposed MIMO system.

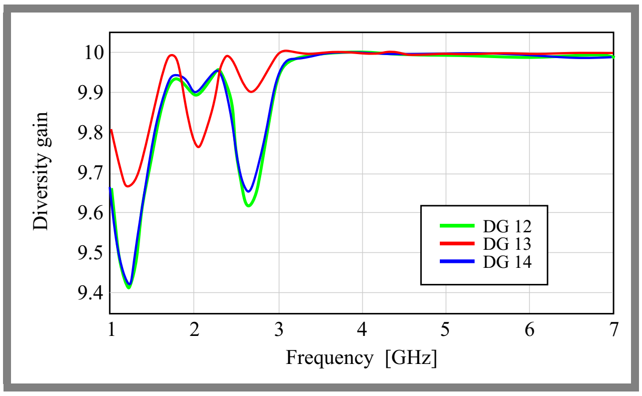

Fig. 10. Diversity gain of the proposed MIMO antenna system.

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