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Mutual coupling reduction between antennas array for 5G mobile applications

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ABSTRACT

This paper introduces the design of a multiple-input-multiple-output (MIMO) antenna optimized for low-profile applications supporting sub-6 GHz fifth-generation (5G) wireless applications. We have started the design from a single antenna with a square patch shape, each antenna array is composed from 4-element radiators fed by using power dividers and quarter microstrip lines. Mounted on a single Rogers RT5880 substrate, the MIMO antenna functions at 3.5 GHz. In order to miniature and to decrease the mutual coupling between the both antennas array we have optimised a magnetic wall based on periodic structures permitting to decrease the mutual coupling between the both antenna array. The unit element from the wall was optimised, studied and validated in order to absorb the surface current and to enhance the isolation between the different radiating elements. The dimensions of the proposed MIMO antenna are 154×220×0.578 mm³. The MIMO antenna final circuit achieves a peak gain of 9 dBi and an isolation around -30 dB. The introduction of the magnetic wall permits to enhance the isolation between the antenna array from -20 dB to -30 dB at 3.5 GHz band. This advancement contributes to the overall performance improvement of the MIMO antenna system.

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1. INTRODUCTION

The advent of the fifth-generation (5G) communications had a significant impact on the development of wireless communication systems [1]–[4]. 5G particularly advocates for the integration of multiple-input-multiple-output (MIMO) technology, which simultaneously utilizes multiple antennas for data traffic [5]–[8]. This offers considerable potential to enhance channel capacity, spectral efficiency, and data transfer rates while ensuring minimal latency. As a result, it contributes to improving the overall reliability of wireless transmission systems [9]. Therefore, the design of MIMO antenna systems meeting the requirements of the 5G standard has attracted microwave research community in these recent years. One of the foremost challenges in this pursuit stems from the difficulty of integrating multiple MIMO components within a confined space. Indeed, each radiating antenna element in a MIMO arrangement must be compact, well-matched, and exhibit minimal interaction with other network elements [10]. The close of antenna elements leads to significant mutual coupling, adversely affecting the performance of the MIMO antenna system.

Hence, the implementation of an effective decoupling structure between array parts in MIMO antennas becomes indispensable to mitigate the mutual coupling among network elements.

Many works have been devoted to this issue. Nguyen and Vu [11], a MIMO antenna that has two sets of four elements (2×2) is suggested. A unique metamaterial construction also allows for a near edge-to-edge separation of the MIMO antenna of 2 mm, resulting in an element-to-element coupling of less than -18 dB. In order to achieve high isolation between a 2-element MIMO antenna, Dey *et al.* [12], propose a hybrid decoupling method based on a unique electromagnetic bandgap (EBG) structure and hair-pin shaped defective ground structure (DGS). Jiang *et al.* [13] eight folded monopole antennas make up the MIMO structure. Here, the isolation between inner antenna elements is increased from 10 dB to 15.1 dB in the 3.45 GHz range (3300-3600 MHz) by the addition of decoupling structures. Similarly, Bhat *et al.* [14], the metamaterial decoupling structure is introduced between the elements of 1×2 arrays and is made up of an array of split-ring resonators (SRRs) joined at the corners by two vertical lines. According to simulation findings, mutual coupling is reduced by 7 dB at 10 GHz and 13.2 dB at 1.575 GHz with no discernible changes in gain. In another work [15], isolation is increased by 5 dB with the use of metasurface. Singh and Tripathi [16] presents another tiny ultra-wideband (UWB) MIMO antenna with dimensions of 25×25×1.6 mm^3, an isolated cross-shaped ground stub, and operating in the 2.97–13.8 GHz frequency range. Excellent diversity gain (DG>9.97), low envelope correlation coefficient (ECC) (<0.05), and excellent isolation (S21<-15 dB), were obtained for this antenna.

Another highly isolated UWB MIMO antenna with a new shape, a smaller area of 50×30 mm^2, and good diversity performance is presented in [17]. Reduced mutual coupling between the two radiating patches was achieved by inserting a stub in the ground plane that resembled the letter “F”. The described MIMO antenna provides an isolation of (S21<-20dB). Another configuration in [18] consists of two identical rectangular patch antennas with transmission line feed and an 8 mm inter-element spacing, with a very low mutual coupling was achieved by combining a ground stub in the bottom layer with an EBG structure in the space between the two rectangular patches in the top layer. A mutual coupling (S21, S12) of less than -30 dB is found between 2.43 GHz and 2.54 GHz by the two manufactured antennas with a 0.190 separation [19]. Zhao *et al.* [20], a new approach to decouple inverted-F antennas (IFAs) in a 5G mobile MIMO architecture at 3.5 GHz from the ground plane's high-order modes. The simulated findings demonstrate that optimizing the placements and orientations of the two IFAs can lead to isolation improvements of 20-40 dB.

This work deals with the introduction of a new technique permitting to reduce the mutual coupling between antenna array. The proposed technique is based on the use of a periodic two F-shaped slots structure permitting to construct a magnetic wall which will decrease the mutual coupling for the MIMO antenna array. The following sections are composed from two parts, the first one is devoted to the description of the design of antenna array optimised and validated into simulation at 3.5 GHz. After that, we find the second part which is reserved to the study concerning the mutual coupling between two antenna arrays. In this part, we studied the mutual coupling for a MIMO antenna by respecting a standard distance between the both antenna array. After that, in order to enhance and to reduce the mutual coupling we have introduced a new technique based on F shaped slot. The optimisation and simulation results were presented and discussed.

2. DESIGN PROCEDURES

2.1. Design of the conventional square microstrip patch antenna

We started by designing a square shaped microstrip patch antenna, operating at 3.5 GHz, fed by a microstrip line. The aim of this work is to provide a novel strategy to enhance the antenna’s radiating performance. The first step was the calculation of the dimensions of the patch using (1) and (2) [21]:

$$L = \frac{1}{2f\sqrt{\varepsilon\sqrt{\mu\varepsilon}}} - 2\Delta L \tag{1}$$

$$W = \frac{1}{2f\sqrt{\mu\varepsilon}}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{2}$$

where:
f_r: the resonant frequency of the antenna
μ_0 et ε_0: Permeability and permittivity in free space.
ε_r: The relative permittivity of the dielectric material.
ΔL: The extension of the patch length around the slots.
The dielectric effective permittivity (ε_{reff}) can be determined using (3).

$$\varepsilon = \frac{\varepsilon+1}{2} + \frac{\varepsilon-1}{2}\left(1+12\frac{h}{W}\right) \quad (3)$$

The height of the substrate is referred to as 'h,' and ΔL may be computed using (4).

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon-0.258)\left(\frac{W}{h}+0.8\right)} \quad (4)$$

The feed widths of different impedances can be calculated using (5).

$$\frac{w_f}{h} = \begin{Bmatrix} \frac{8e^{A}}{e^{2A-2}} & , \frac{w_0}{h} \leq 2 \\ \frac{2}{\mu}\left\{B-1-ln(2B-1)+\frac{\varepsilon_r-1}{2\varepsilon_r}\left[ln(B-1)+0.39-\frac{0.61}{\varepsilon_r}\right]\right\} & , \frac{w_0}{h} \geq 2 \end{Bmatrix} \quad (5)$$

Were,

$$A = \frac{Z_A}{60}\sqrt{\frac{\varepsilon_r+1}{2}} + \frac{\varepsilon_r+1}{\varepsilon_r-1}(0.23+\frac{0.11}{\varepsilon_r})$$

$$B = \frac{377\pi}{2Z_A\sqrt{\varepsilon_r}}$$

After validating the dimensions of the patch element allowing to have a resonant frequency of 3.5 GHz, we used a quarter wave line to match the input impedance to 50 Ohm. The patch antenna is printed on a Rogers RT 5880 substrate, with a relative permittivity ε_r=2.2, a loss tangent tan(δ)=0.0009, a height of 0.508 mm, and a size of 28.1×28.1 mm^2. The optimized square antenna parameters are shown in Table 1.

Table 1. The optimized parameters of the conventional patch antenna at frequency of 3.5 GHz

Parameter	Value (mm)	Parameter	Value (mm)
Wp	28.1	Wf	0.41
Lp	28.1	Lf	16.28
Ws	55	h	0.508
Ls	60	t	0.035

2.2. Design of a 1×4 antenna array containing 4 radiation elements

With the goal of enhancing the gain of the previously introduced elementary antenna, we replicated it to form an array consisting of 1×4 antennas. The design specifications and performance metrics of this array are illustrated in Figure 1. In Figure 1(a), in Figure 1(a), the array antenna structure is presented, where the distance between the radiating elements is fixed at 0.5 λ, and they are fed through power dividers and quarter microstrip lines in a tree topology. Figure 1(b) shows that the 1×4 antenna array has a favourable reflection coefficient below -20 dB at 3.5 GHz, accompanied by a gain improvement of 9 dBi, as presented in Figure 1(c). Additionally, Figure 1(d) illustrates a stable radiation pattern.

2.3. Design of an antenna with a MIMO configuration

After the validation of the antenna array, we have constructed a MIMO antenna by combining two of the previously studied arrays. The design geometry and the relevant S parameters of this structure are illustrated in Figure 2. The MIMO antenna geometry is depicted in Figure 2(a); the two arrays are placed face to face with a specific separation distance of $0.5\,\lambda$. The performance simulations for MIMO antenna were conducted using a 3D electromagnetic solver based on finite integration method. As shown in Figure 2 (b), we reach a good input impedance matching and an isolation at 3.5 GHz around -20 dB. After this study, we have decreased the distance between the antenna array to $0.25\,\lambda$ to miniaturize the final circuit. Nevertheless, this resulted in an elevation of mutual coupling, as illustrated in Figure 3. The following section will present a solution to decrease the mutual coupling between the two arrays of this antenna.

2.4. MIMO structure with two F-shaped slots

To minimize the size of the MIMO antenna without compromising its performance, particularly in terms of mutual decoupling between the radiating elements, our proposed solution involves the introduction of a magnetic wall between the two arrays constructed from two F-shaped slots. All geometrical parameters of the slots and the antenna, along with the S-parameters of the resulting MIMO antenna, are presented in Figure 4. Figure 4(a), gives the geometrical parameters and arrangement of two F slots in a symmetric configuration. The optimized parameters of the F slot are shown in Table 2. Figure 4(b) illustrates the magnetic wall constituted by the periodic arrangement of F slots in the form of a linear band, positioned between the antenna arrays. As depicted in Figure 4(c), the modified structure facilitates a marginal enhancement in isolation, as evidenced by a slight reduction in the S12 parameter when compared to the same antenna configuration without the magnetic wall. To improve isolation, we optimized the last configuration by employing slots in an antisymmetric arrangement. This leads to a modified MIMO antenna, as illustrated in Figure 4(d). The simulation results for this configuration, as depicted in Figure 4(e), reveal a substantial enhancement in reducing mutual coupling, decreasing from -20 dB to -30 dB at 3.5 GHz.

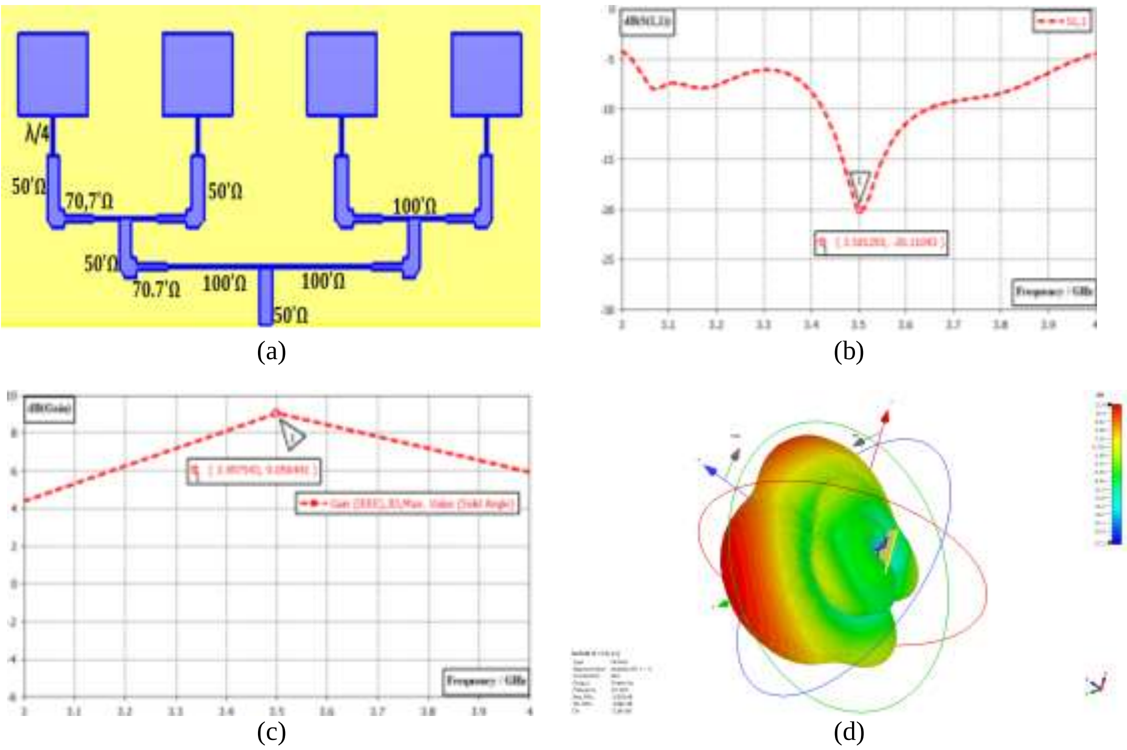


Figure 1. Design specifications and performance metrics of the 1×4 antenna array; (a) geometry of the antenna array and its feeding structure, (b) return loss, (c) gain versus frequency, and (d) radiation pattern

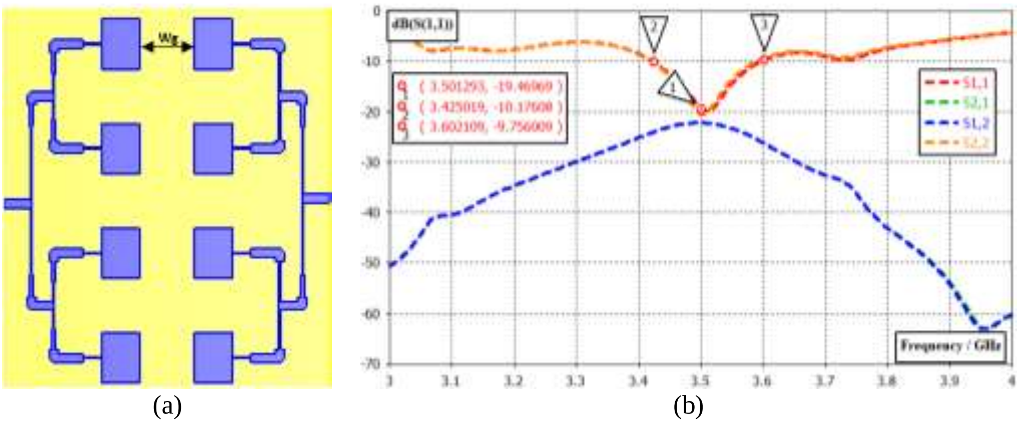


Figure 2. Design geometry and S parameters of the 4×2 MIMO antenna (a) geometry of the antenna showing the two arrays mounted face to face with a separation distance Wg=$0.5 \times \lambda$ and (b) reflection and transmission coefficients

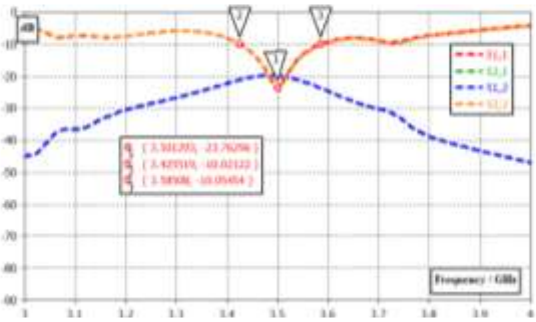
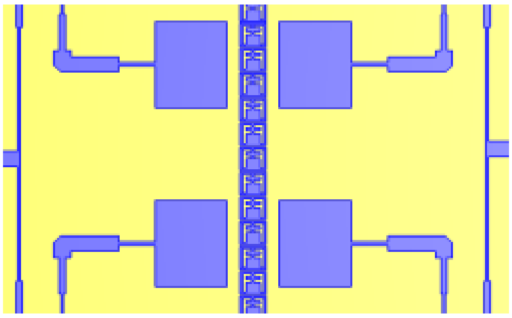
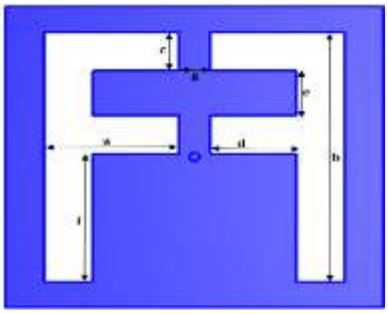


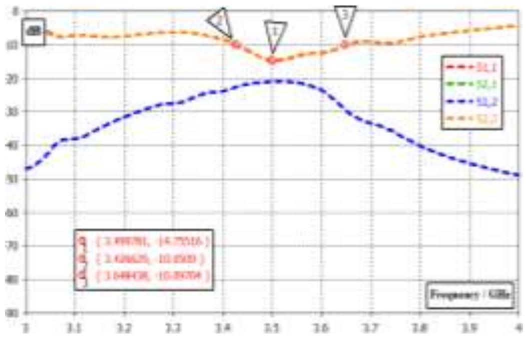
Figure 3. Reflection coefficients and transmission coefficients of MIMO antenna, with Wg= $0.25\times\lambda$



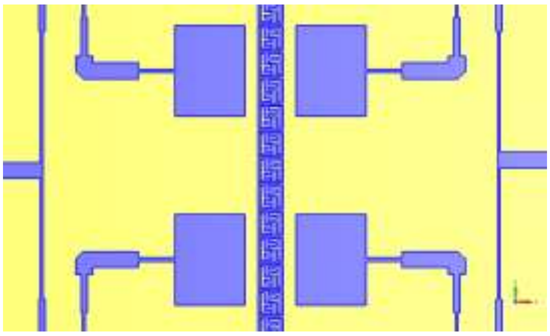
(a)



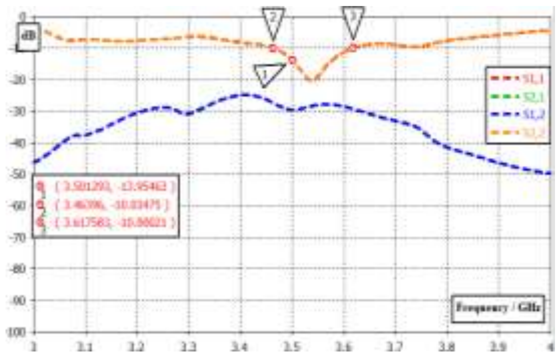
(b)



(c)



(d)



(e)

Figure 4. Geometry and performances of the MIMO antenna with a decoupling structure; (a) geometrical parameters of the F slots in a symmetric arrangement, (b) MIMO antenna with a magnetic wall using two F slots in a symmetric arrangement, (c) return loss and transmission coefficient with a symmetric F slots configuration of the magnetic wall, (d) MIMO antenna with a magnetic wall using two F slots in an antisymmetric arrangement, and (e) return loss and transmission coefficient with an antisymmetric F slots configuration of the magnetic wall

Table 2. Optimized slot F parameters

Parameter	Value (mm)	Parameter	Value (mm)
a	2.5	e	1
b	5.8	f	2.96
c	0.9	g	0.56
d	1.6		

In order to show the originality of the technique used for the reduction of the mutual coupling, we have compared some recent published works with this study. Table 3 shows the comparison between the proposed MIMO antenna with others published studies. We can conclude that the proposed configuration exhibits a high gain and a good isolation for 5G applications.

Table 3. Performance comparison with previous published literatures

Reference	Size (mm^3)	No. of element	Frequency (GHz)	$GAIN_{max}$ (dBi)	Isolation (dB)
Nguyen and Vu [11]	137×77×3.048	2×4	1.78	9	18
Luo *et al.* [22]	98×98×31	4×4	4.9	---	24
Ishteyaq *et al.* [23]	124×74×4	3×6	3.45	---	15.1
Khan *et al.* [18]	26×31×0.8	1×2	3.1	5.67	25
Li *et al.* [24]	170×60×8	1×4	3.6	5	25
Zhu *et al.* [25]	344×344×63	4×4	4.3	8.6	30
This work	154×220×0.578	1×2	3.5	9	30

3. CONCLUSION

In this work we have presented the design of a miniature MIMO antenna presenting good performances in term of radiation pattern, the input impedance matching and the reduction of mutual coupling which was the aim of this study. The two F slots used and repeated periodically permits to construct a magnetic wall which will absorb the distribution of the surface current and avoid them to reach the second antenna array. The final dimensions of the MIMO antenna circuit are miniature and easy for integration with active and passive devices. The new technique used to increase the isolation between the both antenna array, can be matched for other standard of wireless communication.

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