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# Miniaturization Techniques for High-Performance Antenna Arrays in Cognitive Radio-Enabled IoT Devices

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*Abstract* – **The Internet of Things (IoT) is expanding, necessitating reliable and scalable connectivity solutions. Cognitive radio technology, with a focus on the antenna array, enables dynamic device adjustments and enhances efficiency. Our study involves a comparative analysis of two miniaturization design approaches within the contexts of IoT and cognitive radio. Utilizing the CST simulation tool, we investigate four-element antenna arrays in hybrid and parallel structures at 5.8 GHz, a crucial frequency for IoT communications. Simulation results reveal the nuanced effects of modifying geometry and employing metamaterials as techniques of miniaturization on antenna array performance. Specifically, the miniaturized antenna demonstrated a gain of 1.98 dBi and a 27% reduction in size, whereas the four-element parallel antenna array achieved a gain of 9.16 dBi and an $S_{11}$ of -11.66 dB with a 28% size reduction. Additionally, the introduction of metamaterials has resulted in a 13% greater reduction compared to the previous method. These findings underscore the effectiveness of metamaterials in enhancing antenna performance and reducing physical footprint.**

*Keywords* – **Cognitive Radio, CST, IoT, SRR, Metamaterials, Miniaturization.**

## I. INTRODUCTION

In the dynamic realm of wireless communication, two groundbreaking technologies have emerged: Cognitive Radio (CR) and the Internet of Things (IoT). CR optimizes spectrum usage intelligently [1], while IoT connects physical devices to exchange data over the internet [2]. Additionally, the integration of miniaturized antenna arrays further enhances the efficiency and compactness of these communication systems.

Cognitive Radio emerges as a technique aimed at optimizing overall spectrum utilization through opportunistic use of available frequencies [3]. A typical CR network scenario involves the coexistence of M various types of primary radio (PR) networks alongside one or more CR networks in the same geographic area. Additionally, each PR network operates without awareness of CR behavior and requires no special capabilities to coexist with Cognitive Radios [4]. In a CR network, two distinct user types exist: Primary Users (PUs) and Secondary Users (SUs). PUs possesses licensed authorization to operate within specific spectrum bands, while SUs, often lacking licenses, can leverage the entire spectrum licensed to PUs but must refrain from causing interference with PU transmissions [5]. The cognitive functionality is achieved by sensing the radio frequency (RF) environment and leveraging the acquired data to comprehend the local and temporal spectrum usage [6]. Opportunistic users have the capability to dynamically select optimal channels and adapt their transmission parameters to reduce mutual interference with other competing users [7].

Cognitive radio optimizes spectrum utilization, enhancing IoT by improving reliability and security [8][9]. It scans the spectrum, identifies available bands and their status, allowing IoT devices to access and operate more efficiently while mitigating interference [10]. It needs antenna systems for data transmission and reception, requires a thorough analysis of size, bandwidth, radiation pattern, and polarization [11].

To meet strict size constraints, miniaturized antennas have been developed as compact structures designed for confined spaces and low-profile devices. They find applications in various IoT scenarios, including wearable devices, sensors, actuators, and industrial settings such as smart factories and buildings [12].

Significant focus has been directed towards techniques for miniaturizing antennas in recent years, driven by the capability to reduce their physical dimensions without substantial performance compromise [13]. Despite the challenges associated with this task, literature reveals several methodologies for achieving antenna miniaturization. A common method for antenna miniaturization involves making geometric adjustments to both the antenna patch and ground plane. This can be achieved by altering the antenna's shape or incorporating slots or notches [14]. Another approach to miniaturization utilizes metamaterial structures, which are synthetic materials with unique properties not found in natural materials. This enables the creation of significantly smaller antennas compared to traditional designs [15]. However, an alternative strategy involves introducing electrical shorts between the ground plane and the radiating element. It's important to note that this approach carries the risk of undesired consequences, such as increased insertion loss, reduced bandwidth, and a decline in signal quality [16].

In this paper, we will begin by designing a rectangular patch antenna using CST Microwave Studio as our simulation tool of choice. The subsequent step involves miniaturizing the antenna by adjusting the geometry of the patch and ground plane to achieve a miniaturized patch antenna operating at the desired frequency. Following that, our focus will shift to constructing four-element antenna arrays in two

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configurations: parallel and hybrid, employing the same technique as used in the previous stage. Finally, we will further reduce the size of the parallel four-element array using metamaterials and compare it with the previous technique.

## II. Antenna Design

Our study aims to propose a rectangular patch antenna designed to operate at the widely utilized 5.8 GHz frequency within IoT domains. The antenna design must adhere to specific requirements:

- ✓ Substrate with a relative permittivity ($\varepsilon_r$) of 4.3, utilizing FR4 material.
- ✓ Dielectric substrate thickness (*h*) of 1.6mm.
- ✓ Input impedance set at *Zc* = 50Ω [17].

The fundamental structure, depicted in Fig.1, consists of a patch antenna printed on an FR4 dielectric substrate with a 1.6mm thickness, accompanied by a ground plane and fed via a microstrip line.

Our investigation centers on the CST MICROWAVE STUDIO software, a specialized tool renowned for its design, simulation, and optimization capabilities in electromagnetic systems. Widely adopted in leading technology and engineering firms worldwide, CST's core strengths lie in its precision and speed [18].

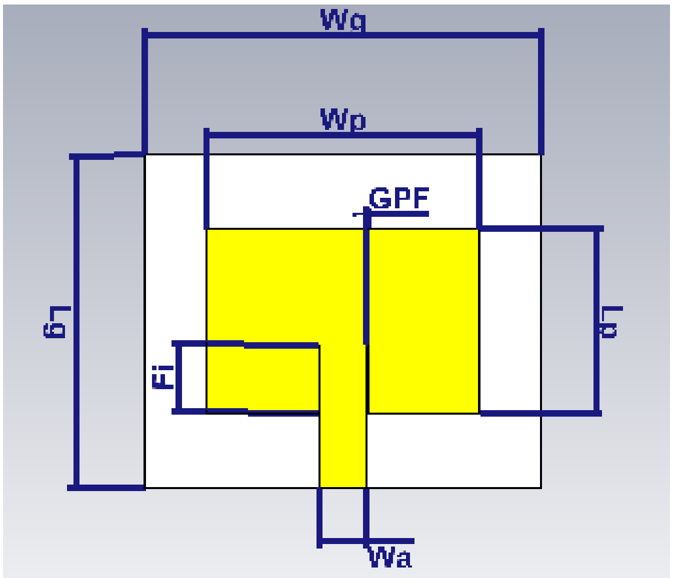



Fig. 1. Rectangular patch antenna structure

The dimensions of the patch (*Wp*, *Lp*) are determined using the following equations [17]:

$$L_p = L_{eff} - 2\Delta l, \quad (1)$$

$$L_{eff} = \frac{c}{2f\sqrt{\varepsilon_{reff}}}, \quad (2)$$

$$\varepsilon_{reff} = \left(\frac{\varepsilon_r+1}{2}\right) + \left(\frac{\varepsilon_r-1}{2}\right)\frac{1}{\sqrt{1+12\frac{h}{w}}}, \quad (3)$$

$$\Delta l = \frac{0.412\, h\,(\varepsilon_{reff}+0.3)\left(\frac{w}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{w}{h}+0.8\right)}, \quad (4)$$

$$w_p = \frac{c}{2f\sqrt{\varepsilon_r+1}} \quad (5)$$

Table 1 illustrates the parameters of the rectangular patch antenna:

TABLE 1
Dimension of Antenna

| Parameters | Dimensions |
|---|---|
| *Wg* | 25.48 mm |
| *Lg* | 21.48 mm |
| *Wp* | 17.6 mm |
| *Lp* | 11.88 mm |
| *Wa* | 3.137 mm |
| *Fi* | 4.38 mm |
| *GPF* | 0.05 mm |

With:
*Wg*: Substrate width ; *Lg*: Substrate length.
*Wp*: Patch width ; *Lp*: Patch length.
*Wa*: Microstrip line width ; *La*: Microstrip line length.
*Fi*: Notch length ; *GPF*: Notch width.

## III. Miniaturization of the Patch Antenna through Antenna Geometry Modification

This miniaturization technique is currently widely used, altering an antenna's structure by adding slots or notches changes the path of electrical currents, lowering its resonance frequency and allowing for a more compact design. This modification induces effects that modify the antenna's impedance. Additionally, adjusting the ground plane geometry, such as integrating meandering slots, further aids in reducing the antenna's size, as detailed in this study [19].

In this section, we will present our previous work [20], where we focused on miniaturizing the single antenna.

### *A. Single Miniaturized Antenna*

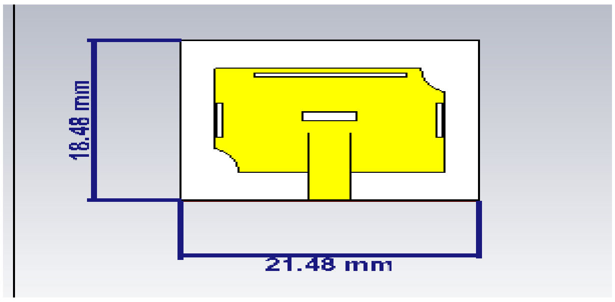
- ➢ At the patch level:

Figure 2 depicts the modified antenna structure after adjustments at the patch level. We will be adding circles at the ends with a radius of 3.25 mm and rectangles in the middle with dimensions of 4 mm x 10 mm.

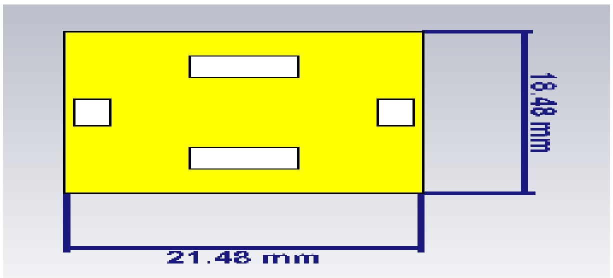
- ➢ At the ground level:

Modifications can also be applied to reduce the overall size of an antenna. By introducing slots in the ground plane, the effective electrical length of an antenna can be increased, achieving similar performance to a larger antenna without occupying the same physical space.

In our case (Fig. 2), we will add two parallel rectangles on the right and left sides, each 3 mm long and 2.25 mm wide, and two other parallel rectangles, one 6.5 mm long and 2.5 mm wide.




(a)




(b)

Fig. 2. Miniaturized antenna: (a) patch, (b) ground

The new dimensions of the miniaturized patch antenna are as follows in Table 2.

TABLE 2
THE NEW DIMENSIONS OF MINIATURIZED ANTENNA

| Parameters | Dimensions |
|---|---|
| Wg | 21.48 mm |
| Lg | 18.48 mm |
| Wp | 16.6 mm |
| Lp | 11.88 mm |
| Miniaturization rate | 27% |

*B. Antenna Arrays*

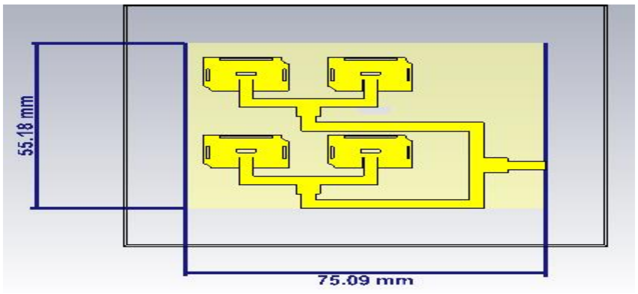
An antenna array is a system comprising multiple antennas interconnected to function collectively. The aim of an antenna array is to further enhance antenna performance [21]. In our scenario, we intend to use it to improve both the gain and directivity of the antenna.

A four-element antenna (2x2) corresponds to a network of two antennas arranged in a 2x2 matrix, where each row and column consists of two antenna elements. It is important to note that there exist various models of 2x2 antennas.

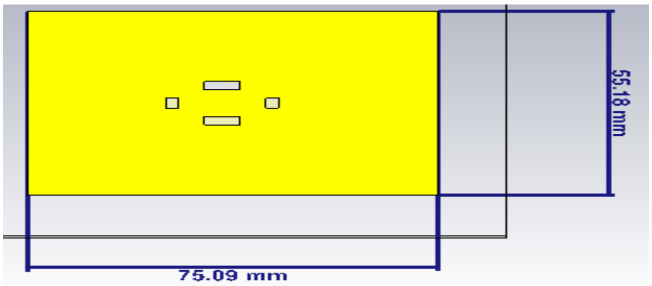
In our present work, we constructed two types of antenna arrays consisting of four elements based on the previous antenna while maintaining the same parameters. These arrays correspond to the hybrid antenna model and the parallel antenna model mentioned in our study. We have an input power supply at 50Ω, a power supply between the antennas at 75 Ω, and an antenna power supply at 75 Ω as well. Subsequently, we will compare these two models to evaluate their performance.

- Four-element parallel antenna array

Figure 3 displays the structure of a four-element parallel array.




(a)




(b)

Fig.3. Structure of a four-element parallel array: (a) patch, (b) ground

Figure 4 shows the reflection coefficient as a function of resonant frequency. We can see that the antenna's performance is at the limit of what is acceptable, with a -11.66 dB match.

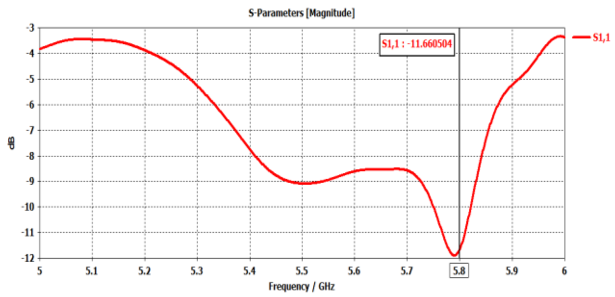



Fig. 4. Four-element reflection coefficient

According to Fig.5, the standing wave ratio is equal to 1.70. This figure is less than 2, indicating excellent impedance matching of the antenna to the feed source, maximizing the energy transfer between them.

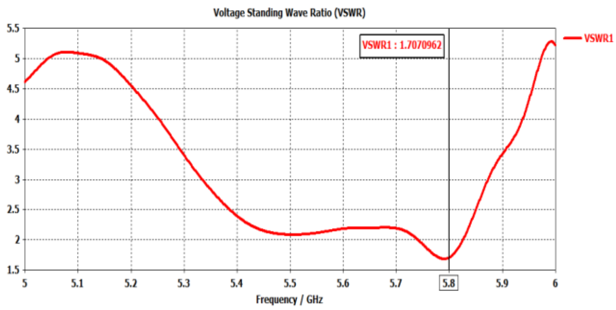



Fig. 5. VSWR of the four-element antenna

According to Fig.6, the gain registers at 9.16 dBi, which aligns with the requirements of our study for IoT. This gain value perfectly meets the specific criteria outlined in our study for IoT applications. This 9.16 dBi gain value fully satisfies the performance standards needed to ensure optimal efficiency in the identified IoT scenarios.
However, the antenna gain is largely positive over the entire frequency range from 5 GHz to 6 GHz, with a minimum value of 7.8 dBi.

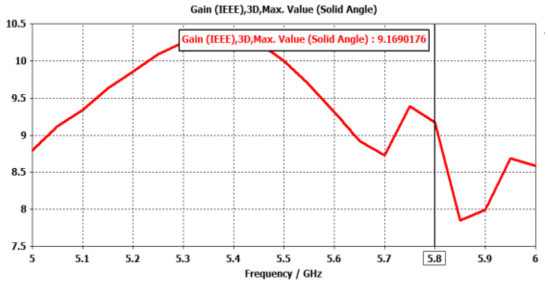



Fig. 6. Gain as a function of frequency

Fig.7 shows the antenna radiation pattern in 2D and 3D with a directivity of 9.42 dBi. We note that for plane E (phi=0) the antenna's main lobe magnitude is 9.29 dBi, with a main lobe direction of 29 degrees, an angular width of 53.9 degrees with a side lobe of -6.4 dB with a quasi-omnidirectional radiation pattern. For the H plane (phi=90) we have a main lobe magnitude of 6.31dBi with a main lobe direction of 2 degrees, an angular width of 49.4 degrees, also with a quasi-omnidirectional radiation pattern.

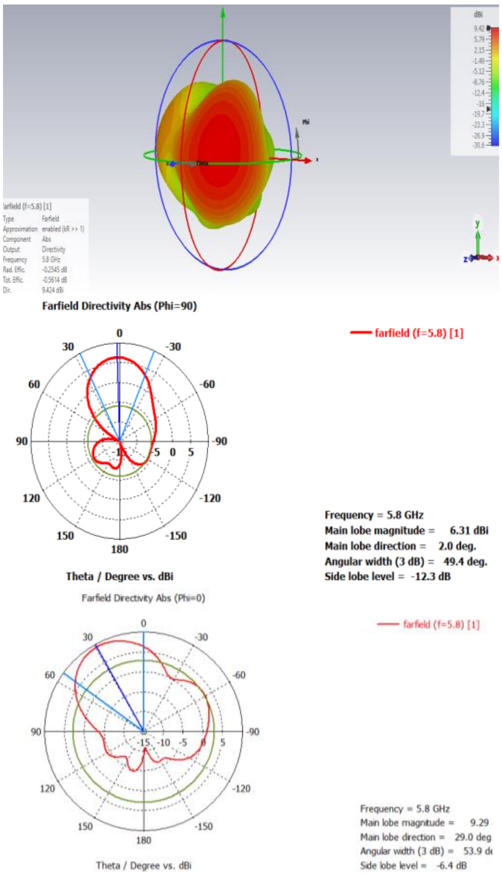



Fig. 7. Radiation pattern in 3D and 2D of the four element parallel array

➢ Four-element hybrid antenna arrays

A hybrid antenna network is a combination of series and parallel antenna networks as illustrated in Fig.8

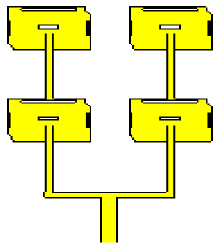


Fig. 8. Structure of a four-element hybrid array

Fig.9 shows the multi-band $S_{11}$ reflection coefficient with several resonance frequencies: 4.2 GHz with an $S_{11}$ of -14 dB, 7.4 GHz with an $S_{11}$ of -11 dB and the desired frequency 5.8 GHz with an $S_{11}$ of -23.60 dB, which is a good result for our study.

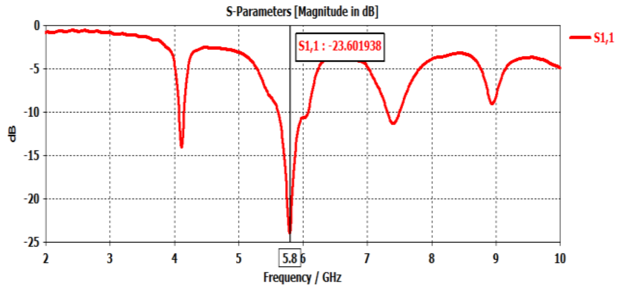



Fig. 9. Reflection coefficient of hybrid antenna array

Fig. 10 below shows the Standing Wave Ratio at 1.14, which is less than 2, indicating good impedance matching between the antenna and the transmission line.

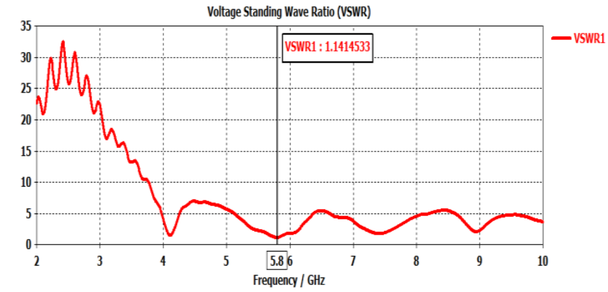



Fig. 10. VSWR of the four-element hybrid antenna

Based on Fig.11, the gain stands at 4.80 dBi. This value holds significance in demonstrating the antenna's amplification or reception capability within the context of the specified application.

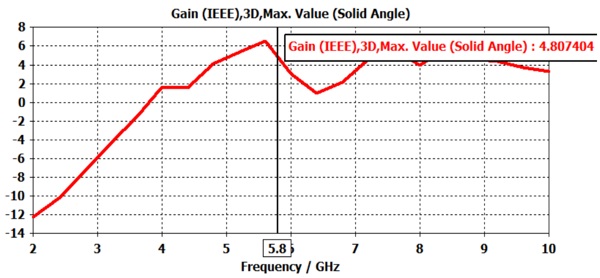



Fig. 11. Gain of the hybrid antenna array

Figure 12 shows the antenna radiation pattern in 2D and 3D for the two planes (H and E), which have a quasi-omnidirectional radiation pattern with a directivity of 10.05 dBi. We note that for plane E (phi=0) the antenna's main lobe magnitude is 3.82 dBi, the main lobe direction 31degrees, an angular width of 44.3 degrees. For the H plane (phi=90) we have a main lobe magnitude of 10.1 dBi with a main lobe direction of 44 degrees, an angular width of 46.2 degrees.

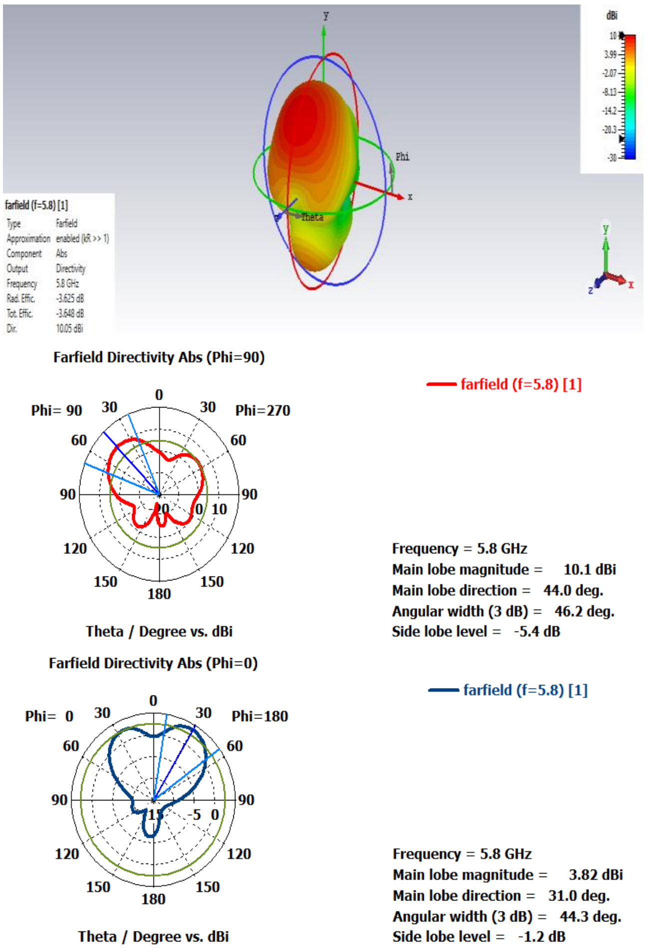



Fig. 12. The radiation pattern of the hybrid antenna array

- Comparison and discuss

The following table (Table 3) provides a comparative analysis of the performance metrics, including gain, reflection coefficient ($S_{11}$), standing wave ratio (VSWR), dimensions, and miniaturization rate, based on the results of simulation between the previously introduced antenna and antenna arrays.

We can observe that miniaturization is a shared characteristic among all the presented antennas, with relatively similar rates of miniaturization around 27-28%. However, each type of antenna displays different performances: for example, the single miniaturized antenna has the lowest gain (1.98 dBi) but better reflection and VSWR characteristics and the smallest in size (18.48x21.48 mm) with a decent miniaturization rate compared to multi-element antennas. The four-element parallel antenna array shows the highest gain (9.16 dBi) but slightly poorer reflection and VSWR characteristics than the others.

On the other hand, the hybrid antenna array falls in between in terms of gain (4.80 dBi) and size (70x70 mm) while offering a good miniaturization rate.

Based on these results, it is evident that the various antenna parameters have improved for gain with an increase in the number of elements in the arrays. However, as expected, the impedance matching decreases. It is a common observation that as the gain increases, impedance matching tends to decrease. This trend is noticeable in the comparison between the hybrid and parallel schemes, where the hybrid scheme demonstrates superior impedance matching, whereas this isn't the case for gain.

In the landscape of IoT, where diverse applications demand specific performance criteria, choosing an antenna involves careful consideration of factors such as required gain, available space, impedance matching, and size constraints. Each antenna type, influenced by cognitive radio principles, navigates the delicate balance between performance and physical dimensions, contributing to the ever-evolving tapestry of IoT technology.

## IV. Miniaturization through Metamaterial Integration in the 2x2 Antenna Array

Metamaterials are artificial substances that exhibit unusual electromagnetic properties not found in natural materials. These materials consist of miniature artificial structures, known as "metamaterial units", which are repeated on a nanoscale to form an overall structure capable of interacting with electromagnetic waves. Shrinking antennas using metamaterials involves utilizing these structures to create smaller, more efficient, and lighter antennas compared to traditional ones [22].

### *A. Design and Simulation of the SRR (Split Ring Resonator) Cell*

The Split Ring Resonator (SRR) serves as an artificial electromagnetic component employed to control various electromagnetic waves, spanning radio waves, microwaves,

TABLE 3
Comparison results

| Antenna | Gain | $S_{11}$ | VSWR | Dimensions | Miniaturization rate |
|---|---|---|---|---|---|
| Miniaturized antenna | 1.98 dBi | -16.36 dB | 1.35 | 18.48x21.48 mm | 27% |
| Four-element parallel antenna array | 9.16 dBi | -11.66 dB | 1.7 | 55x75 mm | 28% |
| Four-element hybrid antenna array | 4.80 dBi | -23.60 dB | 1.14 | 70x70 mm | 28% |

and even light waves. Its functionality lies in its ability to interact with these waves in unique ways, altering their behavior or properties. One prominent application of the SRR is in the realm of antenna miniaturization [23]. When strategically placed on the ground plane or integrated into antenna designs, SRRs contribute significantly to reducing the overall size of the antenna structure while maintaining or enhancing its performance characteristics. This miniature component plays a pivotal role in reshaping the electromagnetic landscape within antennas, enabling more compact yet efficient designs across various frequency ranges [24].

The proposed design is presented in Fig.13 and the parameters for the unit cell at 5.8 GHz on a 22 mm×22 mm ground plane are as follows:

- ✓ Width *W*1=22 mm.
- ✓ Metallization *a*=1.15 mm.
- ✓ The distance between the two rings *b*=2 mm.
- ✓ Distance between slots *c*=3 mm.
- ✓ Substrate height *hs*=1.6 mm.
- ✓ Materials used: 1/For SSR: copper
  2/For the substrate: FR-4

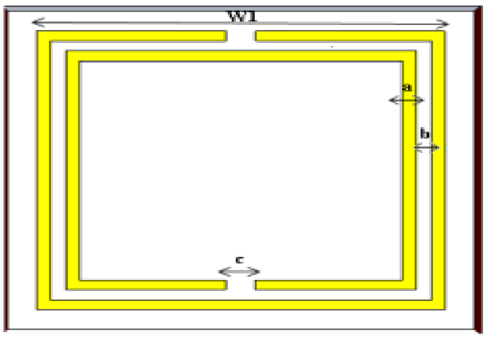



Fig. 13. Representation of the SRR unit cell

The simulation results for the SRR cell are shown in Fig.14, which plots the reflection ($S_{11}$) and transmission ($S_{31}$) coefficients in dB. We note that the transmission coefficient ($S_{31}$) resonates at 5.8 GHz with a transmission level of -14.61 dB. This resonance frequency, associated with the transmission level, indicates a remarkable behaviour within the SRR cell at this specific frequency. The resonance at 5.8 GHz highlights a significant response in transmission, marked by the observed level of -14.61 dB, indicating a distinctive behaviour of the SRR cell in facilitating or inhibiting the passage of electromagnetic waves at this frequency.

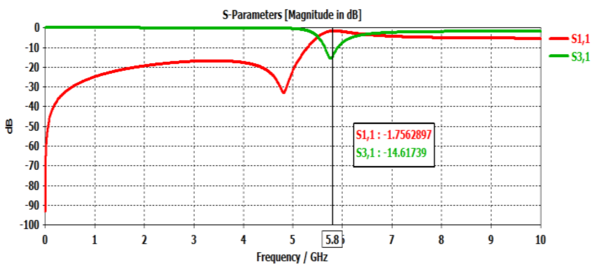
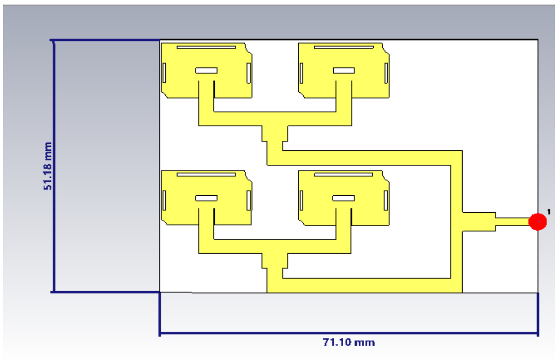


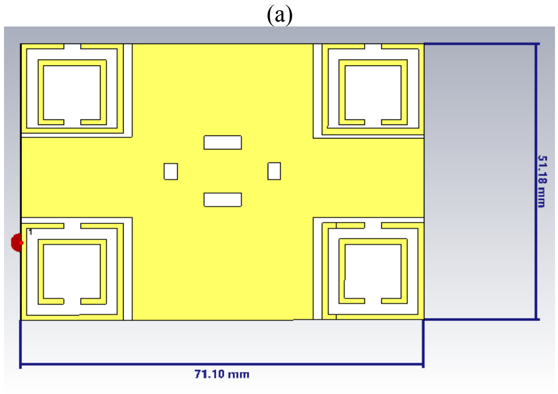

Fig. 14. Reflection and transmission coefficients of the SRR cell

## B. Miniaturized Antenna Integration with SRR Cells

To achieve additional miniaturization of our 2×2 parallel antenna array, we incorporated a ground plane featuring an array of four-square Split Ring Resonator (SRR) cells, as explored in the preceding section. The structure with SRR is shown in Fig.15.




(a)




(b)

Fig. 15. Structure of a parallel antenna array loaded with a network of SRRs : (a) patch, (b) ground

Looking at the $S_{11}$ curve presented in Fig.16, the antenna array resonates at 5.8 GHz and has an optimal match of -16 dB, which is its most efficient radiation point.

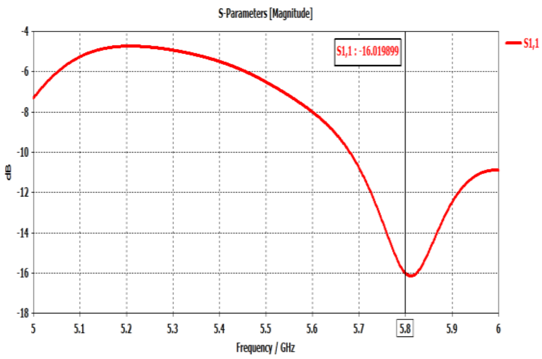



Fig.16. Reflection coefficient of the parallel antenna array with metamaterials

Figure 17 displays the simulated VSWR curve for the patch antenna integrated with the designed metamaterials. The VSWR, measuring below 2, signifies a strong alignment between the antenna and the transmission line, indicating a favorable match.

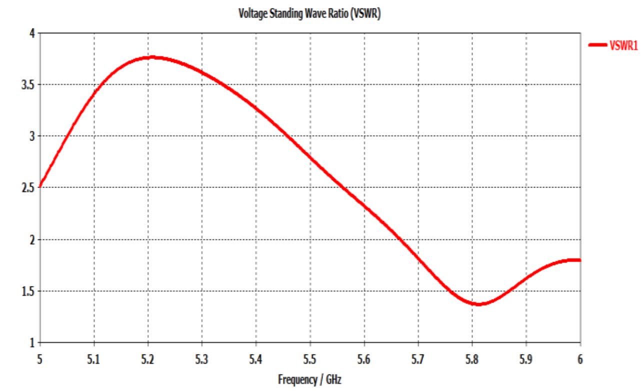



Fig.17 VSWR of the parallel antenna array with metamaterials

The Figure 18 indicates that the antenna achieves a gain of 3.9 dBi in the 5.8 GHz frequency range. This result agrees well with our intended application.

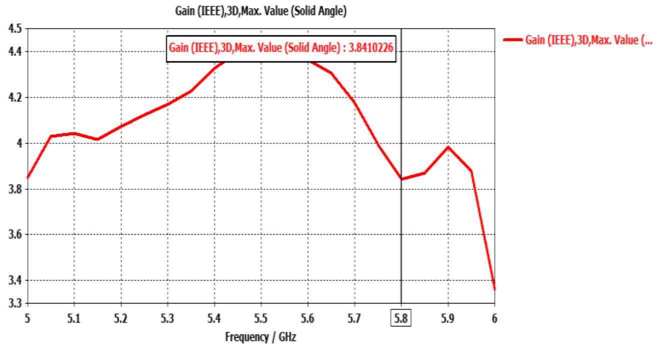



Fig. 18. Gain of the parallel antenna array with metamaterials

Figure 19 below presents the 2D and 3D radiation patterns of the antenna. We observe that the antenna exhibits a nearly omnidirectional radiation pattern in both the E-plane (*phi*=0) and H-plane (*phi*=90) with a directivity of 3.731 dBi. The 3 dB beamwidth is 41.2 degrees in the E-plane (*phi*=0) and 45.6 degrees in the H-plane (*phi*=90).

Table 4 provides a comparison of the performance characteristics of various four-element antenna arrays.

TABLE 4
COMPARISON BETWEEN FOUR-ELEMENT ARRAYS

| Antenna | Gain | $S_{11}$ | VSWR | Dimensions |
|---|---|---|---|---|
| Parallel 2x2 Antenna Array | 9.16dBi | -11.66 dB | 1.7 | 55x75 mm |
| Parallel 2x2 Antenna Array with Metamaterial | 3.9dBi | -16dB | 1.4 | 51x71 mm (reduced by 13%) |

It is evident from the above results and comparison table that the outcomes are superior with metamaterials. It is worth noting that the overall surface area of the antenna has decreased by 12%, with a reduction of 4mm in both width and length dimensions, aligning well with our objectives.

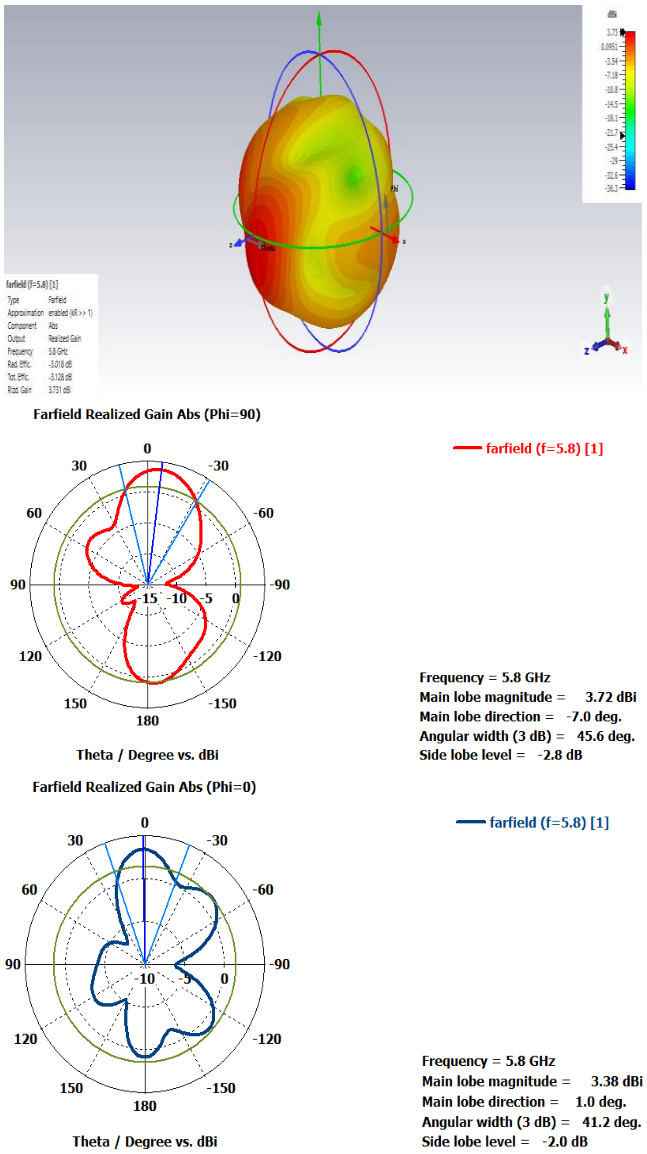



Fig. 19. Radiation Pattern of the antenna array with Metamaterials

## V. CONCLUSION

The aim of this study was to evaluate the impact of miniaturization on antenna characteristics within cognitive radio networks, with a specific focus on their relevance to the Internet of Things (IoT). We conducted a comparative analysis between two miniaturization methods. Initially, we presented our previous study about single antenna. Furthermore, to enhance gain, we developed a four-element antenna array employing both hybrid and parallel structures. The hybrid antenna array achieved a gain of 4.80 dBi, an $S_{11}$ of -23.60 dB, and a miniaturization rate of 28%. The parallel antenna array maintained a gain of 9.16 dBi, an $S_{11}$ of -11.66 dB, and a VSWR of 1.7, while also achieving a 13% reduction in dimensions when adding the metamaterials compared to previous one. This involved geometric modifications to the patch and ground, followed by the utilization of metamaterials. Our findings confirmed the feasibility of designing miniaturized antennas that meet the requirements of cognitive radio networks for IoT applications.

Our perspective involves integrating machine learning algorithms with cognitive radio technology to enable intelligent decision-making for IoT devices. We aim to develop predictive models capable of adaptively optimizing antenna configurations and spectrum usage based on historical data and real-time observations.

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