# Planar hexagonal patch multiple input multiple output 4×4 antenna for UWB applications

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**ABSTRACT**

The combination of multiple input multiple output (MIMO) antennas and Ultra-Wideband (UWB) technology offers several advantages, including reduced interference, improved isolation, and optimized dual paths. These benefits extend the range and enhance signal quality. However, designing UWB-MIMO antennas presents challenges, such as achieving low mutual coupling for high isolation and creating small-sized antennas suitable for portable devices while being effective for UWB frequencies in a MIMO configuration. The proposed antenna is a 4×4 planar MIMO antenna with a hexagon-shaped patch, a partial ground plane featuring an inverted L-stub on the left side, and a plus-shaped slot in the centre ground. It has dimensions of 32×32×1.6 $mm^3$ and is capable of achieving a wide bandwidth of 3-12.5 GHz. The antenna's performance measurements are impressive: return loss below -10 dB at frequencies of 3-12.5 GHz, mutual coupling below -16.5 dB, envelope correlation coefficient (ECC) bellow 0.005, diversity gain (DG) of more than 9.97, total active reflection coefficient (TARC) below -10 dB. Based on these results, the proposed antenna offers excellent performance for UWB applications, featuring high efficiency, minimal interference between antenna elements, and optimal diversity performance.



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## 1. INTRODUCTION

The demand for high-speed data transmission is rising as a result of the development of wireless communication technologies [1]. Ultra-wideband (UWB) technology, which utilizes radio waves with a broad bandwidth [1], has garnered attention due to its substantial capacity, high data rates, low power consumption, and resistance to signal interference [2], [3]. The federal communication commission (FCC) set aside 3.1 GHz to 10.6 GHz as the frequency band for UWB applications in 2002 [4]. However, UWB faces challenges such as multipath fading, making long-distance transmission problematic [5], [6]. To address this, UWB technology has been combined with multiple input multiple output (MIMO) technology [7]. MIMO antennas employ multiple antenna elements to simultaneously transmit and receive multiple data signals through different paths [8], [9]. In portable devices, the close proximity of antenna elements can lead to mutual coupling, which may degrade antenna performance [8], [10]. To mitigate this, each antenna must be spaced and decoupled to minimize mutual coupling [11], [12]. By integrating MIMO with UWB, the strengths of each technology are leveraged to reduce interference, enhance isolation [13], [14], and optimize multipath [14], ultimately extending coverage and improving signal quality.

In recent research [15], a 4×4 MIMO antenna measuring 33 mm × 34 mm achieved a bandwidth of 2.5-12 GHz and demonstrated isolation with mutual coupling of < -15 dB. Another study [16], focused on a 4-port antenna with dimensions of 58×58×0.8 $mm^3$, which exhibited mutual coupling of <-18 dB. Additionally, a compact 4×4 MIMO antenna developed by [12] measured 40×40×1.6 $mm^3$ and displayed a frequency response band of 3.2 to 13.4 GHz with a small mutual coupling of < -20 dB. Based on these studies, the main challenges of UWB-MIMO antennas are achieving low mutual coupling to improve isolation, as well as designing small antennas that are effective for UWB frequencies, making them suitable for portable devices [17].

This study uses an orthogonal arrangement of antenna elements to create a 4×4 MIMO antenna for UWB frequencies with a planar hexagonal patch. The antenna elements are arranged in differing orientations from one another in order to achieve low mutual coupling and a greater range of radiation patterns and directions for signal propagation.

## 2. ANTENNA DESIGN

The antenna to be designed is a 4×4 planar monopole MIMO antenna with UWB working frequency (3.1-10.6 GHz). The design process involves creating a UWB antenna with a single element, followed by configuring it into a MIMO antenna. The antenna is designed with a hexagonal patch and uses the defected ground structure technique.

### 2.1. UWB single-element antenna design

The designed antenna is a microstrip antenna using FR-4 substrate material with dimensions of 16 × 16 $mm^2$, dielectric constant (εr) 4.6, and copper thickness of 0.035 mm. The calculated dimensions of the rectangular single-patch antenna are the width and length of the patch, forming a rectangular patch antenna [18]. Then determine the dimensions of the antenna ground plane in the form of the width and length of the ground plane.

$$Wp = \frac{c}{2f_0\sqrt{\frac{(\varepsilon_r+1)}{2}}} \tag{1}$$

$$\varepsilon_{reff} = \left(\frac{\varepsilon_{r+1}}{2}\right) + \left(\frac{\varepsilon_{r-1}}{2}\right)\left(1 + 12\frac{h}{wp}\right)^{-1/2} \tag{2}$$

The change in length due to the fringe plane is calculated by (3).

$$\Delta L = \frac{0{,}421(\varepsilon_{eef}+0{,}3)(\frac{Wp}{h}+0{,}264)}{(\varepsilon_{eef}+0{,}258)(\frac{Wp}{h}+0{,}8)} \tag{3}$$

Patch length (lp) is calculated by (4).

$$Lp = \frac{c}{2f\sqrt{\varepsilon_{reff}}} - 2\Delta L \tag{4}$$

The ground plane dimensions are calculated using the (5), (6).

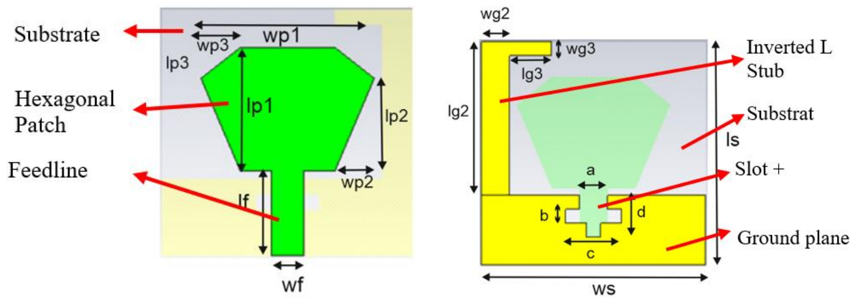
$$W_g = Wp + 6h \tag{5}$$

$$L_g = Lp + 6h \tag{6}$$

The antenna comprises a partial ground plane with an additional slot symbol in the center and an inverted L-shaped stub on the left side, resembling a diamond. This design achieves an extensive bandwidth using the defected structure ground (DGS) approach. The following are the geometric parameters of the suggested UWB antenna with a single element: ws=ls= wg1=16 mm, hs=1.6 mm, wf=2 mm, lf=5.5 mm, hc=0.035 mm, wp1=11 mm, lp1=8 mm, wp2=2.5 mm, lp2=6 mm, wp3=2. 5 mm, lp3=2 mm, lg1=5 mm, wg2=2 mm, lg2=11 mm, wg3=3 mm, lg3=1 mm, a=2 mm, b=1 mm, c=4 mm, and d=3 mm. Figure 1 shows the UWB single element antenna configuration with the front view in Figure 1(a) and the back view in Figure 1(b).

Figure 2 shows the design procedure for a single-element UWB antenna. To achieve a wide working frequency, the antenna is first designed in a rectangular shape with a full ground as shown in Figure 2(a).

This design is then modified with a partial ground as shown in Figure 2(b). Next, the corners of the rectangular patch are cut in Figure 2(c) and Figure 2(d) until the patch is hexagonal in shape, followed by modifying the ground using the DGS technique in stages as shown in Figure 2(e), Figure 2(f), and Figure 2(g). This involves adding an inverted L stub on the left ground and cutting the center ground with a slot in the shape of a plus symbol. The evolution of the antenna into an UWB antenna is completed at Step G, with the s-parameter results shown in Figure 3. From this graph, there is a gradual improvement in antenna performance, with the antenna at Step G showing the best return loss characteristics in line with UWB specifications. Every design modification made between Steps A and G has a major effect on the frequency response and raises the antenna’s overall efficiency.



(a) (b)

Figure 1. Design of a single-element planar UWB antenna (a) front view and (b) back view

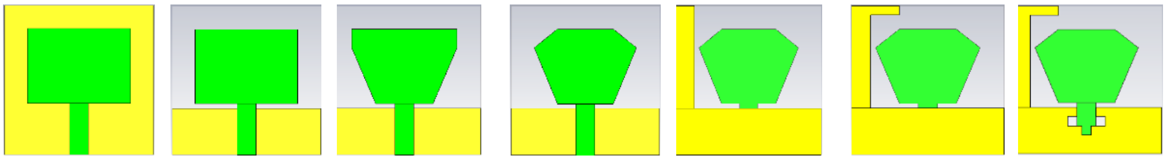

(a) (b) (c) (d) (e) (f) (g)

Figure 2. Stepwise implementation single-element UWB antenna; (a) Step A, (b) Step B, (c) Step C, (d) Step D, (e) Step E, (f) Step F, and (g) Step G

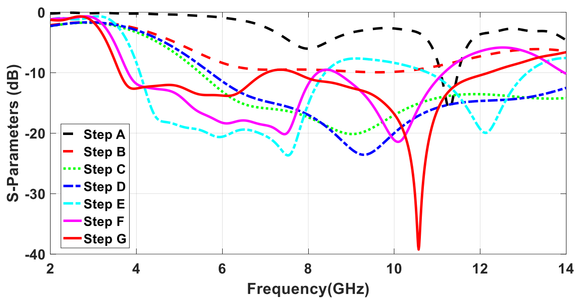
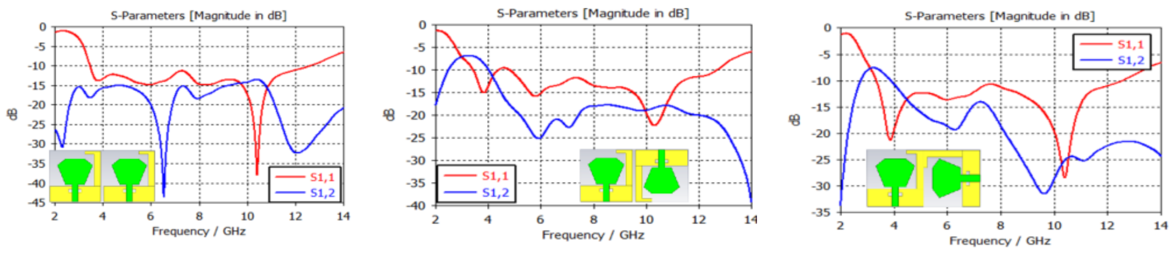



Figure 3. Evolution S-parameters a single-element UWB antenna

### 2.2. UWB-MIMO 4×4 antenna configuration

The antenna radiation and mutual coupling of MIMO antennas are highly influenced by the arrangement of the 4×4 MIMO antenna port during the manufacturing process. Therefore, research into the MIMO antenna configuration is vital. For 2×2 MIMO antennas, there are three possible port locations or configurations: directional [19], counterclockwise [6], and orthogonal [20]. Figure 4 shows the configuration of the MIMO antenna 2-element.

From the three different antenna configurations, it is known that the best port placement scenario to produce the smallest mutual coupling parameter value is the counterclockwise and orthogonal MIMO antenna configuration. Figures 4(a) and 4(b) show that the counterclockwise and orthogonal MIMO antenna port placement provides better isolation compared to the linear MIMO antenna configuration in Figure 4(c). This shows that placing the ports close together and in the same direction increases coalescence and reduces isolation. This is due to the close spacing of the antennas and the same radiation direction, which affects the antenna radiation and impacts the mutual coupling parameters of the MIMO antenna. Therefore, the optimal 4×4 MIMO antenna array and subsequent S-parameters are shown in Figure 5.




(a) (b) (c)

Figure 4. 2-element MIMO-UWB antenna configuration; (a) directional, (b) counterclockwise, and (c) orthogonal

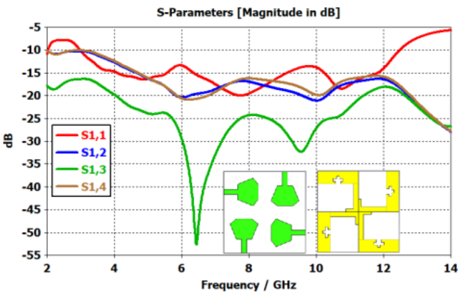
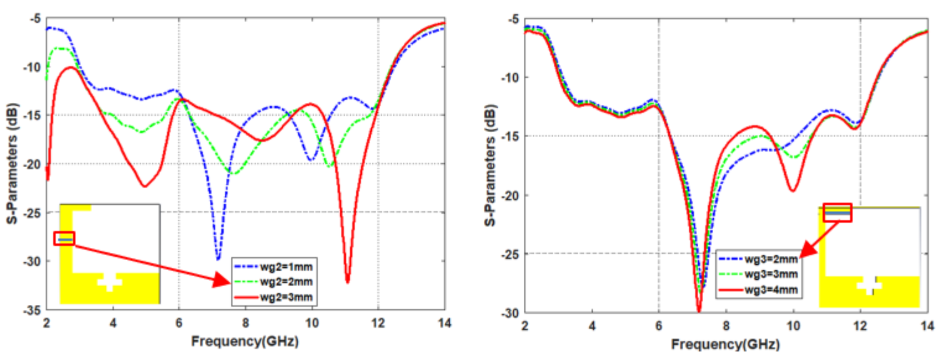



Figure 5. S-Parameters results of planar hexagonal patch MIMO 4×4 antenna

## 3. PARAMETRIC STUDY

The antenna design aims to achieve optimal and improved performance through parameter studies focusing on the width of ground 2 (wg2) and ground 3 (wg3). At this stage, simulation and optimization are performed using the parameter sweep technique, varying wg2 from 1 mm to 3 mm and wg3 from 2 mm to 4 mm. The results of this study allow the antenna design to meet the desired specifications and achieve optimal performance as shown in Figure 6. The results of this study enabled the antenna design to meet the desired specifications and achieve optimal performance as shown in Figure 6 with parameter sweep at wg2 in Figure 6(a) and parameter sweep at wg3 in Figure 6(b).




(a) (b)

Figure 6. Simulation S11 dimensions at inverted L slot at ground plane (a) wg2 (b) wg3

After performing a parameter sweep for ground widths 2 (wg2) and 3 (wg3), the optimal sizes are wg2 = 1 mm and wg3 = 4 mm. The resulting frequency band is 3.02 - 12.5 GHz with the lowest resonant return loss of -27.76 dB. This optimization significantly improves performance compared to the initial design, with a wider frequency band and lower return loss. The refined ground dimensions enhance impedance matching and reduce signal reflection across the UWB spectrum [21], making the antenna better suited for high-performance UWB applications requiring wide coverage and minimal signal loss.

## 4. RESULTS AND DISCUSSION

The prototype antenna fabrication, shown in Figure 7 with both top and bottom views, demonstrates significant performance improvements. Antenna measurements were conducted using telecommunications laboratory measurement tools, including a vector network analyzer [22]. The fabricated antenna achieved a wide bandwidth of 3–12.5 GHz with mutual coupling below -16.5 dB, indicating strong isolation between elements.

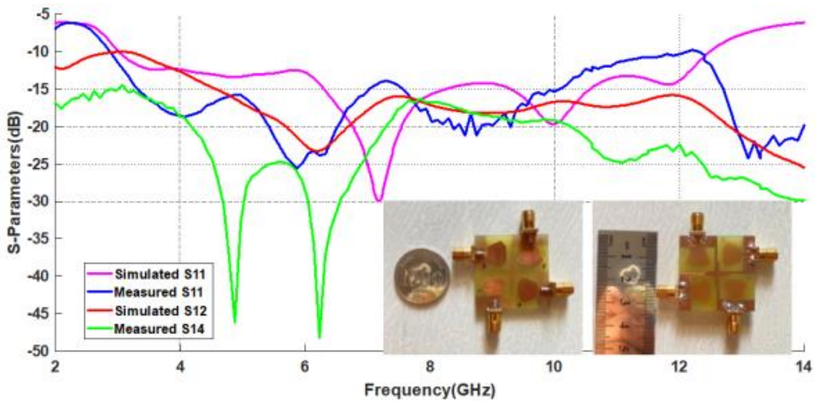
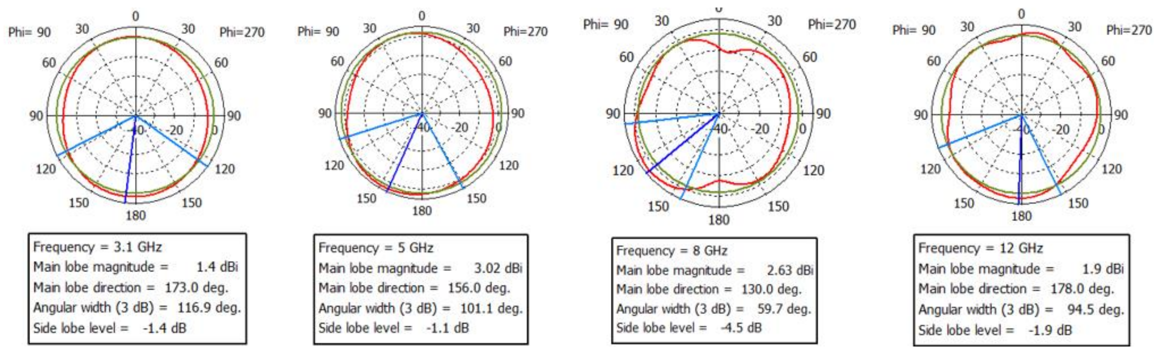



Figure 7. S-parameters and prototype fabrication top and bottom view

### 4.1. Radiation patterns

The radiation pattern generated by the planar hexagonal patch 4×4 MIMO antenna exhibits an omnidirectional characteristic, meeting the essential requirements for UWB antenna applications [17]. Figure 8 presents the radiation pattern and gain results in the polar plane at various operating frequencies: 3.1 GHz in Figure 8(a), 5 GHz in Figure 8(b), 8 GHz in Figure 8(c), and 12 GHz in Figure 8(d).




(a) (b) (c) (d)

Figure 8. Gain and radiation pattern of frequency; (a) 3.1 GHzn, (b) 5 GHz, (c) 8 GHz, and (d) 12 GHz

### 4.2. MIMO performance metric

This section discusses various diversity performance metrics, including envelope correlation coefficient (ECC), diversity gain (DG), and total active reflection coefficient (TARC) to assess the effectiveness of the proposed UWB-MIMO antenna array in environments subject to multi-path fading.

#### 4.2.1. Envelope correlation coefficient

ECC quantifies the degree of similarity between signals received by each antenna. Its values range from 0 to 1, with operators aiming for a value below 0.05 for optimal performance [5]. ECC is defined by equation (7) [12]. The ECC for the simulated and measured UWB-MIMO antennas are below 0.033 and 0.005, respectively, across the operating frequencies of 3-12.5 GHz, demonstrating excellent antenna performance and high DG as depicted in Figure 9. A low ECC value indicates that the signals received by the antenna elements have a low correlation.

$$ECC = \frac{|S_{11}S_{12}+S_{21}S_{22}|}{(1-|S_{11}|^2-|S_{12}|^2)(1-|S_{22}|^2-|S_{21}|^2)} \quad (7)$$

#### 4.2.2. Diversity gain

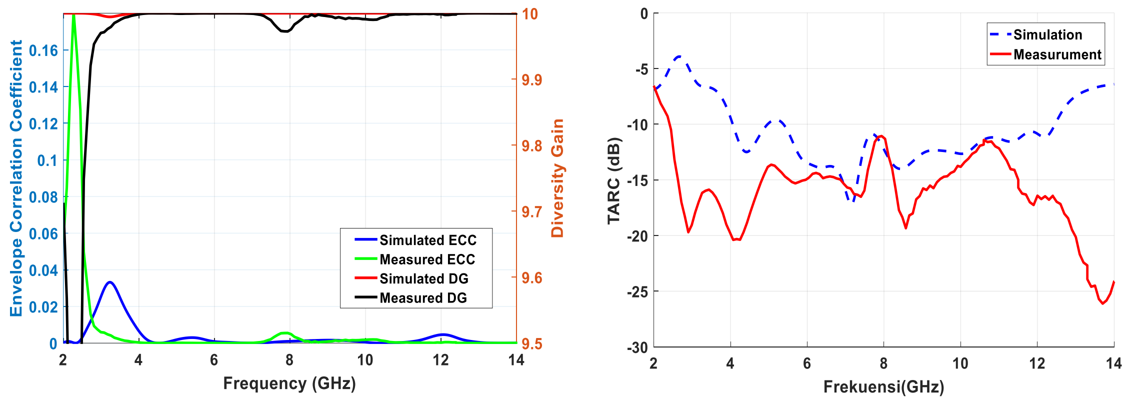
DG refers to the enhancement in signal quality resulting from the use of multiple antennas at the transmitting and receiving ends. The formulation for DG can be found in equation (8) [23]. The suggested UWB-MIMO antenna’s DG which exceeds 9.97 dBi throughout the impedance spectrum, is shown in Figure 9(a). The suggested UWB-MIMO antenna’s DG which exceeds 9.97 dBi throughout the impedance spectrum, is shown in Figure 9(a).

$$DG = 10\sqrt{1-ECC^2} \quad (8)$$

#### 4.2.3. Total active radiation coefficient

TARC is employed to illustrate the effective bandwidth performance between MIMO antenna elements. The TARC value is defined in (9) [9]. The TARC of the proposed antenna is below -10 dB across the entire operating frequency range [24], as illustrated in Figure 9(b). This antenna has minimal reflection power with the lowest TARC value of -17 dB at 7.184 GHz.

$$TARC = \sqrt{\frac{\sum_{i=1}^{4}\left|S_i+\sum_{m=2}^{4} S_{im} e^{j\theta_m}\right|}{4}} \quad (9)$$




(a) (b)

Figure 9. Performance metric of the proposed MIMO-UWB antenna (a) ECC and DG (b) TARC

Table 1 presents a comparison of the suggested design parameters with earlier research. This comparison demonstrates that the proposed antenna exhibits superior performance in key aspects such as wider bandwidth (3-12.5 GHz), higher gain (5.04 dBi), and excellent isolation (less than -16.5 dB). Additionally, the proposed antenna achieves an ECC of less than 0.005, indicating a minimal signal correlation between elements, and a low TARC of less than -10 dB, confirming optimal efficiency in multipath fading environments. This highlights the advantages of the new design over previous works, particularly in terms of improving bandwidth and reducing mutual coupling, making it more suitable for UWB-MIMO applications.

Table 1. Comparison of proposed mimo-uwb antenna parameters with previous research

| Ref. | Dimension (mm³) | Number port | Bandwidth (GHz) | Isolation (dB) | Max. Gain (dBi) | ECC | TARC (dB) |
|---|---|---|---|---|---|---|---|
| [6] | 72,6×88,1×0,25 | 4 | 3,89-17,09 | <-15 | 5,87 | <0.02 | <-10 |
| [16] | 58×58×0,8 | 4 | 3–16 | <-18 | 7 | <0.07 | - |
| [12] | 40×40×1,6 | 4 | 3.2 -13.40 | <-20 | 2 | < 0,005 | - |
| [15] | 34×34×1,6 | 4 | 2,5-12 | <-15 | 5,5 | <0,05 | <0 |
| [25] | 40×40×1,524 | 4 | 3-13,5 | <-15 | 3,5 | <0,4 | - |
| [20] | 40×40×1,524 | 4 | 3,1-10,6 | <-16 | 2,9 | < 0,13 | <-1,94 |
| This work | **32×32×1,6** | 4 | 3 – 12,5 | <-16,5 | 5,04 | **<0,005** | **<-10** |

## 5. CONCLUSIONS

A hexagonal patch planarMIMO 4×4 antenna designed for UWB applications has been effectively modeled and simulated. This MIMO UWB antenna is constructed with a partially grounded structure featuring inverted L stubs and plus symbol-shaped slots, enabling it to achieve a wide operational bandwidth covering 3 to 12.5 GHz. Simulations involved converting a single-port UWB antenna into a 4×4 UWB-MIMO antenna. Various MIMO parameters were analyzed, including S-parameters, mutual coupling, radiation patterns, ECC, DG, and TARC. The proposed antenna exhibits a return loss below -10 dB at frequencies ranging from 3 to 12.5 GHz, with four-element UWB-MIMO antenna isolation of less than -16.5 dB, ECC below 0.005, and DG exceeding 9.9. Consequently, this 4×4 planar hexagonal patch MIMO antenna has been validated as a suitable option for UWB applications.

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