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Compact 4-port planar MIMO antenna with enhanced isolation for WLAN/WiMAX applications

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Abstract. A quad-port MIMO antenna is constructed and studied in this communication with single resonating bands (wideband) for WLAN & WiMAX applications. It is designed by etching out a circular slot from a patch placed on the front side of the substrate & a feeder line on the backside of the substrate. The proposed structure has ≤ -10 dB impedance bandwidth of 2540 MHz (4.36–6.90 GHz). To legitimize the work attributes of the proposed MIMO antenna, diversity parameters such as total active reflection coefficient; envelope correlation coefficient (ECC) & diversity gain are calculated. The isolation is more than 25 dB, justifying the suggested design's acceptability as a quad-port MIMO antenna. The suggested design's examination revealed the steady performance and a high degree of agreement between the simulated and measured findings.

Keywords. Diversity gain; ECC; mutual coupling; reflection coefficient; TARC; VSWR; WiMAX.

1. Introduction

The miniaturized wideband antennas have grown in prominence in modern wireless communications due to the relatively low production cost, high throughput, simple design, and availability of a broad variety of resonance frequencies. The wideband communication systems are analyzed for high data transmission rate, high speed, large channel capacity & excellent accuracy [1]. In order to fulfill these aforementioned features, MIMO antennas have garnered the attention of engineers working in the field of wireless communication systems. MIMO antenna systems are able to provide a fine quality of mobile communication if the created antenna has desired mutual coupling & envelope correlation coefficient (ECC) between its antenna elements [2]. MIMO (Multiple Input Multiple Output) is a technique that uses spatial multiplexing at both the receiver and transmitter ends to enhance communication performance [3]. The strong mutual coupling that occurs between closely spaced antennas leads to decreased antenna efficiency and bandwidth loss, along with degradation in the performance of diversity gain or spatial multiplexing. So the issue arises: How should antennas be assembled that have the lowest possible interaction and use the least possible space. Due to the conflict between these two characteristics, the issue is very difficult. In addition, the three phenomena including near-field coupling, far-field coupling, and surface wave coupling are also believed to be mutually related [4]. For compact MIMO systems, several methods and MIMO architectures have been suggested [5–14]. The described antennas in [5–10] are big and may not be appropriate for the current portable applications. Isolation may also be alleviated by the use of certain techniques. Antenna components have meander line slots between them and fractal-based DGS [11], EBG [12], soft surface structures [13], and neutralization lines [14] among others. It is impossible to establish adequate isolation in such a small structure at low frequencies due to the long wavelength, which makes it exceedingly difficult to minimize mutual coupling at these frequencies.

In the presented manuscript a compact planar quad-port MIMO antenna with orthogonally orientated feed configurations is proposed for wideband wireless (WLAN/WiMAX) applications. The designed antenna has a simple structure with a size of 25×25 mm^2, printed on RT-Duroid 5880 substrate glass microfiber/PTFE (ε_{rsub} = 2.20, $\tan\delta$ = 0.0009, and thickness of 1.570 mm). A complete investigation was provided, which included isolation, low

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correlation, diversity gain, and total active reflection coefficient. The main important attributes of this research paper are as follows.

i. The proposed quad-port MIMO antenna has excellent mutual coupling (>25 dB) by the orthogonal placement of four ports.
ii. The proposed antenna is miniaturized in structure, cost-effective & achieves good diversity performances. The resonant frequency of 5.59 GHz with impedance bandwidth of 4.36–6.90 GHz with percentage impedance bandwidths of 45.11% for WiMAX and WLAN applications is achieved.
iii. The simulated outcomes are supported by mathematical and measurable results from the archetype fabrication.

2. Proposed antenna's geometric layout, fabricated archetype and experimental setup

The geometrical structure of the proposed linearly polarised quad-port MIMO patch antenna which is fed by a 50 Ω microstrip feed line, printed on RT-Duroid 5880 substrate glass microfiber/PTFE (ε_{rsub} = 2.20, tanδ = 0.0009, and thickness of 1.570 mm) is shown in figure 1. Figures 2 and 3 show the photographs of the fabricated archetype & measurement setup of the proposed MIMO antenna respectively. In the first stage, a single entity of the proposed antenna with wideband attributes is achieved by etching out the circular ring from the conductive rectangular patch and placing the feed at the optimized location. After that, a compact 4-port MIMO antenna module is designed by replicating the single entity in an orthogonal manner in close proximity. The dimensional values are mentioned in table 1.

3. Investigation of proposed MIMO antenna

The suggested antenna is simulated, designed, and implemented using an ANSYS HFSS 18 electromagnetic simulator. To understand the operating principle, the analysis must be initiated with a single port antenna and progress to a quad-port MIMO antenna with improved isolation characteristics while maintaining the single port antenna as its basic port. The following sections discuss several aspects of antenna design: - examination of single port, dual port, triple port, and quad-port.

3.1 *Investigation of single port*

The parametric analysis in terms of $|S_{11}|$ by varying feed location, slot shape, and slot dimensions is carried out in order to achieve the single entity of the proposed antenna

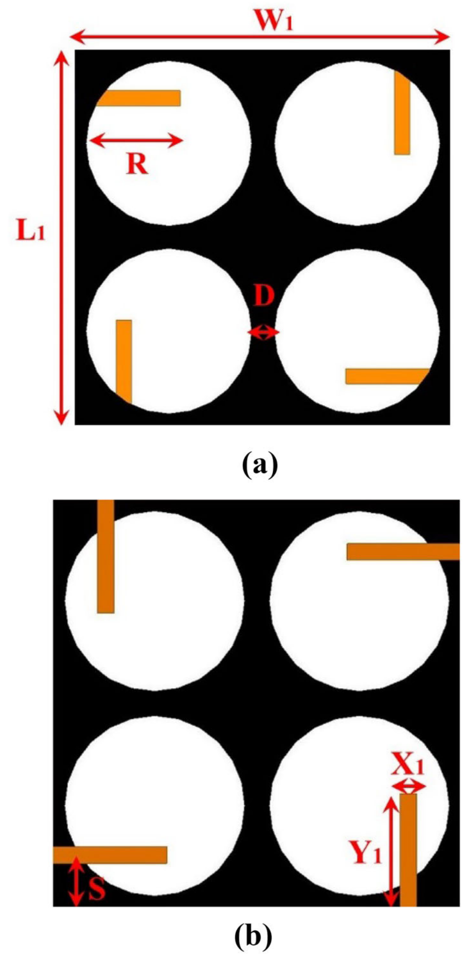


Figure 1. Systematic layout of the 4 port-MIMO antenna (**a**) Front view (Patch), (**b**) Back view (Feed lines).

(c.f. figure 4). The variation of $|S_{11}|$ is observed by etching out the circular, triangular, and square shape slots from the conducting patch. Under this analysis, a single band is achieved for the circular slot (cf. figure 4(a). Variation in the radius (R) of the circular slot is performed to observe the change in impedance bandwidth. From figure 4(b) it can be stated that for R = 12.5 mm proposed entity attained maximum bandwidth at minimum return loss. Further, in order to increase the −10 dB impedance bandwidth, the positional variation (S) of feed is investigated in the step of 1 mm. From the perusal of figure 4(c), it is found that the maximum value of bandwidth is obtained for S = 5.5 mm. Therefore, we have chosen this design to incorporate MIMO structures.

3.2 *Investigation of dual-port*

A Dual-port MIMO antenna is introduced with the help of a single-port antenna. Reflection coefficient $|S_{11}|$ behavior is observed under three different stages: stage 1: single port, stage 2: dual-port with parallel orientation & stage 3: dual

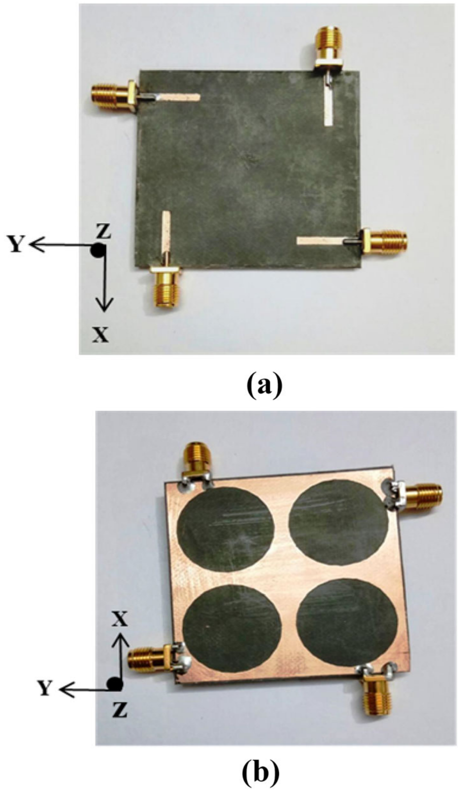


Figure 2. Fabricated archetype of quad- MIMO antenna (**a**) Feeding structure, (**b**) circular patch.

port with orthogonal orientation antenna with respect to a single port antenna in figure 5(a) & it is confirmed that the $|S_{11}|$ is roughly the same in all three stages. From the perusal of figure 5(b), it is observed that high isolation

Table 1. Proposed configuration dimensional parameters.

Parameters	Dimensions (mm)
L_1, W_1 (substrate length and width)	25, 25
Y_1, X_1 (feed length and width)	2, 4
R (radius of circular ring)	12.5
S (feed position from edge)	5.5
D (distance between circular rings)	1

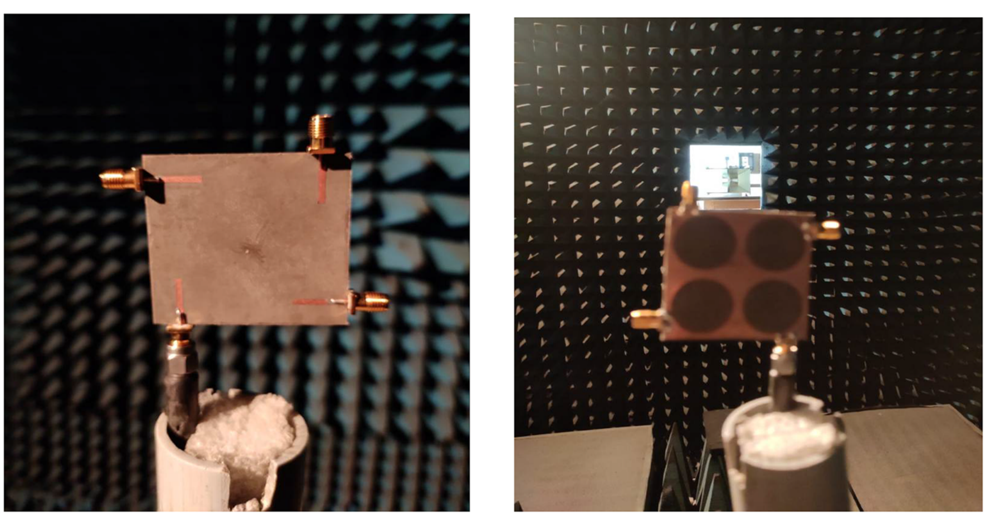
(>25 dB) is achieved when ports are in orthogonal orientation.

3.3 *Investigation of triple port*

Under this investigation the variation of reflection coefficient $|S_{11}|$ have four different stages: stage 1: single-port, stage 2: dual-port, stage 3: triple port with port-2 & port-3 parallel orientation & stage 4: triple port with port-2 and port-3 orthogonal orientation antenna in figure 6(a). From figure 6(a) it is confirmed that the $|S_{11}|$ is roughly the same in all four-stage. The variation of the mutual coupling with different orientations among port-1, port-2, & port-3 for parallel & orthogonal is investigated (c.f. 6-b). Maximum isolation is obtained when all three ports are in orthogonal orientation.

3.4 *Investigation of quad-port*

The proposed quad-port antenna is designed by replicating the single port antennas in an orthogonal fashion. Figure 7



(a) (b)

Figure 3. Antenna measurement setup using VNA (**a**) Measurement of single-port. (**b**) Testing antenna for a single-port.

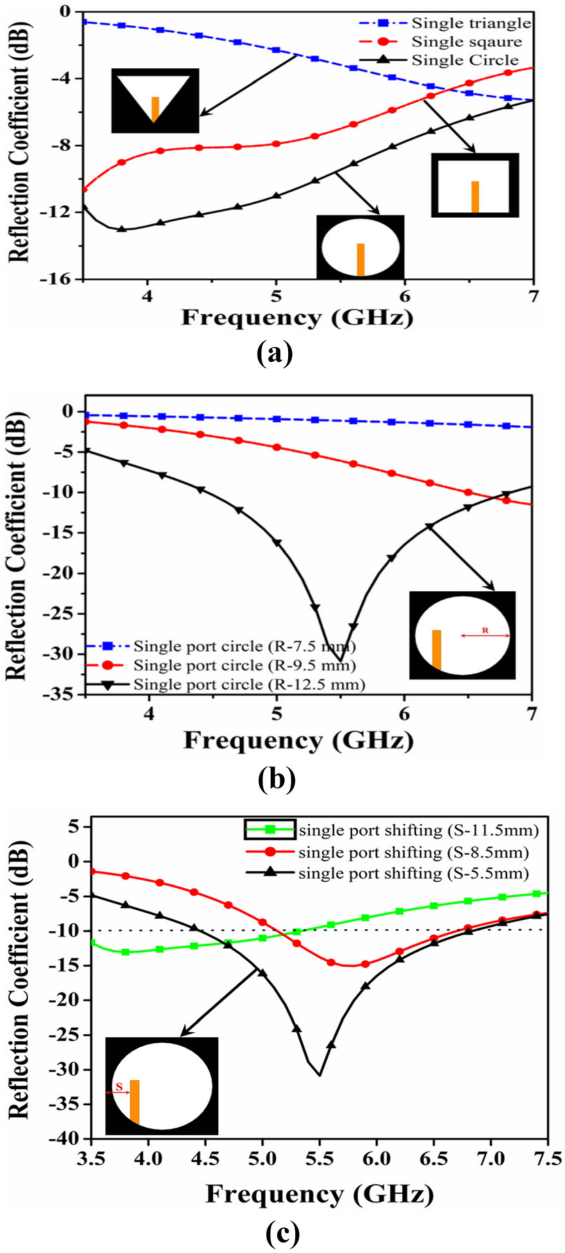


Figure 4. (**a**) Reflection coefficient ($|S_{11}|$) with variation for a single-port, with various types of shaped. (**b**) Reflection coefficient $|S_{11}|$ with varying the radius, proposed (R = 12.5 mm).

illustrates the change in reflection coefficient and mutual coupling for the proposed antenna. As shown in figure 7, the reflection coefficient characteristics for all ports are almost identical, confirming one of the critical criteria for MIMO antennas. The second critical finding is that the mutual coupling between all ports is less than −25 dB. Two ideas are used to create less mutual coupling: polarization diversity and spatial diversity. Port-1 and port-2, as well as port-1 and port-4, comprise the polarization diversity due to their orthogonal orientation. Similarly, port-1 and port-3, as well as port-2 and port-4, exhibit spatial

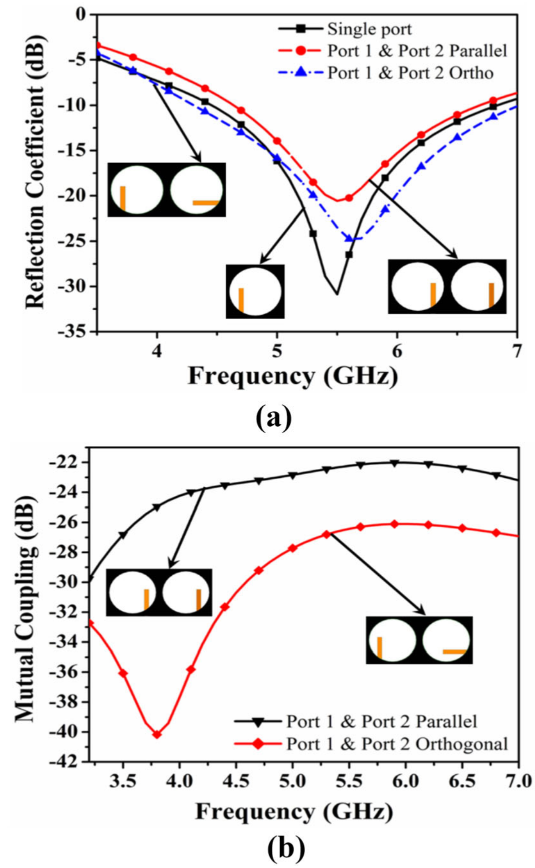


Figure 5. (**a**) Reflection coefficient of port 1 & port 2 parallel & orthogonal placements. (**b**) Mutual coupling of port 1 & port 2 parallel & orthogonal placements.

variety due to their diagonal orientation. This is the fundamental idea behind the decoupling of ports.

4. Experimental results and validation

Three critical points will be addressed in this section: (a) Experimental validation of simulated data; (b) Diversity performance; and (c) Performance comparison of the proposed antenna to existing MIMO antennas. The simulated/measured $|S_{11}|$ as well as the mutual coupling, is shown in figure 8. The impedance bandwidth of the proposed antenna lies in the range of 4.36–6.90 GHz (simulated), 4.76–6.31 GHz (measured). From the survey of figure 8(a), it is observed that the simulated & measured effects are in excellent consistency with slight differences. Greater than 25 dB isolation (simulated and measured) between the antenna units for the proposed configurations makes it suitable for MIMO applications.

Figure 9 displays the simulated radiation efficiency & the simulated/measured peak gain over the whole entire operating band of 4.36–6.90 GHz. The radiation efficiency of the quad-port antenna is more than 90% over the entire

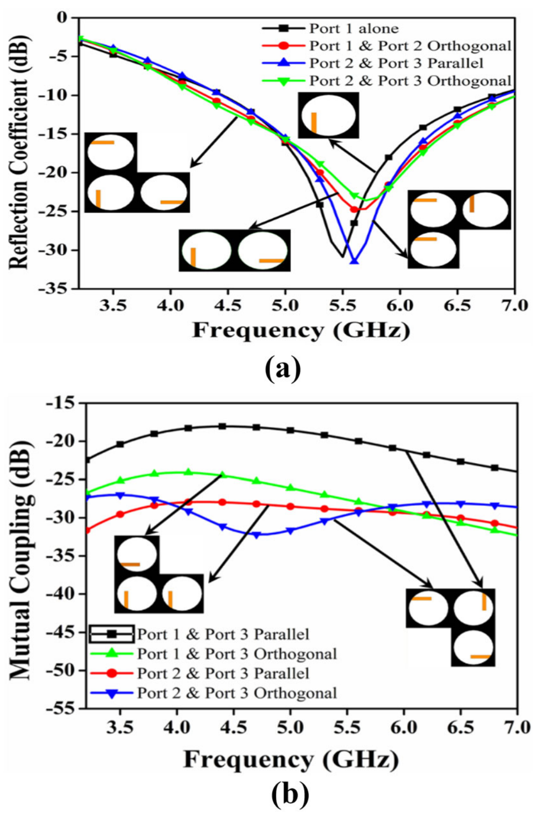


Figure 6. (**a**) Reflection coefficient of port 1, port 2 & port 3 parallel & orthogonal placements. (**b**) Mutual coupling of port 1, port 2 & port 3 parallel & orthogonal placements.

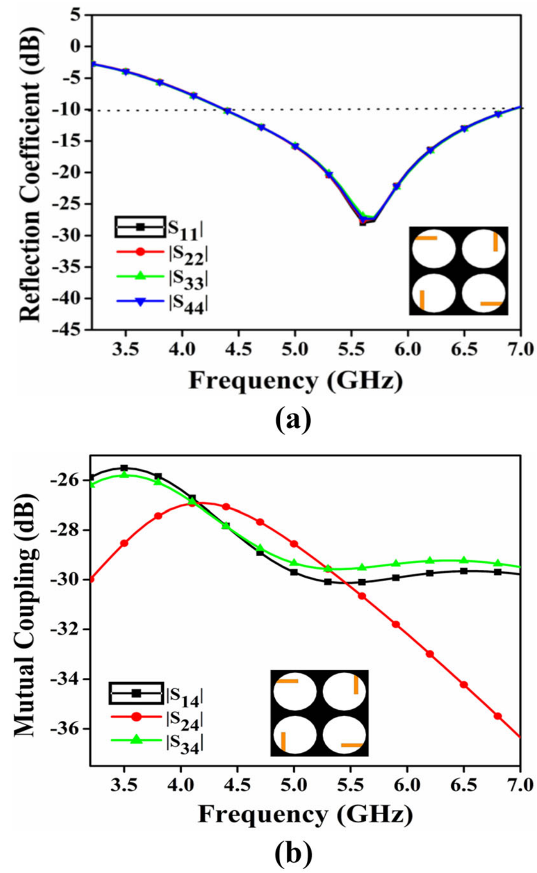


Figure 7. (**a**) Reflection coefficient ($|S_{11}|$). (**b**) Mutual coupling of proposed 4-Port MIMO Antenna.

operational bandwidth & the peak gain is 2 dB (simulated), 2 dB (measured).

The voltage standing wave ratio (VSWR) characteristic of the quad-port MIMO antenna is represented in figure 10(a) and it can be seen that each antenna had similar VSWR value 1.81(simulated) and 1.91(measured) at 5.59 GHz which had met the requirement for VSWR<2. The antenna has a 2:1 VSWR achieved bandwidth for each antenna was 2570 MHz (4.33–6.90 GHz) and nearly omnidirectional radiation patterns.

The surface current distribution of the proposed design at 5.5 GHz is displayed in figure 10(b) when only port 1 is excited. The strength of surface current density is 133.71 A/m. The maximum flow of current on the feeder line and around the circular ring makes the structure resonant for (4.36–6.90) GHz band of operation. This plot also justifies the isolation between the different ports as the maximum current strength is observed near port 1 and other ports are less influenced by the port 1 radiation.

And as per the simulations and measurements, the suggested antenna's Co/Cross polarization patterns in both the E-plane and the H-plane may be seen in figure 11. When the elevation axis coincided with the polar axis ($\theta = 0°$) for the antenna's coordinate system, the far-field radiation patterns of the prototype antenna could be measured in an anechoic chamber. As a result, the azimuth drive produced cuts at a consistent rate ø. Broad band horn was used as the fixed antenna (reference antenna). For the selected measurement, the elevation positioner was rotated from −180° to 180° in increments of 5°. Again, HFSS software was used to generate simulations, and measurements were conducted in an anechoic room. Figure 11 illustrates the main (co-polar) findings, which demonstrate excellent agreement between simulation and measurement. Small differences in the test findings may be attributed to the anechoic chamber's supporting hardware and gain inaccuracy in the standard antenna utilized for the experiments. Although there were some inconsistencies in the radiation patterns detected, this is acceptable and negligible for mobile applications. Figure 11 also illustrates the equivalent findings for cross-polar patterns. These are less than 10–15 decibels than the co-polar patterns. While cross-polar components are undesirable and may introduce uncertainty into MIMO systems, a suppression level of 10–15 dB is sufficient for many applications.

This section examines crucial MIMO performance parameters. A MIMO system's ECC and DG are essential metrics. In a multi-antenna system, ECC refers to the effect

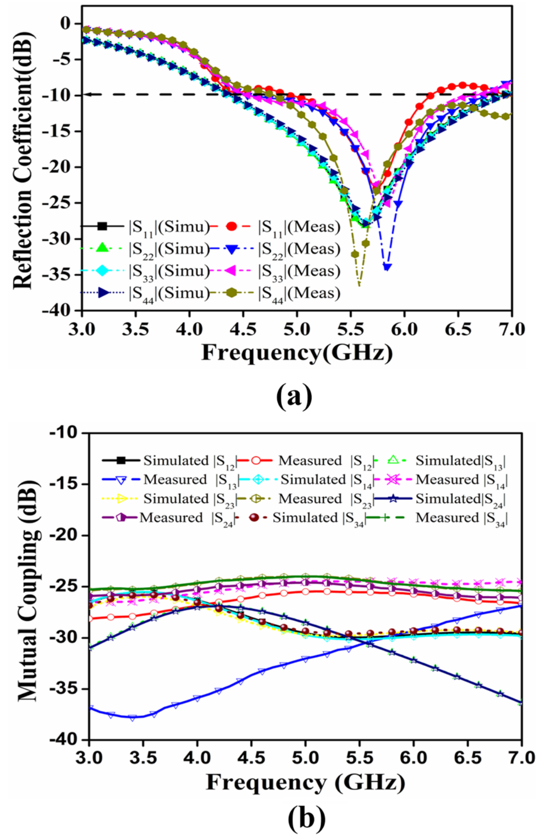


Figure 8. Measured and simulated (**a**) Reflection coefficient, (**b**) Mutual Coupling among the ports.

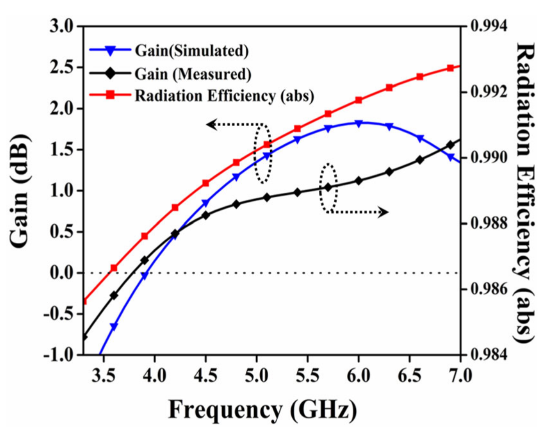


Figure 9. Gain (Simulated and measured) and Radiation efficiency (simulated).

of one antenna on the performance of another. In other words, it measures the impact of one member on another's performance. Equations (1) and (2) demonstrate how to calculate ECC using S-parameters or radiation characteristics (2) [15, 16]. ECC is computed in this article using Equation (2).

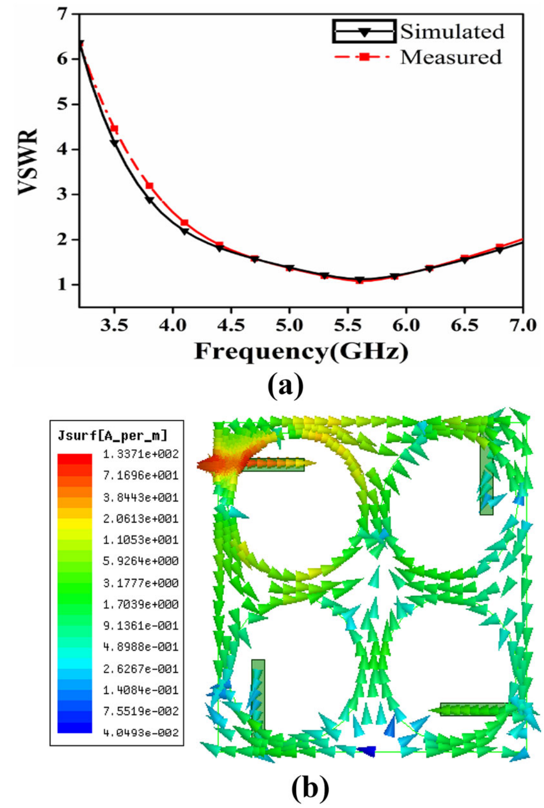


Figure 10. (**a**) VSWR (simulated and measured) variation with respect to frequency. (**b**) Surface current distribution at 5.59 GHz.

$$ECC_s = \left| \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|}{\left|\left(1 - |S_{11}|^2 - |S_{21}|^2\right)\left(1 - |S_{22}|^2 - |S_{12}|^2\right)\right|^{1/2}} \right|^2 \quad (1)$$

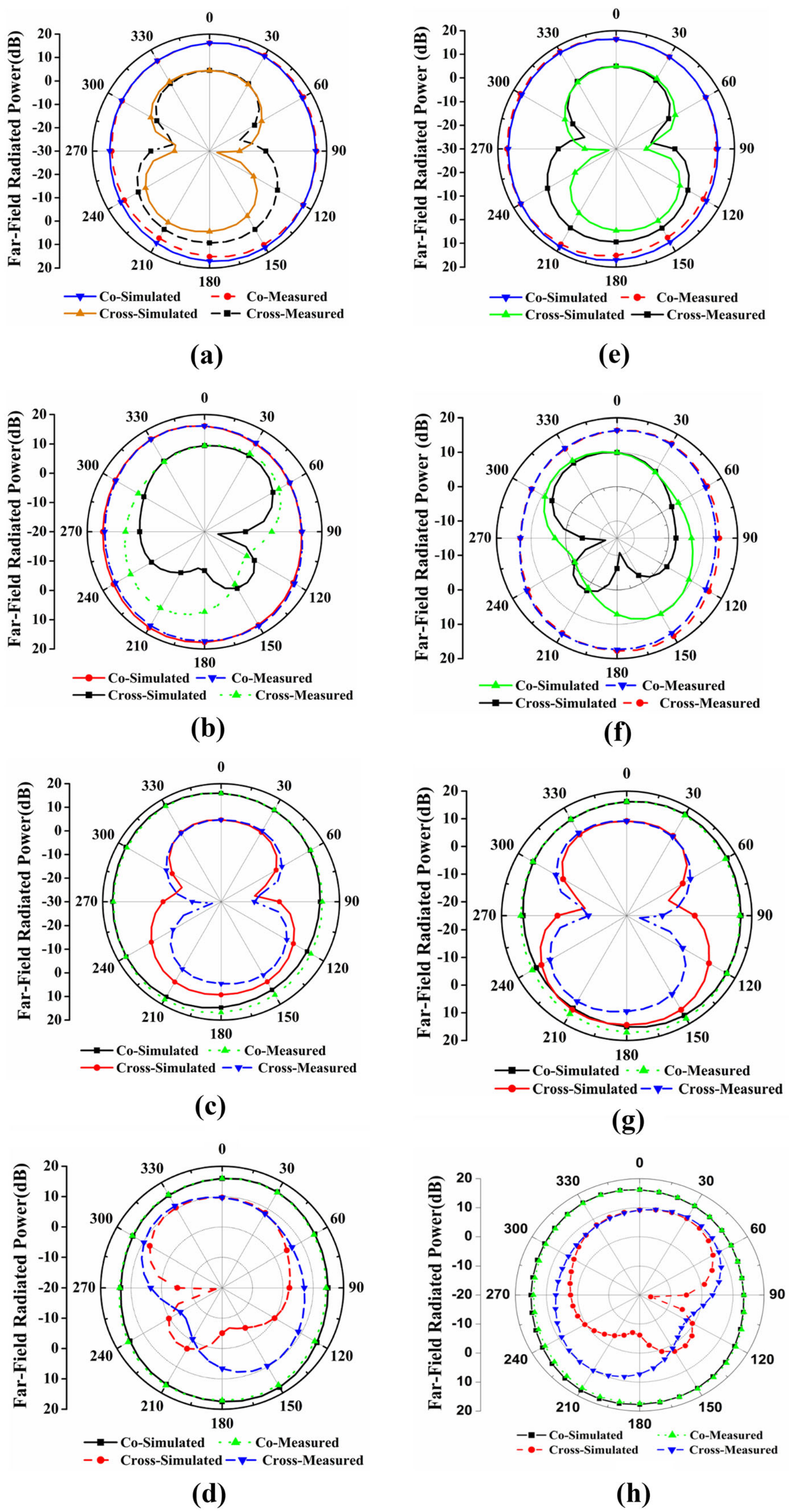
$$ECC_F = \frac{\left|\iint_{4\pi} [E_i(\theta,\phi) * E_j(\theta,\phi)]\, d\Omega\right|^2}{\iint_{4\pi} |E_i(\theta,\phi)|^2 d\Omega \iint_{4\pi} |E_j(\theta,\phi)|^2 d\Omega} \quad (2)$$

The DG, on the other hand, is the process of selecting the strongest signal from a set of N signals. The diversity gain (DG) setting improves the signal-to-noise ratio without raising the input power level. The following equation is used to compute it [17].

$$DG = 10\sqrt{1 - ECC^2} \quad (3)$$

The computed values of ECC and DG are presented in table 2 of this document. Following a review of table 2, it is discovered that the value of ECC is less than 0.08 and the value of DG is near 10 throughout the whole working bandwidth.

To determine the bandwidth and efficiency of multiple input and multiple output antennas, the total active reflection coefficient (TARC) is one of the key factors. In an N-element MIMO system, it is the sum of the square roots of


Far-Field Radiated Power(dB)
Co-Simulated
Co-Measured
Cross-Simulated
Cross-Measured
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)

◀**Figure 11.** Co and Cross-polarization of the proposed design at 5.5 GHz in (**a**) E-plane at port 1, (**b**) H-plane at port 1, (**c**) E-plane at port 2, (**d**) H-plane at port 2, (**e**) E-plane at port 3, (**f**) H-plane at port 3, (**g**) E-plane at port 4 and (**h**) H-plane at port 4.

Table 2. ECC and DG of the proposed MIMO antenna employing a far-field radiation pattern.

Frequency points	ECC	Diversity gain (dB)	Frequency points	ECC	Diversity gain (dB)
4.40	0.072	9.952	5.60	0.031	9.981
4.60	0.065	9.958	5.80	0.038	9.973
4.80	0.054	9.961	6.00	0.047	9.968
5.00	0.041	9.971	6.20	0.053	9.961
5.20	0.039	9.976	6.40	0.059	9.953
5.40	0.032	9.980	6.60	0.68	9.951

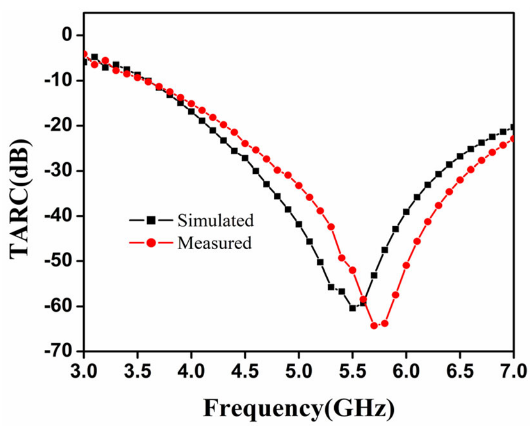


Figure 12. TARC (Simulated and measured) for the proposed MIMO antenna.

the reflected signal intensity and the power provided to the antenna. The TARC value for MIMO systems may be achieved by

$$\Gamma_a^t = \frac{\sqrt{\sum_i^N |b_i|^2}}{\sqrt{\sum_i^N |a_i|^2}} \tag{4}$$

b_i and a_i represent the reflected and incident power, respectively, and are linked by b = [S]a. Figure 12 shows that the TARC value. Figure 12 show that the TARC retains the original $|S_{11}|$ characteristic with a minor bandwidth adjustment.

An evaluation of the suggested MIMO antenna is provided in table 3, which serves to demonstrate its uniqueness. Table 3 compares the proposed MIMO antenna to other MIMO antennas for the same operating bandwidth in terms of impedance bandwidth, radiation efficiency, isolation, gain, and diversity.

5. Conclusion

In this article, a compact 4-port MIMO antenna is modeled, analyzed, investigated & fabricated for WLAN/WiMAX applications with a wideband operating range of 4.36–6.90 GHz (2540 MHz). The isolation between the ports has been achieved greater than 25 dB by using the concept of orthogonal placement of antenna elements. The antenna diversity performance is also examined and investigated in terms of envelope correlation coefficient (ECC<0.08), Diversity gain (DG≥9.9 dB) & total active reflection coefficient (TARC≤10 dB). Good coherence is observed between the simulated and measured counterparts.

Table 3. Comparative analysis of the proposed MIMO antenna with the existing configurations with the same operating range.

Antenna size in terms of wavelength (mm^3)	No. of antennas	Operating band (GHz)/impedance bandwidth (in%)	Radiation efficiency (%)	Isolation (dB)	ECC	Max gain (dBi)
0.07 λ_0×0.07 λ_0×0.002 λ_0 [11]	4	4.30–6.45/40	78	15	0.001	5.5
0.12 λ_0×0.12 λ_0×0.002 λ_0 [18]	2	4.96–5.50/10.3	NR	18	0.5	NR
0.34 λ_0×0.34 λ_0×0.01 λ_0 [19]	2	2.09–2.86,5.05–5.94/31.17,16.19	65	20, 17	0.01	1.74, 2
0.37 λ_0×0.37 λ_0×0.01 λ_0 [20]	4	2.25–2.4,4.7–6.3/6.07,29	80	16	0.07	4
0.09 λ_0×0.09 λ_0×0.002 λ_0 [21]	4	4.8–5.44,5.9–6.3/12.5,6.5	70	20	0.5	NR
0.05 λ_0×0.09 λ_0×0.001 λ_0 [22]	3	5.5–6.25/12.76	70	22	NR	6
0.05 λ_0×0.04 λ_0×0.002 λ_0 [23]	2	5.5–6.3/13.55	78	14	NR	3
0.05 λ_0×0.05 λ_0×0.002 λ_0 [24]	4	5.4–6/0.52	NR	18	0.25	5
0.05 λ_0×0.05 λ_0×0.001 λ_0 [3]	4	3.4–3.7,5.15–5.35/8.45,3.80	88	13, 16	0.13,0.002	5.7, 6
0.03 λ_0×0.03 λ_0×0,002 λ_0 proposed work	4	4.36–6.90/45.11	90	25	0.08	2

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