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Performance analysis of quad-port UWB MIMO antenna system for Sub-6 GHz 5G, WLAN and X band communications

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ABSTRACT

A quad-port Multiple Input Multiple Output Antenna with high isolation is presented in this paper. The MIMO design is intended to receive Ultra-Wide Band response to target various wireless applications. The engineered model has 40 x 40 $\times$ 1.6 mm^3 electrical dimensions. A single antenna achieves size compactness due to an appropriate inclusion of vertical and horizontal conductive strips. Additionally, a diagonal radiating strip is shaped and pooled with the patch geometry. A similar design is positioned orthogonally with each other to receive diversified performance. The four conducting ports are positioned with an appropriate minimum distance to lower down the possible mutual coupling. A partial ground plane having border geometry has been incorporated to receive the ultra-wide band response. An additional plus-sign shaped conducting strips are provided and united with ground lines for isolation enhancement. The MIMO system exhibits ultra-wide frequency response from 3.20 GHz to 13.40 GHz with adequate isolation below -20 dB and an impedance bandwidth of 10.20 GHz. The proposed structure provides an overall gain of 2 dBi having above 80 % efficiency. The presented radiator exhibits excellent MIMO diversity response achieving minimal mutual coupling effect. The other output parameters such as envelope correlation coefficients$<$0.05, diversity gain of nearly 10 dB, mean effective gain$<$0.2 dB, and channel capacity loss$<$0.1 bits/sec/Hz were obtained. The proposed design has been simulated in High Frequency Structure Simulator (HFSS) software. The developed MIMO antenna has been analyzed through VNA N9912A. An encouraging correlation between the software generated and actual responses was observed. The strong agreement between actual results and software results shows the design potential for wireless communications. The highly isolated MIMO system registers its potential for sub-6 GHz 5G, WLAN, and X Band communications.

1. Introduction

The introduction section is explained in three sub-sections. The first section gives idea regarding motivation and incitement. The section explains the factors behind the motivation of the proposed antenna. The second sub-section depicts the literature review. In this section, the till date research on similar domains has been discussed. The MIMO antenna, UWB antenna and certain feeding techniques from various proposed research were mentioned in this subsection. The third sub-section explains the proposed contribution and paper organization. It is about the MIMO antenna proposal with certain geometry and their meaningful outcomes. Also, this sub-section illustrates the systematic organization of the proposed paper.

1.1. Motivation and incitement

Wireless applications demand low-profile, simply configured, miniaturized, cost-effective, and simple integrated antennas. Designing

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MIMO antenna is a little challenging as more radiative components are involved. When more radiators are placed nearby there is an issue of mutual coupling which is the major factor for down falling of output parameters. To receive the desired resonance, the positioning of MIMO ports are extremely important. Ideally, they should be placed orthogonally to reduce the mutual coupling and receive the diversity performance. In similar way, to achieve Ultra Wide Band in MIMO system also becomes an inspiring task. Certain structural techniques should be incorporated to achieve the same. The partial ground plane, a ground plane having Split Ring resonator (SRR) geometry, and an inclusion of metamaterials could be the possible alternatives to achieve Ultra Wide Band. In addition to this, appropriate isolating geometries should be incorporated and united with the ground plane to get the response. These are the motivation factors for the authors to design and analyze the presented MIMO system. MIMO antenna lower down the radio propagation issues because of multiple transmission and reception. The channel state information (CSI) accuracy affects the MIMO response, especially for mm-wave communications. The beam training could neglect high-dimension channel matrix estimation. The MIMO system is having better multipath fading because each channel is working independently to transmit and receive the signal. These are also certain causes of the motivation behind MIMO designing.

1.2. Literature review

The planar antennas are the most suitable candidates for it having all aforementioned advantages [1,2]. The planar antennas could also be utilized for a satisfactory transmission rate such as data transfer using peer to peer communication and wireless transmission for short distances [3,4]. After performing enough research, the researchers have shifted their concentration to Multiple Input Multiple Output (MIMO) antenna systems because of multipath fading reduction, higher data rate, reaching higher distance, and more reliability without increment in bandwidth and transmitted power [5]. The MIMO antenna systems also have better channel capacity. Due to the same, the spectral efficiency could be enhanced [6]. While designing the MIMO antenna system, spacing between the elements, polarization, mutual coupling, and operating bandwidth (BW) should be considered. The major challenge with the structure having multiple radiators is their respective locations. As discussed earlier, higher space provision between the MIMO elements, leads the bigger size of the system which is not well suitable for wireless industries. Similarly, less distance between the MIMO elements leads higher coupling effect between the radiators that eventually low down the antenna performance. A balanced trade-off is required for the same [7]. In recent years, researchers have developed size miniaturized MIMO antenna with certain isolation techniques [8–12]. The defected ground plane or slotted ground plane could be isolation techniques. The dual port common ground-based MIMO antenna was claimed in Ref. [8]. In this paper, satisfactory isolation was achieved by slotted ground just the underneath of substrate. After certain experiments, the research scholars have developed complementary Split Ring Resonator(CSRR) kind of geometries over the ground plane surface [9]. Due to this ultra-wideband (UWB) antenna could be designed. These type of antenna are often utilized in object tracking and for finding the locations. The short pulse based methods are utilized by these antennas to achieve adequate resolution. This is because the short pulse-based structure is appropriate for multipath environments. UWB antennas also claim their potential body area networks (BANs) and wireless sensor networks (WSNs). In both applications, less transmission power is required [10,11]. Typically, the UWB antennas resonate between 3.1 and 10.7 GHz frequency range. This range covers many wireless applications. So it is extremely important to eliminate such bands that exhibit interference. Certain techniques were reported to nullify this interference [12,13]. The MIMO system performance could also be enhanced by utilizing a spatial diversity scheme. By facing the issues of co-channel interference and multipath fading, the UWB antenna system response could be improved. This is called as antenna diversity technique [14,15]. There are additional techniques were reported to increase the transceiver system. By incorporating more antenna elements at either transmitter or receiver signals the link reliability could be improved. Due to this, the receiver could be made secure, efficient, and robust. The combination of UWB and MIMO systems exhibits very less multipath fading which offers optimum transmission rate. The communication system becomes more reliable and with satisfactory transmission characteristics. Various shapes were introduced by the research scholars in the MIMO antenna system to receive an adequate response. A multiple radiator-based antenna with a pair of F upturned radiators at the upper surface was reported in Ref. [16]. This structure radiates for dual bands for WLAN communications. The antenna structure having slots through the surface improves the effective current distribution [17,18]. Similarly, a 4x4 radiator structure having L-shaped and split ring shape resonator geometries was presented in Ref. [19] for wide bandwidth response. The discussed research was further implemented with optimum isolation achievement. In this design, concentric square-shaped ring patches were incorporated [20].

The MIMO antenna system having circular polarization(CP) are highly demanded for many applications such as WLAN, WiMAX, Bluetooth, radar and RFID [21]. The transceiver system having circular polarization does not have the issue of mismatch polarization between the transmitter and receiver side antennas which results large spectral efficiency. The diversity of polarization could also be a technique which could solve the problem of mutual coupling for effective MIMO radiation. The literature claims very less MIMO geometries with circular polarization. Few research scholars have reported MIMO systems with dual radiating elements which utilized the property of polarization diversity [22]. In this geometry, the phase changes could be controlled by a metal strip over the ground surface. This metal strip is tenable for phase alteration. Similarly, in Ref. [23], a twin port circular polarized MIMO structure was reported in which the ground plane was having the cross branch designed to receive the adequate polarization diversity. MIMO structure having one radiating element over the top surface and the other element over the bottom surface was proposed in Ref. [24]. These two elements were for the CP and Linear Polarization (LP). The CP waves could be omitted by the top element and the LP waves could be omitted by the bottom element. The researchers have shown their significant efforts in engineering the various MIMO designs for optimum output parameter receptions. A size miniaturized CP, MIMO system was proposed for Off-body wireless communications [25]. Here the vertical part could be produced by the stub extensions from the ground geometry to the excitation line and the horizontal part could be produced by the current distribution over the width of the ground surface. Various isolation techniques have been incorporated in MIMO designs. A twin-port MIMO antenna for dual-band was presented where adequate isolation could be received by the incorporation of a line patch between the radiators [26]. Various new designs and geometries were experienced by the research scholars to restrict the isolation between the radiators, especially ion MIMO antennas. A serpentine structure as a decoupling element was adopted nearer the radiating geometries to receive satisfactory isolation. In claimed research, a similar antenna having a compact size was proposed for access point communications [27]. The positions of radiating elements play a vital role in enhancing the isolation. A MIMO system using dielectric resonator characteristics was claimed for wideband applications [28,29]. Here, the isolation has been optimized significantly using parasitic patches and diagonal positioning of the radiative elements. This dielectric resonator MIMO structure antenna exhibits circular polarization. In the MIMO system, a pair of conducting ports could be positioned opposite to each other instead of placing them orthogonal to each other. Also, if systematically, slots have been included, the desired response should be received. In Refs. [30,31], the authors have proposed such antennas for dual-band and 5G/Wi-Fi/WLAN applications. The channel capacity of ideal channel systems has been analyzed and presented in Ref. [32]. The authors

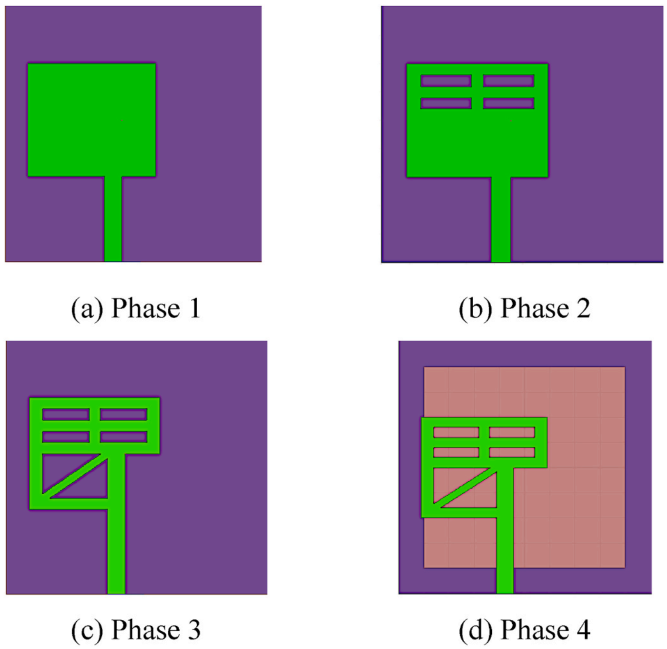


Fig. 1. Phase-wise primary antenna designing.

also explain how in MIMO system, the channel capacity is enhanced.

From the literature review, certain factors are important while designing a MIMO system. The literature review depicts, due to mutual coupling between the conducting patches, the performance of the antenna is significantly reduced. The optimum isolation is recommended to receive a satisfactory response. Various structural techniques should be adopted to have the isolation around 20 dB. However, other output parameters such as gain, efficiency, and radiation patterns should not get lower below expectations, so tradeoff among output parameters is highly required.

1.3. Proposed contribution and paper organization

The MIMO antenna with a partial ground plane having isolating geometry has been presented in this paper. The plus-sign-shaped conducting strips are introduced and united with the border-shaped partial ground plane. Due to this, the desired isolation is achieved. The finalized model depicts the optimum output parameters which are supported by the actual results. In the initial phase, the single radiating patch with systematic geometry development is presented and the parametric response has been discussed. Once the single antenna geometry has been identified, the similar remaining radiating patches are positioned orthogonally to each other to receive the desired response. In the result and analysis section, the simulated and measured responses are matched to claim the potential of the proposed system. Certain MIMO diversity antenna parameters were also carried out and presented. In the last, the proposed research is compared with the existing latest systems to prove its effectiveness. In the conclusion section, all findings and their cause are incorporated.

2. Single antenna development

The phase-wise development of the single element has been performed and illustrated in Fig. 1. Here, the figure sections a, b, c, and d represent phase 1, phase 2, phase 3, and phase 4 of a single antenna respectively. After performing phase-wise development of single antenna, the MIMO structure has been developed by replicating the similar design three times and placing them at 900 with each other at an appropriate distance. This structure has been presented in Fig. 2.

The detailed dimensions of the developed antenna are depicted in Table 1. The FR4 material has been utilized as a substrate material. The actual antenna is visible in Fig. 3. Fig. 3(a)–and (b) depict the MIMO model from top and bottom respectively. At the top surface, four MIMO radiating elements are visible. The SMA (Sub-miniature Version A) connectors are shouldered at the microstrip line feed. These connectors are semi-precision radio frequency connectors. At the bottom surface, ground geometry is visible with additional isolating square-shaped

Table 1
Antenna dimensions.

Parameter	Dimensions (mm)	Parameter	Dimensions (mm)
L_1	0.8	W_6	4.48
L_2	0.8	W	40
W_1	0.8	L	40
W_2	1	L_3	2.9
W_3	1.2	L_5	2
W_4	3.6	W_7	16
W_5	0.5	W_8	4

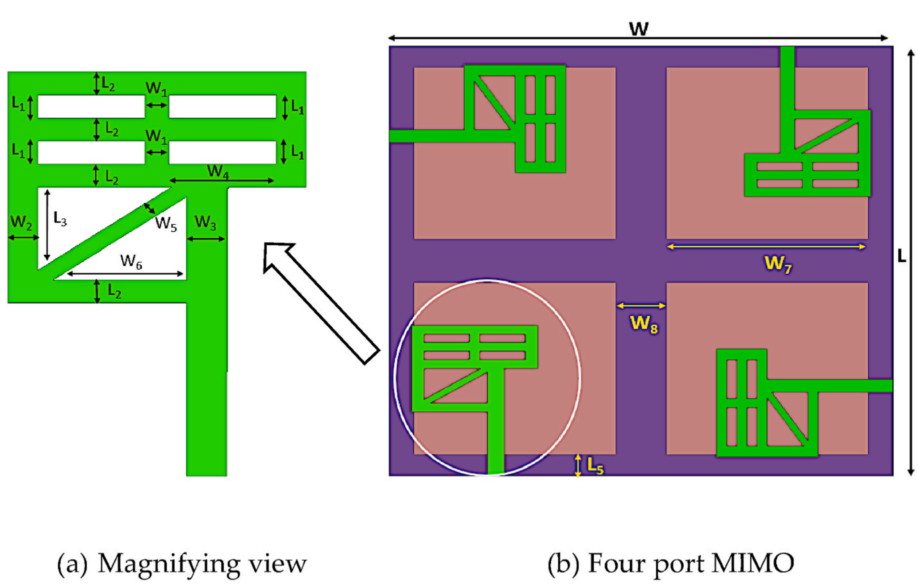
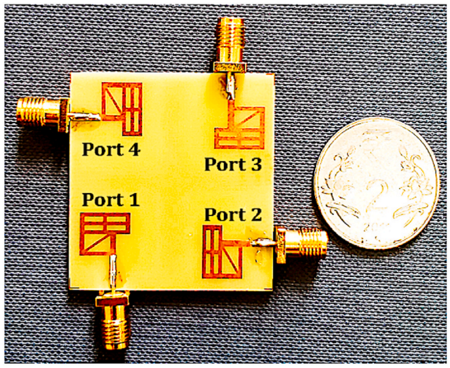
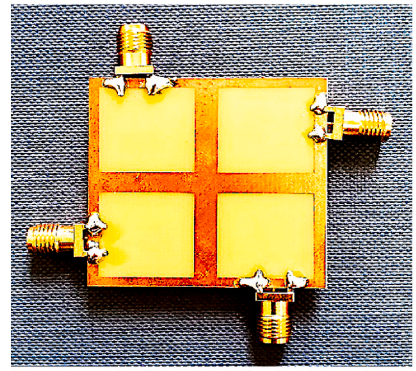


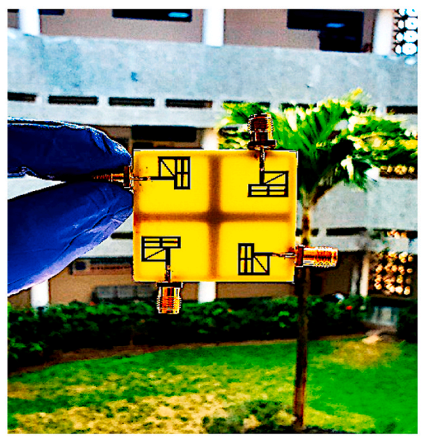
Fig. 2. Offered MIMO design.



(a) View from top



(b) View from back



(c) Semi-transparent view

Fig. 3. Actual MIMO model.

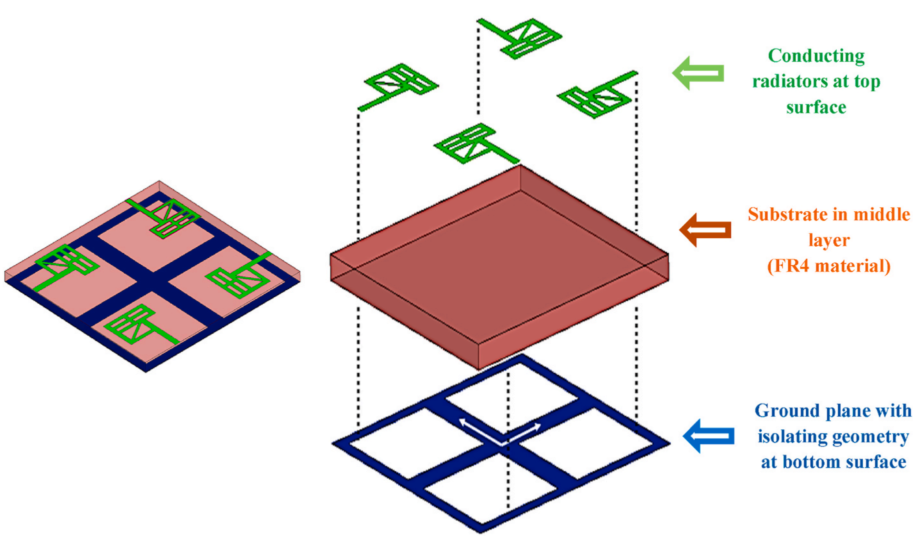


Fig. 4. Layer bifurcation of proposed MIMO structure.

strips. Fig. 3 (c) illustrates the semi-transparent view where radiators at the front and partial ground structure at the back are visible.

Fig. 4 depicts the various layers of presented geometry. The top layer consists four radiators having certain gap between them. The middle layer is a substrate having 1.6 mm height. The bottom layer consists a partial ground geometry. The additional square shaped design is

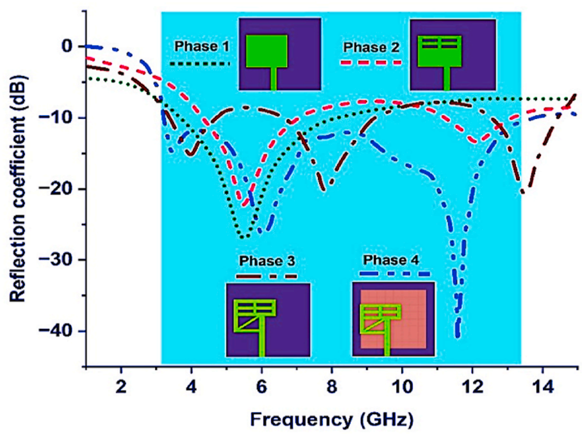


Fig. 5. Phase-wise response from single-element radiator.

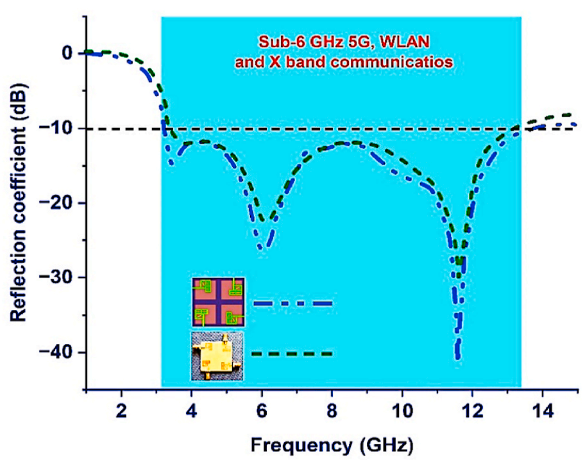


Fig. 6. Reflection coefficients Vs. frequencies.

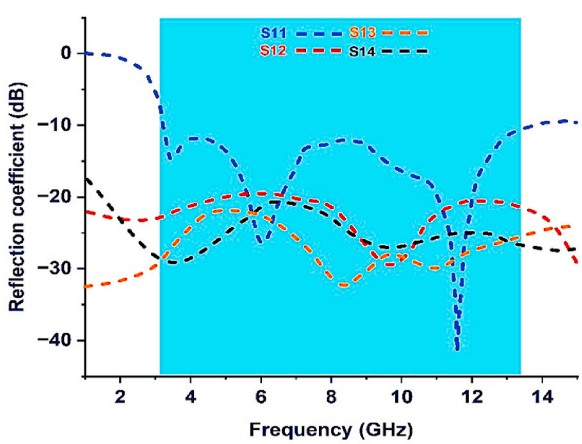


Fig. 7. Port isolation.

depicted to reduce the mutual coupling effect from nearby radiators.

3. Response and analysis

To understand the phase-wise geometry, the reflection coefficients were carried out and the comparison analysis among the various responses was performed. The comparison has been illustrated in Fig. 5. The results get improved by incorporating patch, creating slots, having

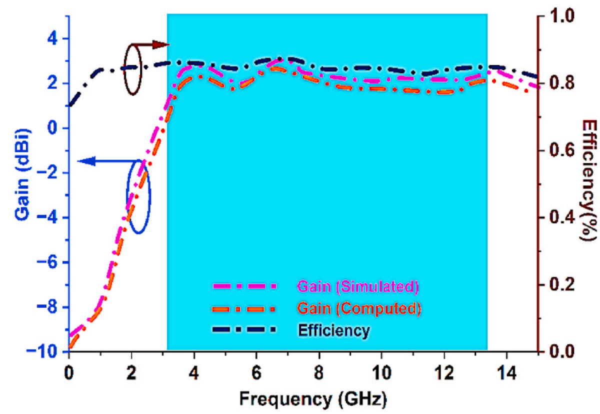


Fig. 8. Gain Vs. efficiency.

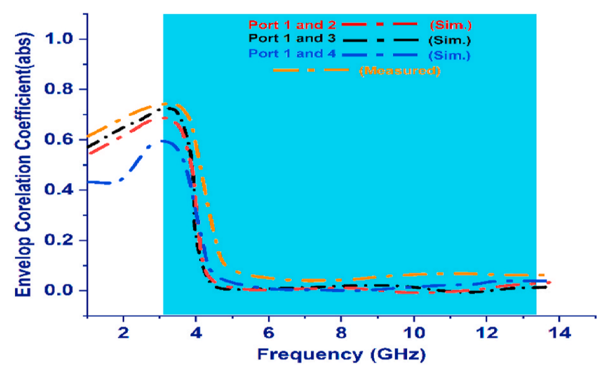


Fig. 9. ECC of MIMO antenna.

additional slot geometry and defected ground plane.

The response from the finalized MIMO model was obtained using simulation software. To find the agreement between the software generated result and the actual result, the graph has been drawn and depicted using Fig. 6. The fabricated MIMO antenna is similarly with reference to the simulated response. In the MIMO antenna system, the radiating ports should be kept at an appropriate distance to suppress the inter-coupling effect. Fig. 7 exhibits the port isolation. The careful analysis depicts the received isolation is less than −20 dB.

The presented design shows a promising gain of 2 dBi and efficiency above 80 % for a wide range of frequency bands. They are visible in Fig. 8.

4. MIMO performance analysis

Various performance parameters of MIMO structures such as CCL (Channel Capacity Loss), DG (Diversity Gain), and ECC (Envelope Correlation Coefficient) should be carried out to examine the overall operation of the MIMO antennas.

The ECC parameter plays a vital role in examining the performance of radiation patterns from radiative components of MIMO. ECC indicates the correlation effect between the radiators hence lower ECC depicts the lesser effect on the other components while working separately which eventually increases the efficiency of overall performance. To ensure the adequate operation of individual antenna, the ideal value of ECC of any MIMO structure in wireless communication applications is below 0.5 [26]. The ECC could be counted from the scattering parameters using equation (1). The typical value of ECC is lower than 0.004

$$ECC = \frac{\left|S_{11}^{*}S_{12} + S_{21}^{*}S_{22}\right|^{2}}{\left(1-\left|S_{11}\right|^{2}-\left|S_{21}\right|^{2}\right)\left(1-\left|S_{22}\right|^{2}-\left|S_{12}\right|^{2}\right)}, \tag{1}$$

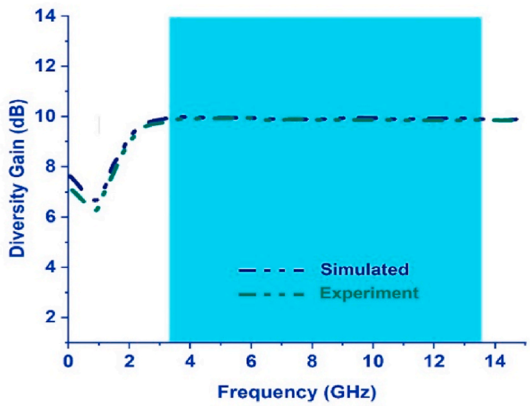


Fig. 10. Diversity gain of MIMO antenna.

Where, S_{11} is the input reflection coefficient, S_{21} forward transmission coefficient (from port 1 to 2), S_{12} is the reverse transmission coefficient (from port 2 to 1), S_{22} is the output reflection coefficient.

The software generated and actual values of ECC are illustrated in Fig. 9. The value is below 0.5 which indicates the optimum isolation between the radiators.

The effective diversity could be described using Diversity Gain (DG). The DG value could be obtained from ECC value. The relation between DG and ECC could be found using the following equation (2). The ideal value of DG is 9.98 dB.

$$DG = 10 \times \sqrt{1 - |ECC|} \tag{2}$$

The value of DG (Diversity Gain) from scattering parameters of the presented MIMO structure is depicted using Fig. 10. In the targeted ultra-wideband, the value of DG is approximately 10 dB which indicates the strong MIMO response.

The Mean Effective Gain (MEG) basically the generated power of the diversity antenna to the power received by the antenna which is omni-directional in nature. The value of MEG could be found using equation (3). Fig. 11 (a) shows the MEG graph. The typical value of MEG lies between 3 dB and −12 dB.

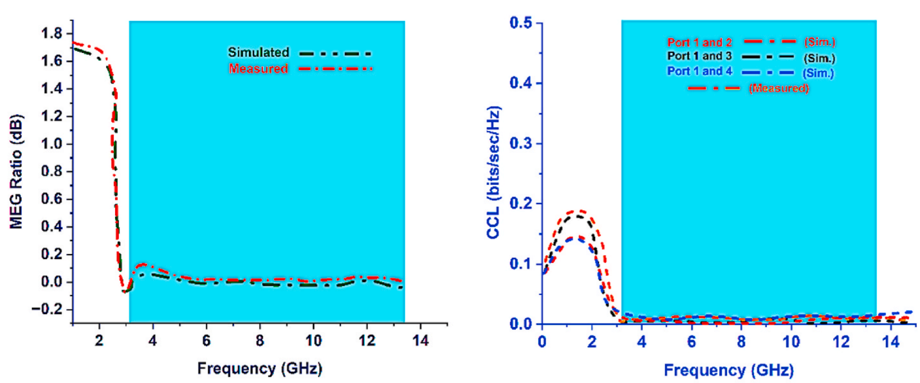
$$MEG = 0.5\left(1 - \sum_{j=1}^{M} |S_{ij}|^2\right) \tag{3}$$

Fig. 11 (b) displays the Channel Capacity Loss (CCL). The CCL value for targeted frequencies is less than 0.1 bits/sec/Hz. The allowable CCL value is 0.4 bits/sec/Hz. The channel capacity loss could be obtained from the following equations [38].

$$C_{loss} = log_2\, det(\psi^R) \tag{4}$$

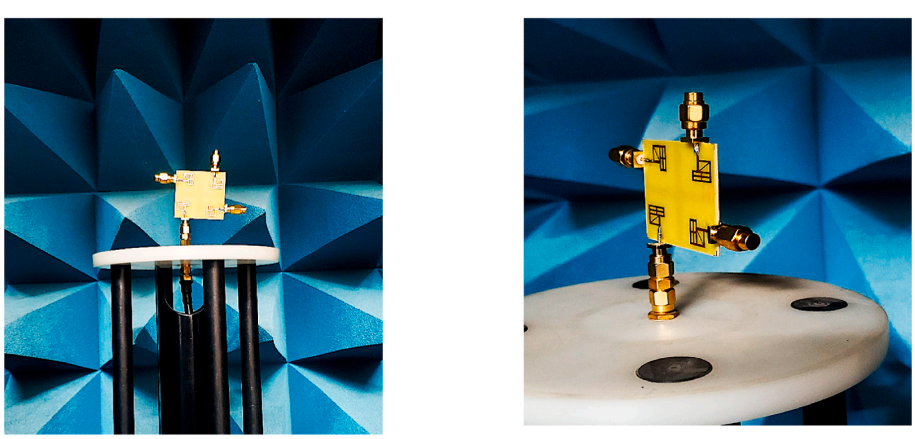
Where, ψ^R is the matrix of correlation of the receiving side antenna which is expressed as:

$$\psi^R = \begin{pmatrix} \psi_{ii} & \psi_{ij} \\ \psi_{ji} & \psi_{jj} \end{pmatrix} \tag{5}$$



(a) (b)

Fig. 11. (a) Mean Effective Gain (b) Channel Capacity Loss of MIMO model.



(a) Antenna mounting (b) Port termination

Fig. 12. Antenna testing inside anechoic chamber.

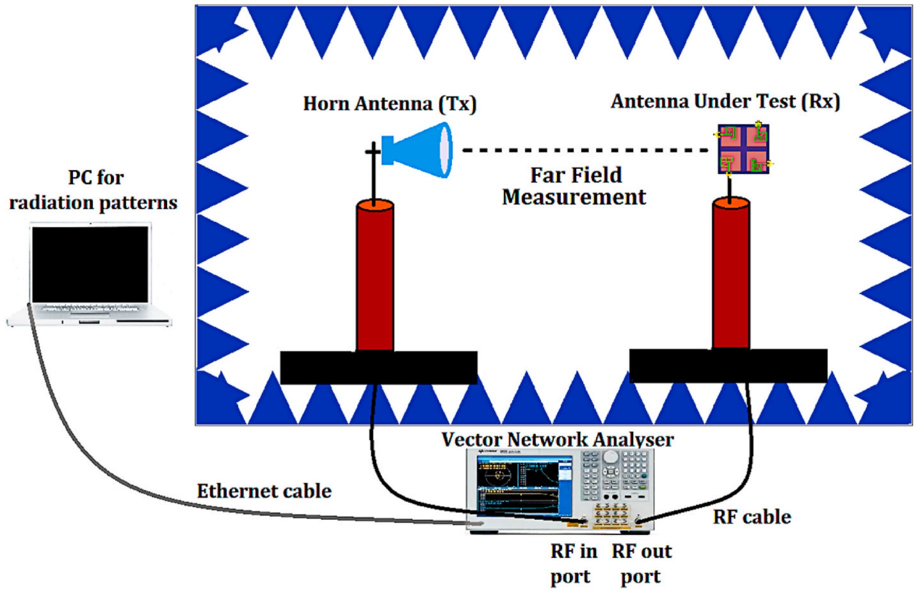


Fig. 13. Antenna measurement diagram.

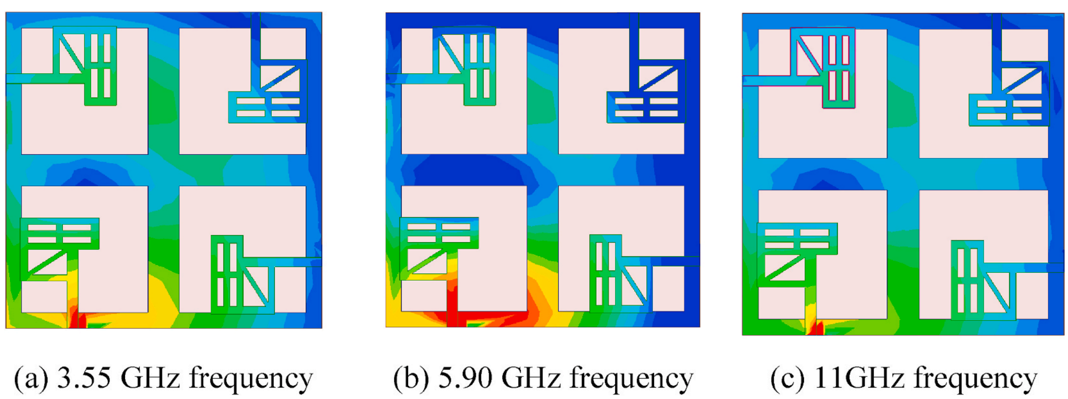


Fig. 14. Current distribution.

$$\psi_{ii} = 1 - \left(|S_{ii}|^2 + |S_{ij}|^2\right) \quad (6)$$

$$\psi_{ij} = -\left(S_{ii} * S_{ij} + S_{ji} * S_{jj}\right) \quad (7)$$

$$\psi_{ji} = -\left(S_{ji} * S_{ji} + S_{ii} * S_{ij}\right) \quad (8)$$

$$\psi_{jj} = 1 - \left(|S_{jj}|^2 + |S_{ji}|^2\right) \quad (9)$$

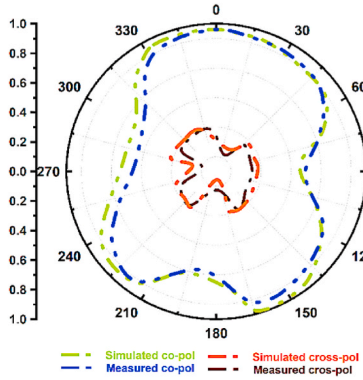
Fig. 12 (a) illustrates the antenna set-up inside anechoic chamber. The anechoic chamber is having 5 m × 5 m x 5 m in size. The four port MIMO is fixed at one end using SMA connector with a chamber terminal whereas the other three connectors are fixed with 50 Ω load terminator. The load terminator is visible in Fig. 12 (b).

Fig. 13 depicts the measurement setup diagram. The horn antenna is fixed as a transmitter antenna inside an anechoic chamber. The proposed MIMO antenna is connected at the receiver end as the receiver antenna. The sufficient far field distance is fixed to receive the desired response. Both the antennas (horn antenna and proposed antenna) are connected to a vector analyzer where the return loss graph is observed. The vector network analyzer is further connected to the PC(Personal Computer) via an ethernet cable. The antenna under test is moving 360° in clockwise direction inside the anechoic chamber. For the mentioned angles, the gain values could be captured and a 2-dimension radiation pattern has been generated in the PC. The current distribution over the surface has been illustrated in Fig. 14. Port 1 is excited for targeted frequencies. Similarly, the remaining ports could be excited to receive the other current distributions. Fig. 15 exhibits the software-generated and measured normalized 2D radiation patterns one of the radiators is excited for the targeted frequencies. The other radiators are connected with a 50 Ω load. It is observable that the radiation figures are having omni direction for simulated and measured values.

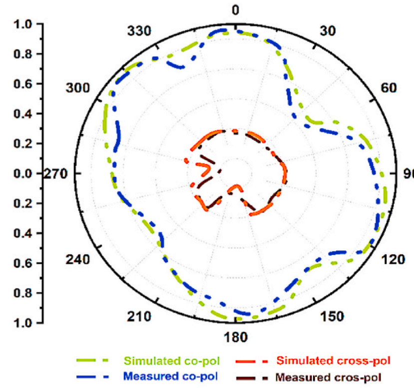
The potential of the proposed MIMO model has been verified with the existing MIMO antennas. The comparison is given by Table 2. The proposed structure is compared based on output parameters such as antenna size, no. of radiators, impedance bandwidth, ECC, DG, MEG etc. The close observation depicts that the presented antenna gives adequate response for utilization in targeted applications.

5. Conclusion

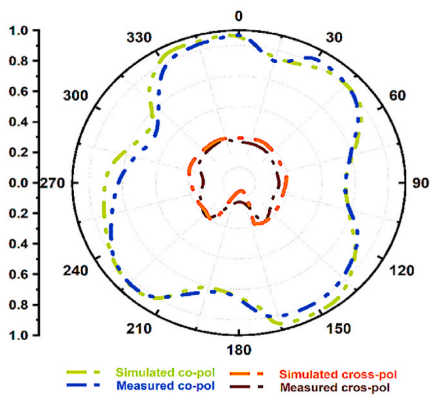
A miniaturized low-profile Ultra-wide band MIMO antenna covering the frequency range from 3.20 GHz to 13.40 GHz has been analyzed, fabricated, and proposed. The targeted resonances were achieved by the geometry containing cross section of vertical and horizontal strip lines and diagonal strip line. The partial ground plane with isometric geometry plays a vital role to receive the wide band response and satisfactory isolation respectively. The optimum isolation of 20 dB has been received



(a) 3.55 GHz frequency



(b) 5.90 GHz frequency



(c) 11GHz frequency

Fig. 15. Normalized 2D radiation patterns.

Table 2
Comparison of output parameters from proposed MIMO and existing structures.

Ref.	Antenna Size (mm)	Number of radiating ports	Impedance Bandwidth (GHz)	Isolation (dB)	ECC	DG (dB)	MEG
[33]	60 ×	4	7.9	>20	<0.004	–	–
[34]	45 × 45	4	8.6	>17	<0.005	9.39	0.6
[35]	37 × 46	4	9.5	>20	<0.005	9.7	0.55
[36]	45 × 45	4	7	>19	<0.045	–	–
[37]	47 × 47	4	8	>20	<0.005	–	–
[38]	80 × 80	4	8.4	>20	<0.001	–	–
[39]	80 × 80	4	8.32	>15	<0.015	>9.90	–
[40]	58 × 58	4	10.5	>22	<0.008	–	–
[41]	94 × 94	2	11.25	>14	<0.005	–	–
[42]	100 × 50	2	9.95	>20	<0.005	–	–
[43]	97 × 27.69	4	9.90	>18	<0.003	>9.80	0.7
Proposed	40 x 40	4	10.20	>20	<0.005	>9.90	–

with a wide bandwidth of 10.20 GHz. The machine-generated results and the software-generated results have having decent correlation. A moderate gain of 2 dBi with 80 % efficiency were reported. Apart from reflection coefficients, the other primary factors like ECC, MEG, CCL, DG and radiation patterns were analyzed to judge the MIMO antenna performance. The actual analysis and radiation patterns offer solutions for miniaturized sub 6 GHz diversified antenna for sub-6 GHz 5G, WLAN, and X band communications. The MIMO antenna is a fundamental unit for modern wireless communication applications with higher data rates, enhanced signal quality, and improved reliability in various applications like point-to-point links, cellular networks, and wireless LANs. The proposed MIMO systems have global applications such as the Internet of Things (IoT), telecommunications, automotive radars, remote sensing, radio astronomy, and the military.

CRediT authorship contribution statement

Killol Pandya: Writing – original draft, Methodology. **Trushit Upadhyaya:** Formal analysis, Conceptualization. **Upesh Patel:** Investigation. **Vishal Sorathiya:** Resources. **Aneri Pandya:** Visualization. **Ahmed Jamal Abdullah Al-Gburi:** Writing – review & editing, Validation, Supervision, Project administration. **Mohd Muzafar Ismail:** Funding acquisition, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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