A cutting-edge Wide-Band MIMO Antenna for Modern Wireless Applications

Sanjay Chouhan, Debendra Kumar Panda, Sarthak Singhal, and Jitendra Yadav

***Abstract*—The present work explores the insights of a design which is defined as an octagonal geometry based four port wide-band MIMO antennas for wireless systems. The isolation essentialities have been considered through the parasitic elements (PE) with T-shaped isolation structure for isolation boost. The antenna under consideration is optimized to achieve the best MIMO performance parameters. It has functional band of 2.16-4.30 GHz and the antenna fabricated on substrate size of 60.0 X 76.0 mm². The gain 3.44 dBi, envelop correlation coefficient (ECC) < 0.03, and mean effective gain (MEG) ≤ -2.90 dB are achieved. The total active reflection coefficient (TARC) bandwidth is found 1.35 GHz. The specific absorption rate and channel capacity loss are evaluated, and both found to be within acceptable limit recommended by international telecommunication union (ITU). The results obtained through the proposed design are found to be within the acceptable limits of stability for effective communication system.**

***Index Terms*— Diversity, ECC, MIMO antenna, TARC Bandwidth.**

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I. Introduction

Wireless communication technologies are changing rapidly and need continuous intervention from the researcher's side. The growth of contemporary wireless applications, including 3G, 4G and 5G networks, Internet of Things (IoT) gadgets, and high-speed data transfer, has a need for extremely effective and adaptable antenna systems [1]. A radical expansion in wireless communication has been observed in recent years viz. continuous exploration in designing specific antennas capable of adapting various frequencies and providing dependable performance in a wide range of applications [2]. Maintaining great signal quality is a challenge for antennas designed to handle wider frequency bands [3]. Wide-Band MIMO antennas are a game-changing advancement in wireless communication technology, promising improved performance and adaptability in a variety of contemporary wireless applications [4]. These antennas can send and receive numerous data streams simultaneously thus greatly enhancing communication efficiency and data throughput [5].

The compact dimensions of these MIMO systems lead to higher coupling of elements, which results into degradation of system's overall performance. In the available literature [1]-[34], researchers have reported multiple ways to minimize mutual coupling or to enhance inter port isolation. Some of those techniques are split ring resonator (SRR), coupling networks, de-coupling isolating structures, PE, metamaterials, slot loaded radiator or ground plane, modified feed-line, modified ground plane, modified radiator, cross-coupled semi loop (CCSL), flag shaped stub, tunable network etc. All the above discussed geometries have either narrow bandwidth or large dimensions. Thus, various techniques used for isolation and capacity enhancement have been reported in literature in last decade. A few MIMO antennas design tried to enhance capacity and, isolation and identification of radio frequencies by leaky-wave radiator for 2.45-GHz [6]. In addition, DGS fulfilled the requirement of isolation up to some extend by disturbing or changing the direction of surface current [7]. The change in current direction fosters improved isolation by cancelling the inner element currents. The same attributes can also be achieved by polarization diversity [8]. Some of the applications require appropriate isolations for the optimum performance such as 2 x 2 MIMO antennas for USB application [9]. In compact antenna design isolation can be improved by hybrid balun circuit [10]. Apart from this the isolation achievement in dual band antenna for all bands has put challenges to the research community [11]. Sometimes the slotting in antenna has emerged out as one of the important techniques for isolation enhancement [12]. The isolation technique improves the isolation but it also shifts the resonating frequency [13]. Thus, the placement of isolating elements requires lot of analysis and precautions [14]-[15]. The CSRR structure is also instrumental in producing good isolation among antenna ports [16]. Optimum isolation in compact antenna is also one of the complex tasks in compact antennas [17]-[18]. Presently, some of the techniques [19]-[20] for MIMO antenna isolation enhancement have become obsolete and new techniques and tactics like metamaterial, hybrid ring, and resistive elements for single band and multiband applications are in developing phase [21]-[22]. Sometimes the shape of antenna also gives better results from isolation point of you, like use of some serpentine structure, some non-mathematical structure etc. [23]-[24]. The non-mathematical structure is generally generated by hit and trial method

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and on the basis of trail the performance of the antenna is observed [25]-[26]. Flag shaped stub, dual feeding, tunable network, fractal antenna and CE radiators had also been capable of in achieving good isolation among antenna elements [27]-[28].

Though a great deal of study has been done and is documented in the literature to attain optimal isolation, efforts are always being made to use novel approaches in order to obtain improved results [29]–[30]. The goal of the suggested study is to minimize port coupling and arrive at the ideal MIMO parameter value. Good isolation, higher efficiency, a wide bandwidth, and optimal gain are a few of the goals of the suggested work that are successfully met. To improve isolation, the current work uses a modified feeding strategy, PE, partial ground approaches, and a folded T-shaped structure.

The present work offers a Wide-Band Multiple-Input Multiple-Output (MIMO) antenna that is specifically engineered to satisfy the stringent requirements of modern wireless technologies. This study examines the design, creation, and characterization of a cutting-edge Wide-Band MIMO antenna that not only addresses these changing issues but also helps to improve the infrastructure for wireless communication. The complexity of this antenna's design, its amazing wide-band capabilities, and its potential to revolutionize contemporary wireless applications are all covered in the parts that follow. This study marks a significant advancement in the search for antennas that can keep up with the rapidly changing wireless communication environment.

Four uniformly shaped elements are used in this design for wideband 2.16–4.3 GHz applications.

The numerous MIMO antenna performance characteristics are examined and measured to provide the best possible performance of the MIMO antenna design. This study proposes an full octagonal shaped antenna for wireless applications using MIMO techniques. The reported antenna geometry offers several advantages, including a broader working bandwidth, minimal ECC, and compact dimensions. The antenna geometry is created, studied, and optimized using the CST MWS simulator and fabricated on FR4 substrate. The simulated results are verified by measured results. The design antenna uses two isolation methods for upgradation of isolation among antenna ports.

II. Antenna Design, Methodology And Material

The design and construction of antennas serve as crucial pillars upon which the framework of contemporary connectivity is formed in the ever-expanding field of wireless communication. The search for effective and cutting-edge antenna solutions has taken on a level of significance never before seen as our world grows more and more dependent on smooth wireless connectivity [37]. "Antenna Design and Methodology" is a thorough investigation of the complex field of antenna engineering, revealing the ideas, procedures, and methodologies that guide the development of antennas for a variety of uses.

The frequency range, intended application, climatic circumstances, and design requirements are only a few of the variables that influence the material choice for antenna fabrication [38]. Electrical conductivity, dielectric characteristics, mechanical strength, cost, weight, and the unique needs of the antenna design and application all play a role in the material choice. To choose the best materials for their antenna projects, engineers and scientists frequently run simulations, verify their hypotheses, and optimize their choices. A typical substrate for PCB-based antennas is FR-4. It is affordable, widely accessible, and appropriate for lower-frequency applications. The electronics industry uses FR-4, an abbreviation for "Flame Retardant 4," extensively, particularly for printed circuit boards (PCBs). It is renowned for its mechanical tough-ness, flame-retardant qualities, and electrical insulating qualities.

The proposed prototype is demonstrated in Fig. 1 and its optimized parameters size is given in Table 1. The fabricated material is chosen as FR4 having thickness, permittivity and loss tangent of 1.6 mm, 4.4 and 0.02 respectively. Fig. 2 explains the design stages adopted for antenna element. The MIMO antenna geometry consists of four identical copies of a stepped microstrip line fed octagonal monopole with partial ground plane. Two elements are

Table 1.
Optimized Antenna Dimensions In Mm.

Design Parameter	a	b	c	d	e	f	g
Size	60	76	3.30	9.90	3.26	5.40	1.04
Design Parameter	h	i	j	k	w	m	n
Size	2.92	12.62	27.02	0.24	10.80	10.80	5.4
Design Parameter	o	p	q	r	r2		
size	0.62	20.43	0.48	1.02	9.71		

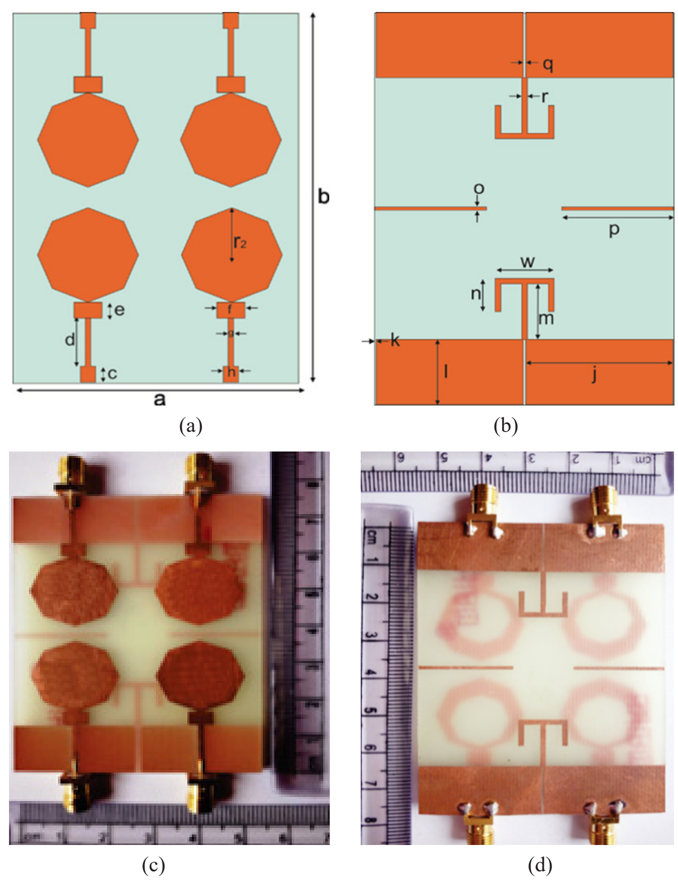


Fig. 1. Designed MIMO antenna (a) schematic of proposed antenna front view (b) schematic back view (c) fabricated picture front (d) fabricated picture back.

arranged adjacent to each other (spatial diversity configuration) and remaining two elements are placed in mirror configuration to the first two elements (mirrored along x-axis). To increase the isolation between the adjacent ports, folded T-shaped stubs are used to connect the adjacent ground planes. In case of directly opposite ports, parasitic elements are used. The total footprint for the designed MIMO antenna substrate is 60×76 mm^2.

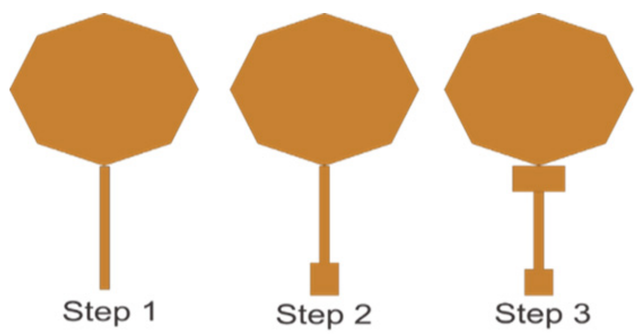


Fig. 2. Design steps diagram of antenna.

III. Results And Discussion

The design steps reflection coefficients are illustrated in Fig. 3. One can observes that the design stages 1 to 3 have an operating frequency range of 3.40-5.50 GHz, 3.40-4.40 GHz, and 3.10-4.60 GHz respectively. The folded T-shaped isolating structure gives isolation more than 12 dB and it's also connecting both ground plane. The isolation between the directly opposite ports and diagonally opposite ports is observed to be more than 12 dB and 16 dB respectively. In addition to isolation enhancement, folded T-shaped stubs and parasitic elements resulted into shifting of frequency lower side while higher side it remains same, thus results in wider frequency band. The presented results also show the frequency band is significantly higher in the S-parameter with T-shaped structure than in the one without. The frequency moves from 3.80 GHz to 2.40 GHz, and the whole operating band from 3.1-4.6 GHz to 2.16-4.30 GHz, leading to antenna shrinkage.

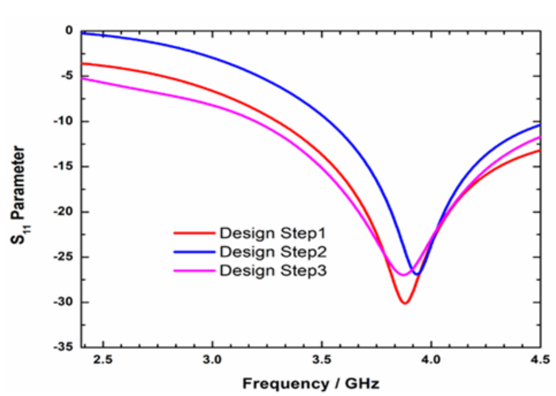


Fig. 3. Design steps results using S_{11} Parameter

The return loss and isolation with and without use of PE and folded T-shaped stub are illustrated in Fig. 4. It shows the better isolation and return loss using PE element and T shaped stub, while without parasitic element and T-Shaped stub (WPE&T) has good isolation between port 1-4 only. The presented results clear the use and effects of PE and T-Shaped isolating structure.

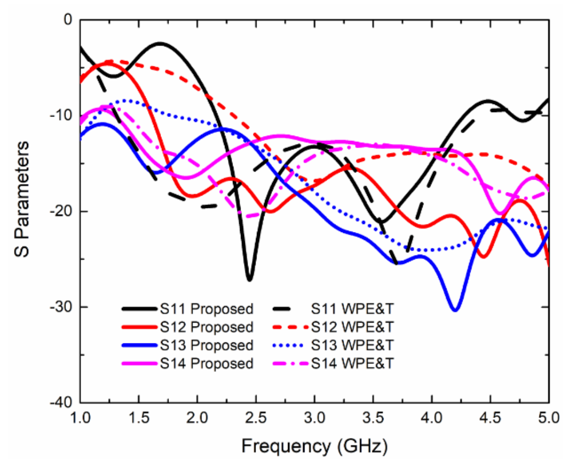


Fig. 4. Scattering parameters with and Without PE & T-shaped Stub (WPE&T).

The outcomes of the measured and simulated S-parameters are displayed in Fig. 5. The frequency range is 2.16 GHz to 4.3 GHz. The slight variation between the simulated and measured S-parameters may be seen. The reported findings further demonstrate the good isolation performance of the suggested design across the whole band.

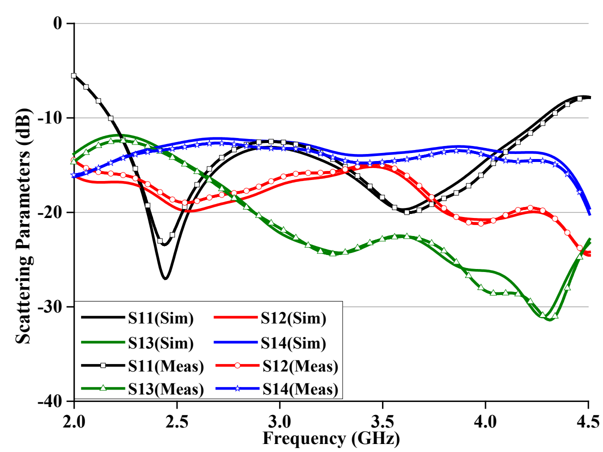


Fig. 5. Simulated and measured Scattering parameters

Surface current distribution measures the amount of current on the surface. Fig. 7 depicts the distribution of current on the antenna's surface at both resonances. When antenna port 1 is energized, a large amount of power is getting coupled to other ports in non-existence of folded T-shaped stubs and PE (WPE&T). In the presence of folded T-shaped element and PE, the amount of power getting coupled to other ports is significantly reduced. The maximum surface current due to port 1 is either cancelled or transfer in other direction due to the both isolating elements. The both isolating elements provide good improvements in isolation as compare to design without PE&T.

Fig. 6 displays the S-parameter data, which indicate a higher side shifting of the resonant frequency at 3.7 GHz. The isolation is poor as compare to non-connection ground thus the design with non-connecting ground is considered.

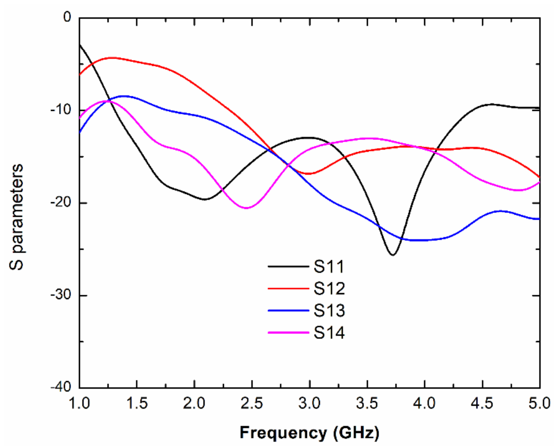
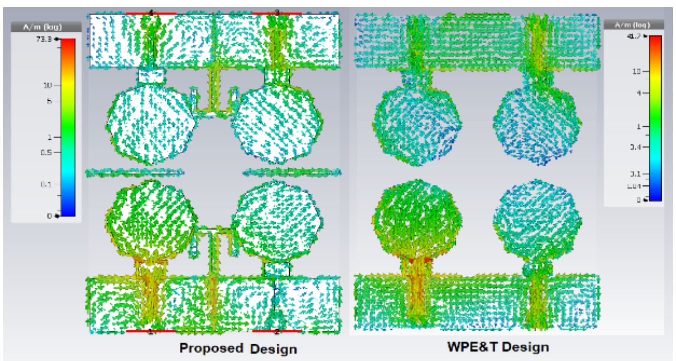
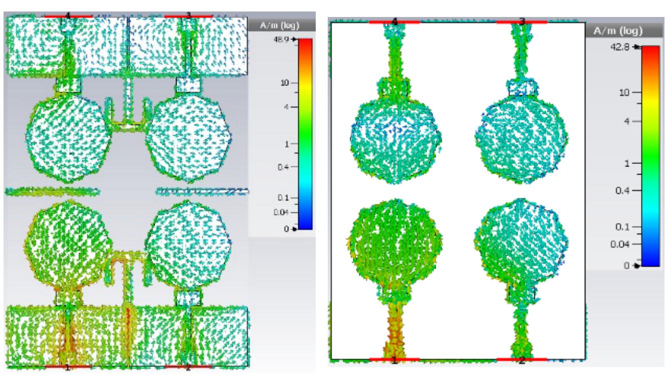


Fig. 6. Simulated Scattering parameters for connected ground.



(a) 2.40 GHz

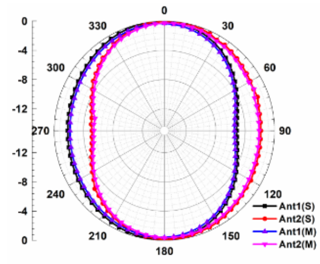


(b) 3.59 GHz

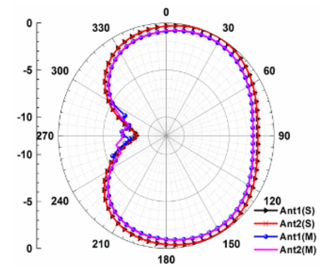
Fig. 7. Graphical picture of surface current distribution.

The far field properties of any antenna for desired applications are one of the deciding parameters for effective design. The polar plot of E/H field is presented in Fig. 8. The polar plot shows the graphical behavior of distribution of energy. The major lobe radiation is found in the direction of 354°. Similarly polar plot of H-field shows the main lobe direction of 25°. The simulation and measured environment are slightly different thus small changes can be observed in both radiation patterns.

The gain shows the radiation ability of antenna in given direction. The gain and efficiency are the two basic parameters which show the suitability of antenna in outside world. The gain and efficiency plot in the whole band are presented in Fig. 9. The gain of the antenna varies from 2.35-3.44 dBi. The simulated radiation efficiency ranges between 83 to 93%.



(a)



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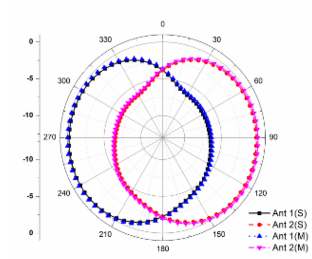
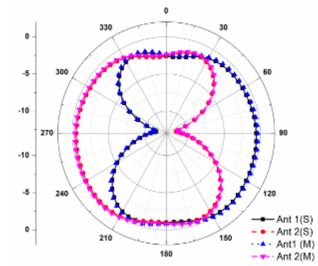


(c)



(d)

Fig. 8. Far-field characteristics (a) E-field at resonance 2.40 GHz (b) H-field at resonance 2.40 GHz (c) E-Field at resonance 3.59 GHz (d) H-field at resonance 3.59 GHz

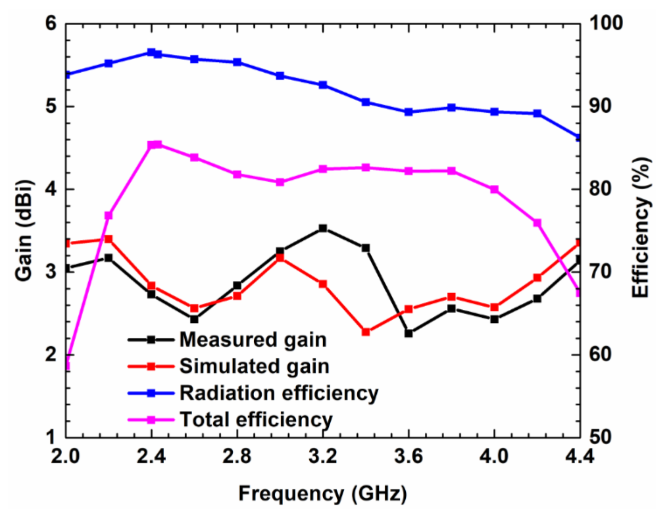


Fig. 9. Gain, total efficiency and radiation efficiency of proposed antenna.

One of the important performance parameters for any multi-element antenna system is its ECC characteristic. The Envelope Correlation Coefficient (ECC) can also be used to study isolation between the MIMO antenna's ports. A low ECC value—ideally zero—indicates greater isolation between the MIMO antenna's ports.

ECC plays a critical role in this regard. The calculation of ECC is done by given equation (1):

$$|\rho_e(i,j,N)| = \frac{\left|\sum_{n=1}^{N} S_{i,n}^{*} S_{n,j}\right|}{\sqrt{\left|\prod_{k(=i,j)} \left[1 - \sum_{n=1}^{N} S_{i,n}^{*} S_{n,k}\right]\right|}} \quad (1)$$

Where, total number of antennas are N and the antenna elements are i and j.

The ECC values calculated from scattering parameters are shown in Fig. 10. The ECC is < 0.03. It indicates the good diversity management. The good ECC is the guaranty of better performance in MIMO antenna.

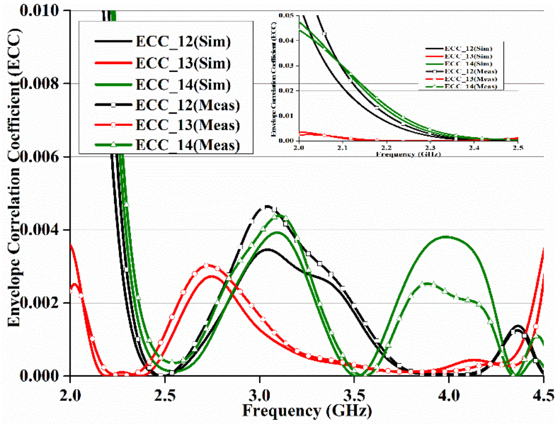


Fig. 10. Envelop correlation coefficient results.

Some indoor-outdoor characteristics of antenna are evaluated by parameter mean effective gain (MEG) in wireless channels. The MEG diversity parameter holds significance for MIMO antennas as it measures the proportion of power received by the MIMO antenna relative to the power received by the isotropic antenna.

The MEG determines average received signal strength of individual antenna. It is observed for both indoor applications at XPR= 6 dB and outdoor applications at XPR = 0 dB using equations (2) and (3).

$$\mathrm{MEG}_i = \frac{P_{\mathrm{rec}}}{P_{\mathrm{inc}}} = \oint \left[\frac{\mathrm{XPR}\cdot G_{\theta i}(\Omega) + G_{\phi i}(\Omega)\cdot P_{\phi}(\Omega)}{1+\mathrm{XPR}}\right] d\Omega, \tag{2}$$

$$\mathrm{MEG}_i = \int_0^{2\pi}\int_0^{\pi}\left(\frac{\mathrm{XPR}}{1+\mathrm{XPR}}\mathrm{G}_\theta(\theta,\emptyset)\mathrm{P}_0(\theta,\emptyset) + \frac{1}{1+\mathrm{XPR}}\mathrm{G}_\emptyset(\theta,\emptyset)\mathrm{P}_\emptyset(\theta,\emptyset)\right)\sin\theta\, d\theta\, d\emptyset \tag{3}$$

For evaluation of MEG, two mediums are considered i.e. isotropic and Gaussian. It is examined for certain cross polarization ratios (XPRs). The result is calculated for 0 and 6 dB of XPR. The MEG value is shown in Fig. 11 and listed in Table 2. MEG has a constant value of -2.90 dB for the isotropic case with XPR 0 dB, whereas it ranges between -4.1 dB and -4.8 dB for XPR 6 dB. Similarly, in the Gaussian situation, with XPR 0 and 6 dB, MEG has -3.10 to -4.10 dB and -6.10 to -7.0 dB. The MEG data at resonance are also presented in the table.

Table 2. MEG Of Isotropic And Gaussian Mediums

Resonance Frequency (GHz)	Medium			
	Isotropic (XPR in dB)		Gaussian (XPR in dB)	
	0	6	0	6
2.40	-2.94	-4.32	-4.12	-7.1
3.59	-2.94	-4.21	-3.92	-6.3

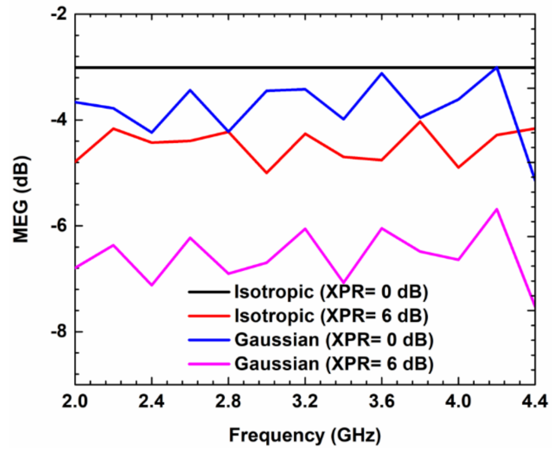


Fig. 11. MEG for Isotropic and Gaussian medium.

TARC is also a vital diversity parameter for multi element antenna system and array. The total return loss of the MIMO antenna array is known as TARC. TARC can be expressed mathematically as the square root of total incident power divided by the square root of total reflected power.

The TARC parameter is measured by Equations (4) and (5)

$$\Gamma = \sqrt{\frac{\text{received power} - \text{transmitted power}}{\text{received power}}} \tag{4}$$

$$\Gamma_a^t = \frac{\sqrt{\sum_{i=1}^{N}|b_i|^2}}{\sqrt{\sum_{i=1}^{N}|a_i|^2}} \tag{5}$$

Where [S]*[a] = [b]. The scattering matrix [S], excitation vector [a] and [b] are reflecting vector corresponding.

The complete return-loss of MIMO system is represented by TARC. It relates the incident power to the outgoing power in MIMO antenna. Fig. 12 displays the TARC curves at various excitation angles. The TARC bandwidth of 1.30 GHz is observed with best combination of 150°, 180° angles. The TARC bandwidth at different excitation angels is given in Table 3.

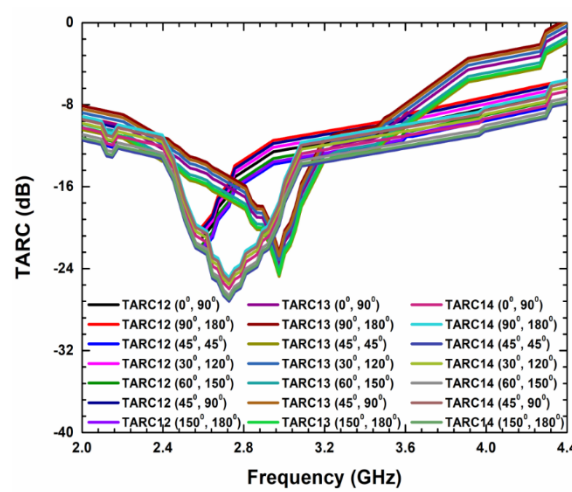


Fig. 12. TARC for different excitation angels.

TABLE 3. TARC BANDWIDTH FOR DIFFERENT EXCITATION ANGLES

Excitation angles (port 1-2, 1-3, 1-4)	Bandwidth (GHz) (port 1-2)	Bandwidth (GHz) (port 1-3)	Bandwidth (GHz) (port 1-4)
0^0, 90^0	1.1	1.2	1.1
90^0, 180^0	1.3	1.1	1.2
45^0, 45^0	1.2	1.2	1.2
30^0, 120^0	1.1	1.1	1.0
60^0, 150^0	1.0	1.1	1.1
45^0, 90^0	1.1	1.2	1.1
150^0, 180^0	1.3	1.35	1.38

The CCL and diversity gain also calculated for the proposed antenna. The Diversity gain (DG) result is specified in Fig. 13. The CCL is very important for message rate evaluation. The CCL limit is 0.4 bits/s/Hz [25]. In the suggested design, CCL is less than 0.4 b/s/Hz across the whole band. The CCL results are shown in Fig. 14.

DG can be computed by equation (6) which shows it is affected by correlation (ρ_e).

$$G_{DG} = 10 \times \sqrt{1 - |\rho_e|^2} \tag{6}$$

The calculation of CCL has been done by using the following given equation (7). It can be used to monitor system performance decline.

$$CCL = -\log_2 det(\eta) \tag{7}$$

where η is the correlation matrix

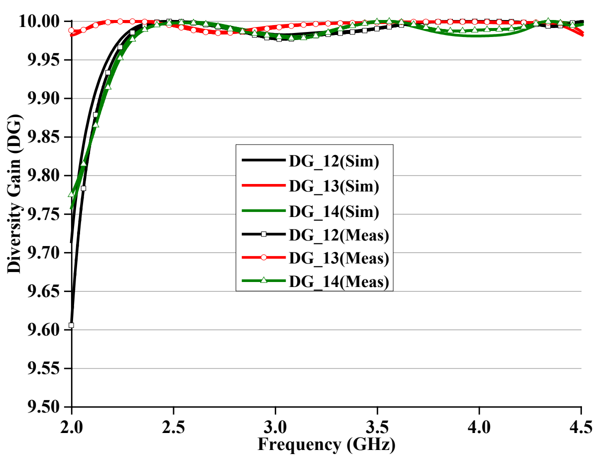


Fig. 13. DG of proposed MIMO antenna.

The amount of electromagnetic radiation (EM radiation) that communication antennas in wireless devices are permitted to create is measured by the specific absorption rate, or SAR.

Since the antenna is planned for wireless-applications, therefore the evaluation of its SAR is very necessary. Fig. 15 presents the human head model with proposed antenna placed near to head. The SAR values are calculated by averaging method IEEE/ICE 62704-1. As per ITU standard the value of SAR cannot be more than two watts per kilogram.

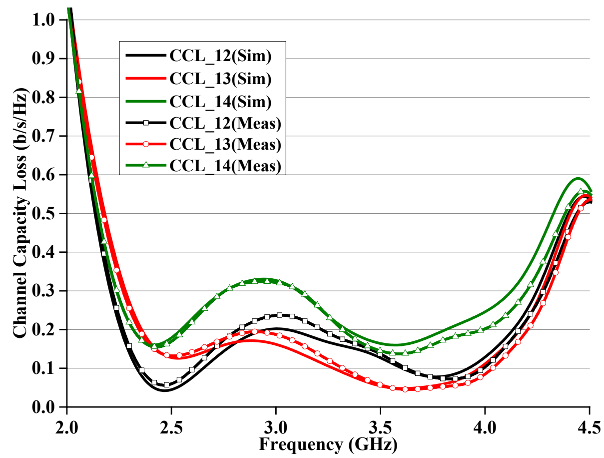


Fig. 14. results of CCL for proposed antenna.

Fig. 16 illustrates that the maximum SAR values near the human head for 10g and 1g are 7.52 nW/Kg and 8.83 nW/Kg respectively.

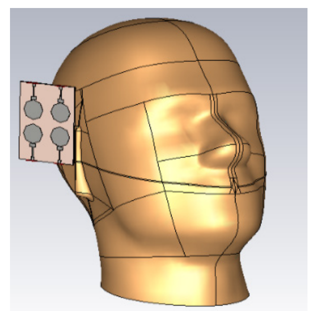
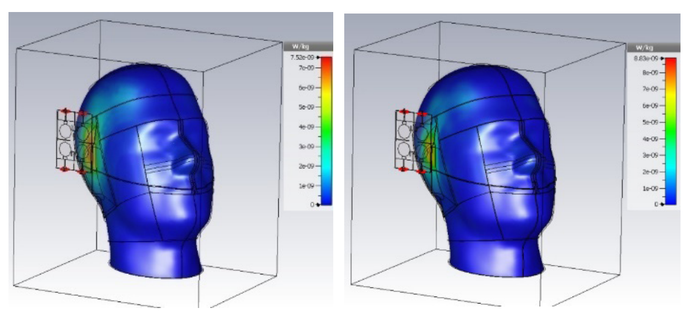


Fig. 15 Human head model with proposed antenna for SAR analysis



For10(g) (b) For 1(g)

Fig. 16 SAR analysis setup of proposed antenna.

The previously reported work and proposed work is compared on the basis of operating bandwidth, dimensions, ECC, isolation, peak gain, TARC and MEG in Table 4. The proposed design covers all frequencies band of WLAN and Wi-MAX. It has wider bandwidth than other antenna geometries. The size of the proposed design is also good and comparable to other designs. The values of MIMO performance parameters for proposed MIMO antenna are in acceptable limits.

Table 4. Proposed 2X2 Mimo Antenna And Previous Work Comparison

Reference	Frequency Band (GHz)	Size (mm^2)	ECC	Isolation at f_r in dB	Gain at f_r dBi	MEG (dB) at f_r
[16]	2.4-2.475	60 x 60	0.4	22	4	-
[19]	2.4-2.485	61 x 61	0.02	28	3.8	0.8
[21]	2.396-2.45	119 x 119	0.02	42	5.1	-
[22]	2.4-2.485	150 x 150	0.005	35	7.1	-
[31]	2.37-2.42; 3.33-3.90	70 x 60	0.01	25	1.8	-
[32]	2.34-2.56	72 x 72	0.01	12	2.0	3.0
[33]	2.24-2.50	56 x 37	0.08	10	2.0	2.5
[39]	2.12-2.15	120 x100	0.08	15	0.45	3.0
[40]	1.5–2.1	40 x 81.7	$5x10^{-3}$	17	1.0	3.0
[41]	2.18–2.50 5.33–9.06	88 x 31	--	--	3.5	--
Proposed	2.16-4.34	60 x 76	0.03	12	3.3	3.0

f_r =resonant frequency

IV. Conclusion

The creation of cutting-edge Wide-Band MIMO antennas shines as a beacon of progress in the ever-changing world of contemporary wireless communication, offering improved isolation and optimum performance. This investigation into the world of wide-band MIMO antennas has revealed the technology's transformative potential for a wide range of modern wireless applications. The main challenge in MIMO antenna design is the antenna coupling. The coupling degrades the performance of antenna i.e. efficiency, gain and isolation etc. Thus, proposed octagonal full shaped geometry based on four element design with T-shaped and PE for wide band of frequency has been proposed. In this design, two different approach is proposed for improving in isolation. The designed antenna produces improved isolation, acceptable MEG and TARC as per MIMO antenna needs, wide bandwidth, and good efficiency. For wireless communication CCL is also important parameter and it is found in acceptable limit while the SAR also shows the value under the limit. The designed MIMO antenna is fulfilling the modern antenna requirement.

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