A Comparative Study on Efficient MIMO Antennas in Wireless Communication

Hemalatha T, Bappadittya Roy[1]

Abstract—**In multipath channels, to enhance capacity over single antenna topologies, multiple-input-multiple-output (MIMO) wireless systems have multiple operating components at both the transmitter and the receiver. In such systems, the antenna characteristics and the multipath channel parameters play a critical role in determining communication effectiveness. In this study, the results of contemporary research on antennas and MIMO system propagation are examined. Investigations are conducted on the effects of antenna parameters as well as the computation of channel capacity, channel measurement, and modelling methodologies.The majority of MIMO antennas have issues with Voltage Standing Wave Ratio (VSWR), Reduced Bandwidth, Mutual Coupling, and low gain. A microstrip line fed pentagonal shaped patch antenna with I-shaped slot is designed and simulated. The proposed antenna enhanced the bandwidth and achieved good radiation performance and high gain. The return loss of -54.3 dB is achieved at 12.74 GHz frequency.**

Keywords—**Antenna array, Multiple-input-multiple-output systems, Mutual coupling (MC), Bandwidth, Isolation.**

I. INTRODUCTION

Modern wireless communication uses the effective transmission mechanism known as MIMO (Multiple Input Multiple Output). MIMO is frequently used for high-bandwidth communications when it is crucial to avoid microwave or Radio Frequency (RF) system interference. The MIMO system offers better data rates via the use of spatial multiplexing and higher reliability through the use of diversity. The major drawbacks of the MIMO system are expensive RF modules needed for the numerous antennas, the requirement for frequent channel matrix updates, the complexity of the hardware and software, and other constraints such as limited movement speed. Academic and commercial researchers are now interested in wireless communication systems due to the use of MIMO technology at transmitter and receiver terminals to increase data transmission capacity and decrease multipath fading [1].

Single Input Single Output (SISO), Single Input Multiple Output (SIMO), Multiple Input Single Output (MISO), and MIMO are the four components of multiple input multiple outputs.

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Multiple users and single-user MIMO are employed in this type of MIMO. This technology, multi-user MIMO, is employed extensively in many communication networks and leading sectors [2].

Fig. 1. Massive MIMO uses enormous antenna arrays at base stations

As shown in Fig. 1, the main idea is to set up enormous antenna arrays at base stations to simultaneously provide services to numerous autonomous terminals. People in the next generation expect high speed, high data rate internet connections. This confrontation necessitates the use of a MIMO antenna. MIMO antennas are a vital component of next-generation smart antennas, and they can aid with 5G communication via wireless. In order to alleviate the fading in the multipath channel constraint of communication over a short distance, multiple-input multiple-output is integrated with UWB technology. This results in high data transmission capacity [3].

In a research study from the 1970s, MIMO was initially discussed in terms of crosstalk and multichannel digital communication systems. MIMO Orthogonal Frequency Division Multiplexing (OFDM), an easy-to-implement Wireless Local Area Network (WLAN), was introduced in 2001. With IEEEs support, 100 MBPS may be delivered. Qualcomm launched MIMO-OFDM in 2006, allowing for up to 600 MBPS speeds. MIMO-OFDM also aided in the development of Wi-Max technology, resulting in the 802.16e standard. LTE (Long Term Evolution) 4G is a fourth-generation communication system. MIMO - OFDM and the third generation project are primarily responsible for the development of this standard.

MIMO provides spatial multiplexing gain through the use of multi carrier modulation and multiband functioning is required for further standards [4]-[5], MIMO + OFDM [6]-[7] can provide enhanced spectral efficiency. As a result of MIMO technology’s increased diversity, this technique can also improve connection stability and provide high-quality service (QoS). However, current narrowband communication technologies like IEEE 802.11 WLAN systems, which operate between 5.15 GHz and 5.85 GHz, produce electromagnetic interference in the Ultra Wideband (UWB) band [8] and outline many design strategies. Antenna characteristics and multipath channel characteristics are relevant in such systems and are important in deciding communication performance. As a result of the space-filling property, the antenna's effective electrical channel length can be extended in a more condensed space [9].

UWB antennas are created using fractal geometries [10-11] as the Koch snowflake, Sierpinski triangle and hexagonal form. To counteract the detrimental impacts of interferences, antenna configurations including configurable, engraved, dielectric resonator, and meta-material are widely used [12]. It can accomplish full diversity, lower hardware complexity and cost, and increase gain rate in the case of transmit antenna selection. These objectives can be accomplished with minimal computational expense. Antenna selection can be divided into two types: successive selection and norm-based selection. When the Signal to Noise ratio (SNR) is low, the former strategy ispreferable, whereas the latter is better for high SNR. Both strategies can be used to choose an antenna for transmittingor receiving data [13].

To provide Ultrawide Band (UWB) with high isolation, reduced mutual coupling, band notch or band rejection characteristics, compact structure, and multiple wideband, several antennas were proposed by the researchers. Parasitically linked semi-circular patches with closed dimensions and a tapered slotted ground plane [14-17] for triple notch band characteristics. Other techniques like Koch geometry [18], Electromagnetic band gap structures (EBG) [19], Near field resonator decoupling techniques are efficient for mutual coupling reduction and enhancement of isolation in UWB MIMO applications [20-27]. Metamaterial insulators, split ring resonators with different geometries, and waveguide materials were incorporated to enhance the antenna performance, which is suitable for C and X-band applications [28-39].

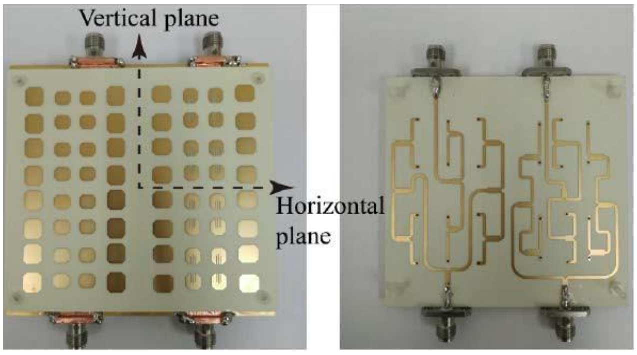
Compactness is an important aspect of MIMO systems because it helps to maximize the number of independent data streams that can be transmitted, reduce channel correlation, and minimize interference between different antennas in the system. Array antennas [40-43] are also significant components of MIMO systems, which offers diversity techniques, beamforming, and spatial multiplexing. Many other designs using slots and slits [44-50] were also evolved for the UWB MIMO applications with enhanced directivity, gain and bandwidth.

To meet the growing demands for 5G and beyond wireless communications increased capacity, low latency, energy efficiency, seamless connectivity, enhanced security, and flexibility are required. More comprehensive studies [51-62] have examined the effect of capacity loss and energy efficiency. To achieve the necessary MIMO performance, the antenna design [63-66] is essential. To reduce interference between antenna paths, [67-69] implemented self-isolation and reflectors.

Section II describes the literature survey of different MIMO antennas. Section III focuses on the proposed antenna design, dimensions and results. The proposed antenna is designed using HFSS software, the results in terms of return loss and bandwidth were compared with other different structures and comparative analysis was tabulated in Table I.

II. LITERATURE SURVEY

L.Kong, X.Xu *et.al* – The authors of this study miniaturized Dual Band Dual Polarized (DBDP) microstrip antennas by sharing two parasitic patches between each and every driven patch pair between the two bands shown in Fig. 2 [70]. A defected ground structure was integrated to the design to suppress the cross polarization in H-plane. A 4 x 6 array was constructed and measured for use in the X-band Horizontal, X-band Vertical, Ku-band Horizontal, and Ku-band Vertical operating modes and achieved wide impedance bandwidth.



(a) (b)

Fig. 2. Array of DBDP antennas: (a) Array structure, (b) Network [70]

Shrivishal Tripathi, Akhilesh Mohan *et.al* - In a compact design, the author developed a fractal UWB MIMO antenna (FUMA) shown in Fig. 3 for featuring WLAN band notches [71]. Koch geometry is used to attain wideband. Grounded stubs were aided in between the orthogonally positioned fractal antennas to achieve better isolation. C-shaped slots were grooved into the fractal MIMO antenna structure for band rejection at the 5.5 GHz frequency.

The antenna is 45mm x 45mm in size, which is quite compact. The diversity performance is characterized in terms of the Envelope Correlation Coefficient (ECC) which is calculated using Eq. (1) with S-parameters [71].

$$\rho_{e_{ij}} = \frac{\left|S_{ii}^{*}S_{ij}+S_{ji}^{*}S_{jj}\right|^{2}}{\left[\prod_{k=i,j}\left(1-\sum_{n=i,j}\left|S_{n,k}\right|^{2}\right)\right]\sqrt{\eta_{radj}\eta_{radi}}} \quad (1)$$

where η_{radi} and η_{radj} are the radiation efficiencies of the i^{th} and j^{th} antennas.

The ECC value achieved for the FUMA is below 0.005 across the entire UWB.

T. K. Roshna, U. Deepak *et.al* – The authors of this study developed a compact UWB MIMO antenna with enhanced isolation which is suitable for portable UWB MIMO communication systems. Fig. 4 illustrates the surface current distribution of the MIMO antenna [72]. A strip reflector was placed in between the radiating elements to provide the isolation i.e., < -20 dB. This MIMO antenna achieved a bandwidth from 3.1–11.3 GHz and a high gain of 5.2 dBi, and a 90 % radiation efficiency.

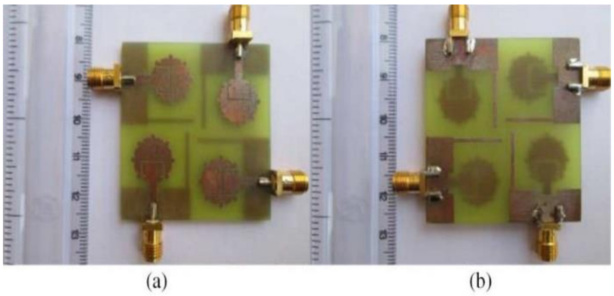


Fig. 3. FUMA fabrication: (a) Front view, (b) Rear view [71]

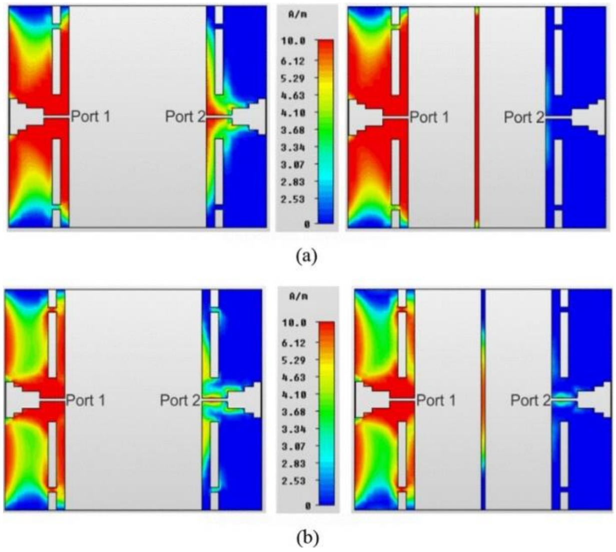


Fig. 4. Distribution of antenna current with and without a strip: (a) at 4.5 GHz, (b) at 8.5 GHz [72]

$$|\rho_{ij}|_{guaranteed} = |\rho_{ij}| + \sqrt{\left(\frac{1}{\eta_{radi}} - 1\right)\left(\frac{1}{\eta_{radj}} - 1\right)} \quad (2)$$

where

$$\rho_{ij} = \frac{\left(-S_{ii}S_{ij}^{*} - S_{ji}S_{jj}^{*}\right)}{\sqrt{\left(\left(1-|S_{ii}|^2-|S_{ji}|^2\right)\left(1-|S_{jj}|^2-|S_{ij}|^2\right)\eta_{radi}\eta_{radj}\right)}} \quad (3)$$

$$|\rho_{eij}|_{guaranteed} = |\rho_{ij}|^2_{guaranteed} \quad (4)$$

The ECC value for the UWB band is ≤0.1641 which is calculated by using Eqs. (2) and (3). η_{radi} and η_{radj} represents the radiation efficiency of the antenna elements i and j. The guaranteed value of the ECC ($|\rho_{eij}|_{guaranteed}$) is also calculated in this article by using Eq. (4) [72].

A. Ramachandran, S. Valiyaveettil Pushpakaran *et.al* – The authors of this research developed a four-port MIMO employing concentric square rings shown in Fig. 5 [73]. A non-periodic resonant structure was incorporated by the authors to reduce mutual coupling between the polarized elements.

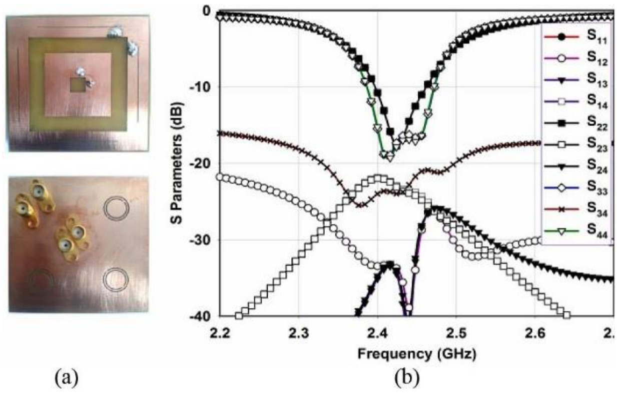


Fig. 5. (a) Four port MIMO with concentric square rings, (b) Parameters measured [73]

Fig. 6. Frequency reconfigurable MIMO antenna and the measurement setup [74]

Complementary split ring resonator (CSRR) is etched on the ground at the ring corners. CSRR reversed the polarity of coupling current on a common shared ground which led to the enhancement of isolation (< -22 dB). The dimensions of the rings and CSRR were tuned to get the same resonating frequency for all four ports i.e., at 2.4 GHz.

X. Zhao, S. Riaz *et.al* – In this article, the authors developed a frequency reconfigurable MIMO UWB triangular shaped monopole antenna elements shown in Fig. 6 [74]. The authors used six PIN diodes and two varactors for frequency reconfiguration. The PIN diodes were positioned in such a way that the switching conditions made the antenna work for dual – purposes. By tuning the varactor diodes, this antenna can provide a wide frequency reconfigurable communication band from 0.9 to 2.6 GHz. The authors utilized only one varactor diode per antenna which leads to the major advantage of compact size and cost effectiveness.

Chun Xu Mao., Qing Chu., *et.al* – In this paper, the authors designed two antenna elements with one pentagonal radiator fed by two orthogonally placed microstrip feedlines shown in Fig. 7 [75]. To achieve high isolation, the authors etched a T-shaped groove in the radiator and extended a stub from the ground.

To guarantee good channel characteristics, the received signals from the antennas should fulfill $|MEG_i / MEG_j| \cong 1$, where i and j denote the antenna elements.

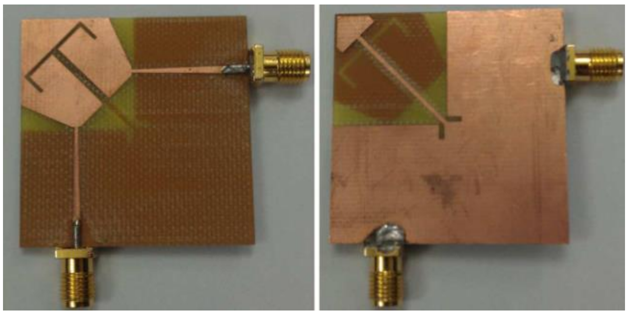


Fig. 7. Pentagonal Radiator with perpendicular microstrip feed lines

Mean Effective Gain (MEG) can be calculated by using Eq. (5) [75],

$$MEG_i = \frac{P_{rec}}{P_{inc}} = \oint \left[\frac{(XPR.G_{\theta i}(\Omega).P_\theta(\Omega)+G_{\varphi i}(\Omega).P_\varphi(\Omega))}{(1+XPR)}\right] d\Omega \quad (5)$$

which is the ratio of the mean received power (P_{rec}) and the mean incident power (P_{inc}). P_θ and P_φ represents the θ and φ components of the angular density functions of the incoming plane waves. G_θ and G_φ are the θ and φ polarized components of the antennas' realized active power gain patterns and Ω indicates the solid angle.

XPR is the cross polarization which is equal to '1' in the case of a uniform propagation environment. Eq. (5) [75] can be simplified as

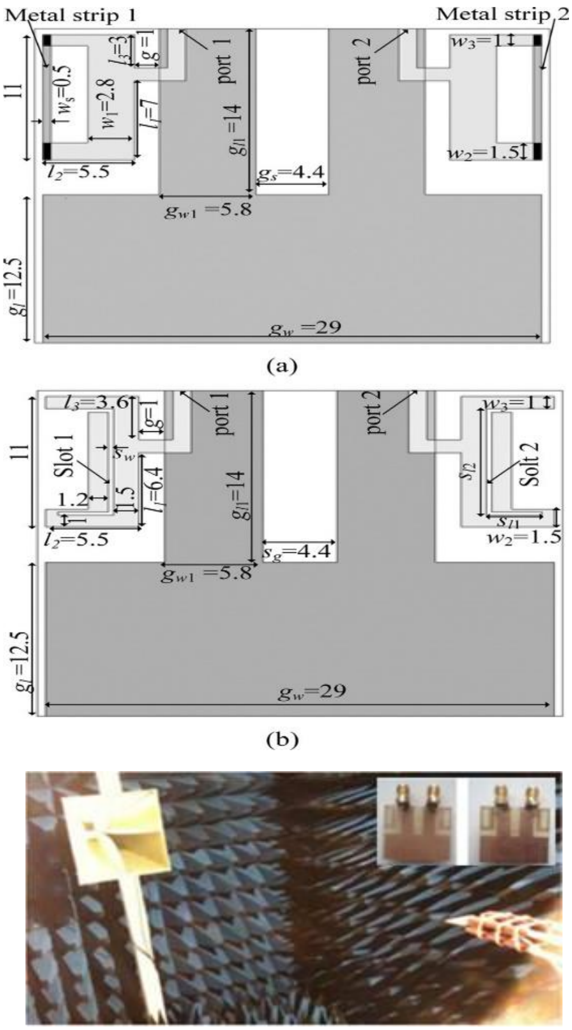
$$MEG_i = \frac{e^i_{tot}}{2} \quad (6)$$

where e^i_{tot} is the total efficiency of the i^{th} antenna element and can be calculated using Eq. (7) [75],

$$e^i_{tot} = e^i_{mis} \cdot e^i_{rad} \quad (7)$$

where e^i_{mis} and e^i_{rad} represents the antenna mismatch and radiation efficiencies.

Jian Feng Li., Qing Xin Chu., *et.al* – In this research study, the authors proposed two symmetric antenna elements and each antenna element comprised of a U-shaped radiator with a rectangular metal strip illustrated in Fig. 8 [76].



(c)

Fig. 8. (a) U-shaped radiator with a rectangular metal strip, (b) UWB with stubs, (c) the measurement setup of the fabricated prototype [76]

To shift the resonating frequency to the lower level and to improve the input impedance matching, a protruded ground plane was integrated into the UWB antenna. A rectangular metal strip producing a loop path and an open slot etched into the radiator led to two rejected bands of 3.3 - 3.7 GHz and 5.15 - 5.85 GHz.

Gunjan Srivastava *et.al* – The authors of this research paper designed a stepped slot UWB antenna depicted in Fig. 9 [77]. The mutual coupling between the radiating elements was reduced by varying the distance between the radiating elements.

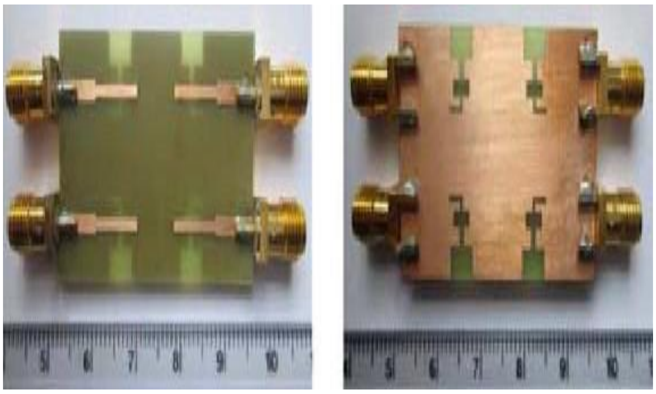


Fig. 9. Ultra wideband MIMO antenna geometry [77]

The authors analyzed the antenna performance in terms of ECC using Eq. (3) and Channel Capacity Loss (CCL) and achieved radiation efficiency > 80%. Eq. (8) with S-parameters is used to calculate the capacity loss of the designed antenna.

$$C_{loss} = -\log_2 \det(\Psi^R) \tag{8}$$

where Ψ^R represents the correlation matrix of the receiving antenna that can be expressed as

$$\Psi^R = \begin{bmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{bmatrix} \tag{9}$$

$\rho_{ii} = 1 - \left(|S_{ii}|^2 + |S_{ij}|^2\right)$, $\rho_{ij} = -\left(S_{ii}^* S_{ij} + S_{ji}^* S_{ij}\right)$ for i, j = 1 or 2.

Z. Li., C. Yin, and X. Zhu., *et.al* – The authors of this paper developed dual band notched UWB vivaldi antenna of size 26 x 26 mm^2 antenna shown in Fig. 10 [78]. Taconic RF-35 substrate with a dielectric constant of 3.5 was used for designing the antenna.

To reduce the mutual coupling a rectangular slot etched on the ground plane and further enhancing the isolation T-shaped slot were etched on the ground plane. Two notch bands corresponding to WLAN and satellite communication were identified with low ECC.

Deepika Sipal, Mahesh P. Abegaonkar *et.al* – In this research work, the authors designed a planar microstrip fed UWB slotted angular ring antenna depicted in Fig. 11 [79]. This antenna was fabricated using Neltec substrate with a dielectric constant of 3.2. Rectangular slots were introduced to generate additional resonances in the design. The radiating elements were placed orthogonal to each other with 2mm minimum spacing to provide good isolation.

M. Li, B. G. Zhong *et.al* – In this paper, the authors developed a Near Field Resonator (NRF) comprising of five split rings shown in Fig. 12 [80]. The authors placed the NRF on a rectangular patch which led to the generation of strong magnetic coupling between the NRF and patch, which further leads to the reduction of resonant frequencies of the antenna.

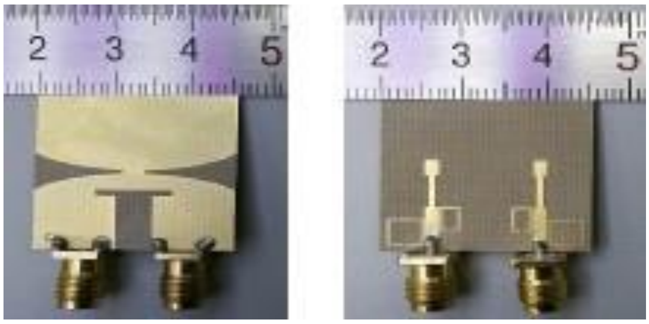


Fig. 10. Dual-band notched UWB vivaldi antenna [78]

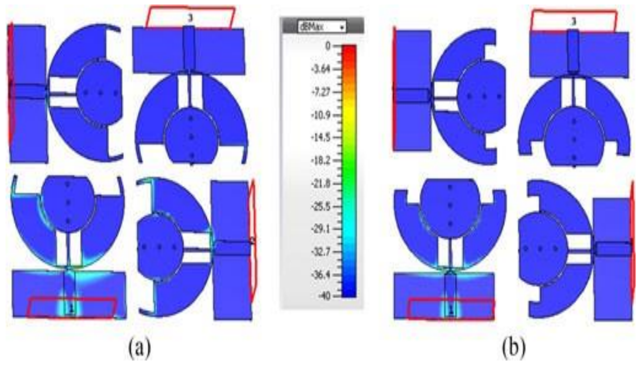


Fig. 11. Surface current distribution of a UWB slotted ring resonator: (a) First array, (b) Final array (with port-I excited) [79]

The NFR decoupling technique produced isolation of < -20 dB with the shortest edge separations when compared to other designs which use artificial structures for decoupling patches.

Zicheng Niu, Hou Zhang *et.al* – In this research endeavor, the authors developed a rectangular patch with diagonal feeding illustrated in Fig. 13 [81] to achieve the dual bands.

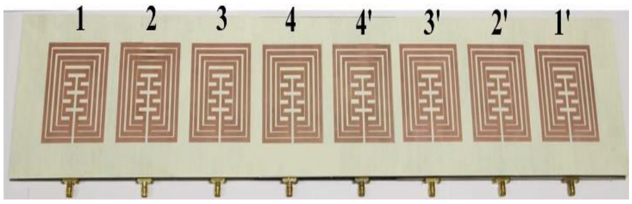


Fig. 12. 8-port NRF MIMO antenna [80]

Antennas were placed mirror symmetrical and the 2.8 mm edge-to-edge distance was maintained between the patches. To reduce the mutual coupling, a layer of modified array antenna decoupling structures and a pair of H-shaped defected ground structures were integrated into the designed antenna. The aforementioned mechanisms enhanced the isolation level to -30 dB in the lower and upper bands.

Shoaib, Nosherwan *et.al* - In this research report, the authors designed meandered monopoles printed diagonally on the non-grounded portion, the decoupling structure comprising of slots and metallic branches was integrated on the ground plane as shown in Fig. 14 (a) [82]. Fig. 14 (b) depicts the measurement setup of the fabricated prototype.

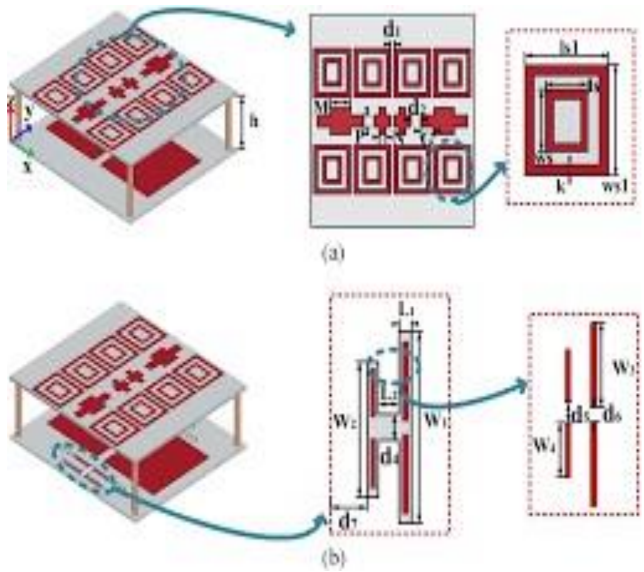
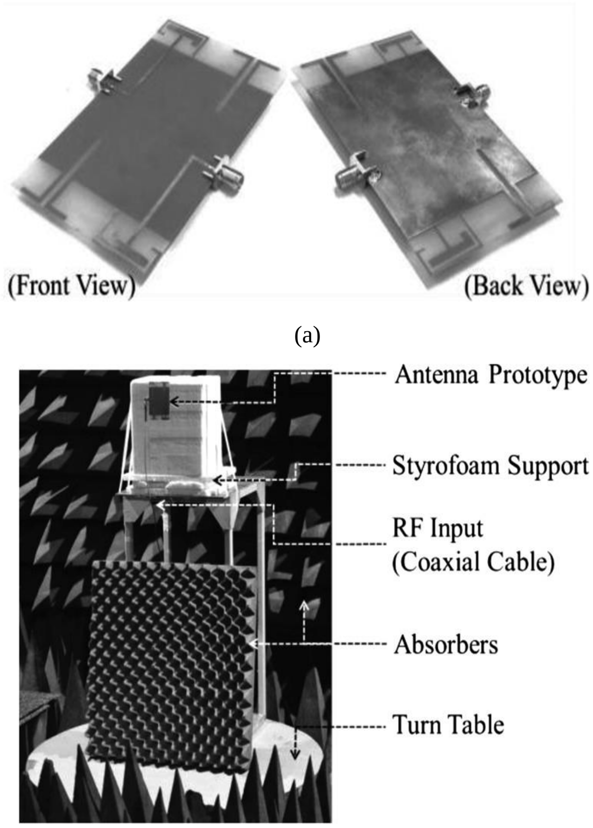


Fig. 13. Rectangular patch with diagonal feeding antenna decoupling process: (a) Phase I, (b) Phase II [81]



(b)

Fig. 14. (a) MIMO monopole antennas printed diagonally on the top of the substrate, (b) Measurement setup of the fabricated prototype [82]

For the measurement of radiation patterns, the authors placed the fabricated prototype inside an anechoic chamber. The designed antenna achieved good isolation by etching the two decoupling structures diagonal to each other.

Bhattacharya A, Roy B. *et.al* – The authors designed an extremely compact 20 x 20 mm^2 antenna comprising of two mutually orthogonal slotted radiating elements with a single parasitic strip shown in Fig. 15 [83]. The radiators were placed perpendicular to each other to obtain diverse polarization. The designed antenna has the unique ability to eliminate interference from the WLAN and WiMAX bands and other advantages like compactness, and enhanced isolation.

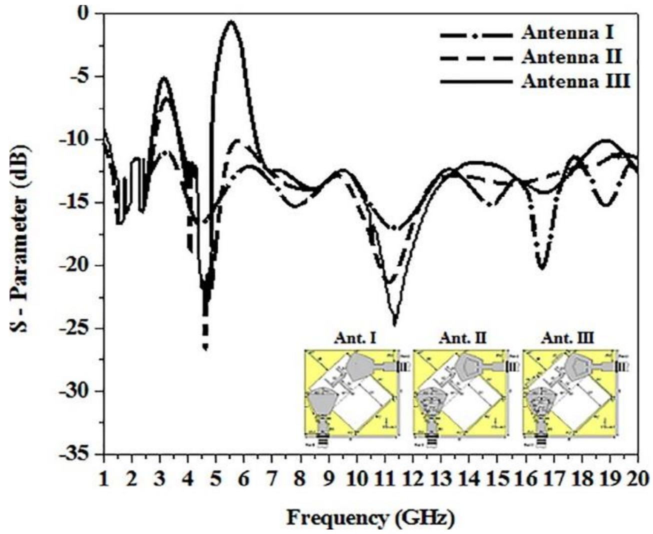


Fig. 15. MIMO antenna Frequency response [83]

III. Proposed Antenna

The proposed antenna design consists of an ‘I’ shaped slot on a pentagonal patch as depicted in Fig.16. As a dielectric material, FR4 epoxy substrate with a dielectric constant of 4.4 is employed. The proposed antenna was created and tested using commercial HFSS software.

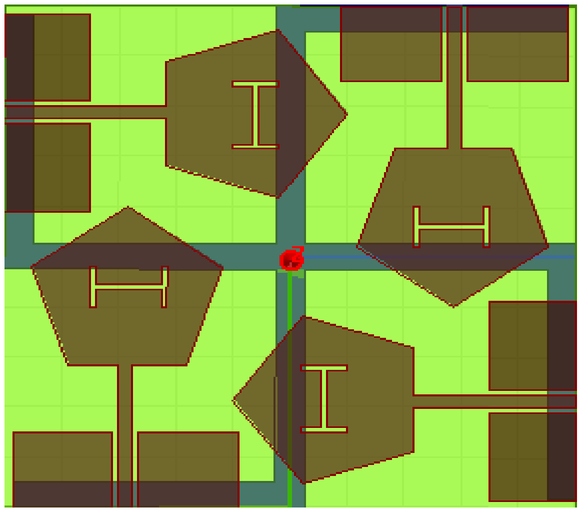


Fig. 16. Proposed MIMO antenna Top-view

The substrate's measurements are 20 x 20 x 1.6mm^3. Fig. 17 depicts the dimensions of the patch and 'I' shaped slot.

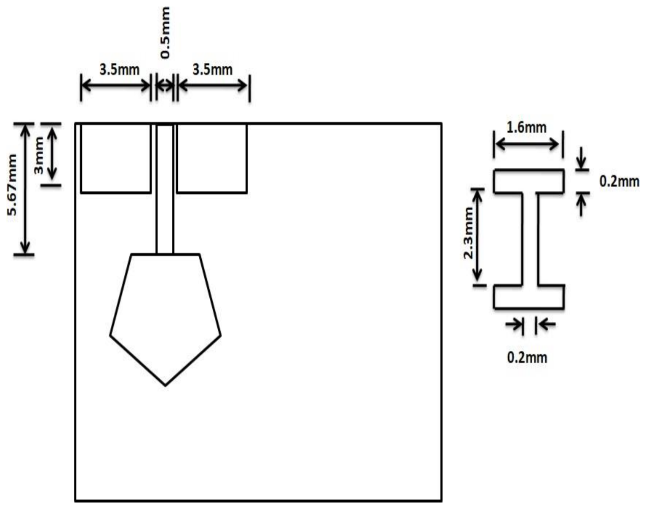


Fig. 17. Patch and slot dimensions

Fig. 18 demonstrates the S11 return loss of the proposed antenna. The proposed MIMO antenna achieved a bandwidth of 01.41 – 13.13 GHz with a band notch in the lower half frequency. The figure depicts the comparative performance of the proposed antenna in terms of Return loss to that of the same antenna with different feeding positions labeled as Feed position 1 and Feed position 2.

The simulation results clearly show that the proposed antenna with feeding position as shown in Fig. 16 outperformed the other two feeding positions (1 and 2).

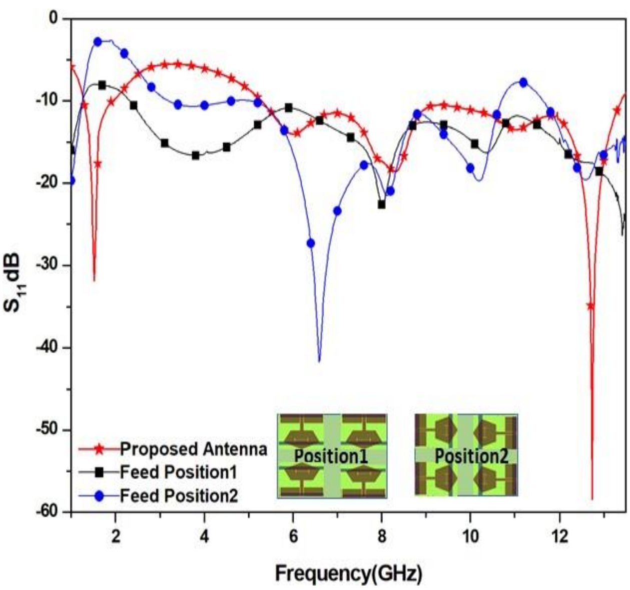


Fig. 18. S- Parameters of the proposed MIMO antenna

Figs. 19 and 20 illustrate the proposed antenna's 2D and 3D radiation patterns when implemented on various substrates like FR4 epoxy, Rogers RT/duroid 5880, and Rogers RT/duroid 6010 with dielectric constants 4.4, 2.2, and 10.2 respectively.

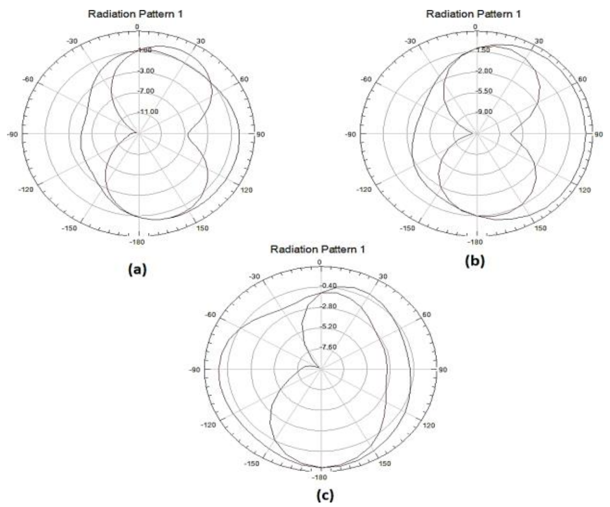


Fig. 19. Proposed MIMO antenna's 2D radiation patterns for various substrates are shown in (a) FR4 Epoxy, (b) Rogers 5880, and (c) Rogers6010

Fig. 20 represents the 3D radiation pattern of the proposed antenna. As per the simulation results, it is evident that the gain of 3.53 dBi is achieved for the pentagonal patch 'I' shaped slotted antenna.

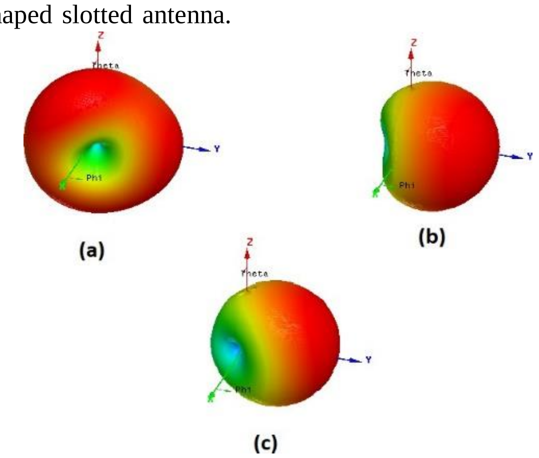


Fig. 20. Proposed MIMO antenna's 3D radiation patterns for various substrates are shown in (a) FR4 Epoxy, (b) Rogers 5880, and (c) Rogers 6010

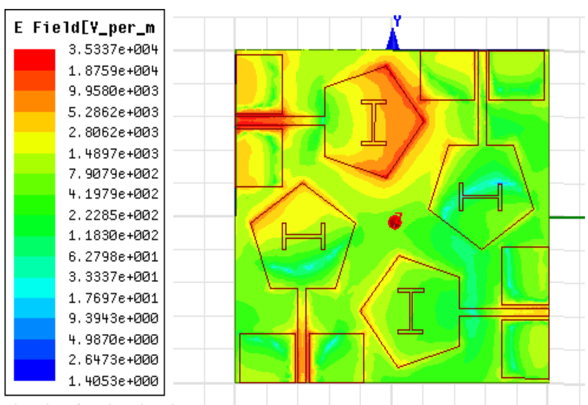


Fig. 21. E-field pattern of the proposed antenna

Fig. 21 represents the surface current distribution of the proposed antenna. It can be observed from the figure, the current originates from the feed and distributes itself uniformly at the edges of the patch which results in the enhancement of the impedance bandwidth, gain at the resonating frequency.

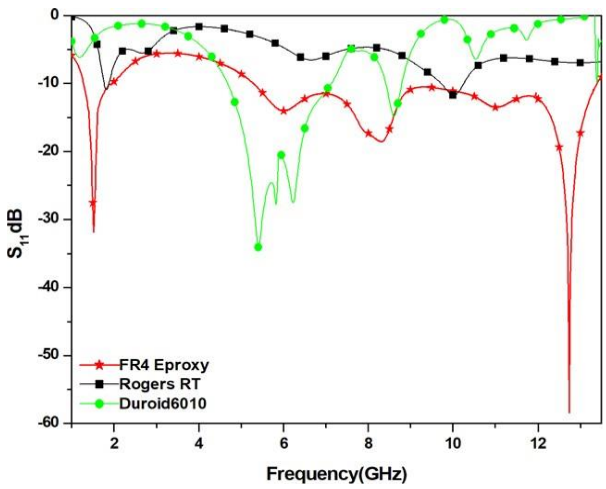


Fig. 22. S_{11} plot for different substrates

Fig. 22 depicts the return loss of the proposed antenna for three different substrates namely FR4 epoxy, Rogers RT/duroid 5880 and Rogers RT/duroid 6010 with dielectric constants 4.4, 2.2 and 10.2 respectively. It is seen that the proposed antenna with feed position as shown in Fig. 16 with FR4 substrate covered high bandwidth of 01.41 – 13.13 GHz with a notched band in the lower half and a high return loss of -54.37 dB is obtained at 12.74 GHz frequency.

IV. Conclusion

Different MIMO Antennas are analyzed in this review paper. The comparative analysis part of the study is highlighted in this paper. Mutual coupling is a serious issue in several MIMO antennas. In addition to that most of the antennas that were designed are low gain antennas. Dimensions, radiation efficiency, gain, materials, ECC and diversity gain are compared for all MIMO antenna designs.

This paper presents a wide range of designs to help with mutual coupling improvement. Mutual coupling minimization with a low profile is an active research area that has the potential to directly influence the advancement of wireless communication systemsin 5G and 6G. A microstrip line feed pentagonal shaped patch antenna with I-shaped slot is proposed and simulated. The proposed antenna achieved high impedance bandwidth of 01.41 – 13.13 GHz with a notch band, good radiation performance, and high gain. Return loss (S_{11}) of -54.37 dB is obtained at 12.74 GHz frequency.

MIMO technology will probably be utilized to boost the throughput of wireless networks as the demand for data keeps rising. This could be accomplished by utilizing higher-order MIMO systems, such as 8x8 or 16x16. Utilizing MIMO to increase wireless network energy efficiency is another potential development in the field. Advanced beamforming algorithms, antenna position optimization, and the use of better power management strategies can be used to achieve this. By enhancing the diversity of the wireless channel, MIMO technology can also be utilized to increase the reliability of wireless communications.

Acknowledgment

The management of VIT-AP University and the SENSE department are acknowledged for their tremendous support and encouragement throughout this endeavor by the authors.

TABLE I
Comparative analysis of different MIMO antennas

S.No	Ref No.	Shape	Frequency	Bandwidth	Band	Remarks
1	[70]	DBDP Antenna Array chamfered edges	8.9GHz - 10.2GHz	12.3 GHz	Dual	Wide beamwidth and stable peak gain
2	[71]	Fractal antennas by etching a C-shaped slot	5.5 GHz	2 to 10.6 GHz	Single	Good pulse preserving capability
3	[72]	CPS fed two-port MIMO	4.5GHz and 8.5GHz	3.1–11.3 GHz	Dual	High Peak gain and peak efficiency
4	[73]	Four - port MIMO using concentric square rings	2.4GHz	2.45 GHz	Single	Improved isolation
5	[74]	Two-port antenna with a printed monopole antenna design in the shape of a triangle	1 GHz to 4.5 GHz	0.9 to 2.6 GHz	Single	Effective performance was achieved in terms of gain, effectiveness, input impedance matching, isolation, and ECC.
6	[76]	A rectangular metal strip and a radiator in the shape of a "U"	5.15 to 5.85 GHz	3.0 to 11.0 GHz	Dual	High Isolation
7	[77]	Four-element microstrip fed stepped slot	3.1 to 12 GHz	3.2 to 12 GHz	Single	The directional radiation properties provide high isolation among antenna components.
8	[78]	A ground plane with a T-shaped slot	2 to 14GHz	2.9 to 11.6 GHz	Dual	Stable gain, good radiation characteristics and ECC is quite low
9	[79]	Microstrip fed slotted annular ring-Array of four and eight elements	3 GHz	3 - 10 GHz	Single	High isolation and good impedance bandwidth matching
10	[80]	Five rectangular split rings	2.24	5.8 to 6.1 GHz	Single	Good radiation performance
11	[81]	Ground with an H-shaped defect and modified array antenna decoupling surface (MADS)	3.7 and 4.1 GHz	1.48% and 2.07%	Dual	34.2 and 36.3 dB of isolation at 3.7 and 4.1 GHz
12	[82]	Coupled-fed monopoles	2.45 GHz	1.7–2.9 GHz	Single	Better isolation for overall frequency bands
13	Proposed Antenna	Four pentagonal patches etched with I-shaped slot	2.4 GHz to 12 GHz	01.41 – 13.13 GHz	Dual	Enhanced bandwidth, good radiation performance and high gain

REFERENCES

[1] Foschini, Gerard J., and Michael J. Gans, "On Limits of Wireless Communications in a Fading Environment when Using Multiple Antennas", *Wireless Personal Communications*, vol. 6, no. 3, pp. 311-336, 1998.

[2] Sangwan, Munesh, Gopal Panda, and Pranay Yadav, "A Literature Survey on Different MIMO Patch Antenna", 2020 *International Conference on Inventive Computation Technologies (ICICT*, IEEE, 2020.

[3] Najam, Ali Imram, Yvan Duroc, and Smail Tedjni, "UWB-MIMO Antenna with Novel Stub Structure", *Progress in Electromagnetics Research*, C 19, pp. 245-257, 2011.

[4] Cho, Yong Soo, et al., *MIMO-OFDM Wireless Communications with MATLAB*, John Wiley & Sons, 2010.

[5] Reddy, Ambavaram Pratap, and Pachiyaannan Muthusamy, "Enhancement of Bandwidth and Gain using Proximity Coupled DGS Structure Patch Antenna for WiMAX/5G Band Applications", *Microwave Review*, vol. 28, no 1, 2022.

[6] Chang, R. W. "Orthogonal Frequency Division Multiplexing", US Patent 3.

[7] Jensen, Michael A., and Jon W. Wallace, "A Review of Antennas and Propagation for MIMO Wireless Communications", *IEEE Transactions on Antennas and Propagation*, vol. 52, no. 11 pp. 2810-2824, 2004.

[8] Li, L., Zhou, Z. L., Hong, J. S., and Wang, "Compact Dual-Band-Notched UWB Planar Monopole Antenna with Modified SRR", *Electronics Letters*, vol. 47, no. 17, pp. 950-951, 2011.

[9] Werner, Douglas H., Randy L. Haupt, and Pingjuan L. Werner, "Fractal Antenna Engineering: The Theory and Design of Fractal Antenna Arrays", *IEEE Antennas and Propagation Magazine*, vol. 41, no. 5, pp. 37-58, 1999.

[10] Anguera, Jaume, et al. "Fractal Shaped Antennas: A Review", *Encyclopedia of RF and Microwave Engineering*, 2005.

[11] Chouhan, Sanjay, et al. "Multiport MIMO Antennas with Mutual Coupling Reduction Techniques for Modern Wireless Transreceive Operations: A Review", *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 28, no. 2, e21189, 2018.

[12] Sanayei, Shahab, and Aria Nosratinia, "Antenna Selection in MIMO Systems", *IEEE Communications Magazine* vol. 42, no. 10, pp. 68-73, 2004.

[13] Nahar, Tapan, and Sanyog Rawat, "Electromagnetically Coupled Semi-Circular Patch Antenna with Tapered Slotted Ground for V band, W Band and M Band Applications", *Microwave Review* vol. 28, no. 1, 2022.

[14] Larsson, Erik G., et al. "Massive MIMO for Next Generation Wireless Systems", *IEEE Communications Magazine*, vol. 52, no. 2, pp. 186-195, 2014.

[15] Gustafsson, Mats, et al. "Physical bounds of antennas", *Handbook of Antenna Technologies*, pp. 1-32, 2015.

[16] Bhattacharya, Ankan, Bappadittya Roy, and Anup K. Bhattacharjee, "Compact, Isolation Enhanced, Band-Notched SWB–MIMO Antenna Suited for Wireless Personal Communications", *Wireless Personal Communications*, vol. 116, no. 3, pp. 1575-1592, 2021.

[17] Agrawal, Sachin, and Akshat Gururani, "Rectangular Slot Super Wideband Antennas with Band Notch Characteristic Fed by CPW and Microstrip Line", *Microwave Review*, vol. 27, no. 2, 2021.

[18] Yang, Fan, and Yahya Rahmat-Samii, "Microstrip Antennas Integrated with Electromagnetic Band-Gap (EBG) Structures: A Low Mutual Coupling Design for Array Applications", *IEEE Ttransactions on Antennas and Propagation*, vol. 51, no. 10, pp. 2936-2946, 2003.

[19] Prasad, Ramjee, *OFDM for Wireless Communications Systems*, Artech House, 2004.

[20] Rajo-Iglesias, Eva, Oscar Quevedo-Teruel, and Luis Inclan-Sanchez, "Mutual Coupling Reduction in Patch Antenna Arrays by Using a Planar EBG Structure and a Multilayer Dielectric Substrate", *IEEE Transactions on Antennas and Propagation*, vol. 56, no .6, pp. 1648-1655, 2008.

[21] Farahani, Hossein Sarbandi, et al. "Mutual Coupling Reduction in Patch Antenna Arrays Using a UC-EBG Superstrate", *IEEE Antennas and Wireless Propagation Letters*, vol. 9, pp. 57-59, 2010.

[22] Bait-Suwailam, Mohammed M., Omar F. Siddiqui, and Omar M. Ramahi, "Mutual coupling Reduction Between Microstrip Patch Antennas Using Slotted-Complementary Split-Ring Resonators", *IEEE Antennas and Wireless Propagation Letters*, vol. 9, pp. 876-878, 2010.

[23] Marzetta, L. Thomas. "Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas", *IEEE Transactions on Wireless Communications*, vol. 9, no. 11, pp. 3590-3600, 2010.

[24] Li, Geoffrey Ye, et al. "Energy-Efficient Wireless Communications: Tutorial, Survey, and Open Issues", *IEEE Wireless Communications*, vol. 18, no. 6, pp. 28-35, 2011.

[25] Tang, Ming-Chun, et al. "Improved Performance of a Microstrip Phased Array Using Broadband and Ultra-Low-Loss Metamaterial Slabs", *IEEE Antennas and Propagation Magazine*, vol. 53, no. 6, pp. 31-41, 2011.

[26] Habashi, Asieh, Javad Nourinia, and Changiz Ghobadi. "Mutual coupling Reduction Between Very Closely Spaced Patch Antennas Using Low-Profile Folded Split-Ring Resonators (FSRRs)", *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 862-865, 2011.

[27] Kelly, James R., Peter S. Hall, and Peter Gardner, "Band-Notched UWB Antenna Incorporating a Microstrip Open-Loop Resonator", *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 8, pp. 3045-3048, 2011.

[28] Hsu, Chih-Chun, Ken-Huang Lin, and Hsin-Lung Su, "Implementation of Broadband Isolator Using Metamaterial-Inspired Resonators and a T-shaped Branch for MIMO Antennas", *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 10, pp. 3936-3939, 2011.

[29] Di Renzo, Marco, Harald Haas, and Peter M. Grant, "Spatial Modulation for Multiple-Antenna Wireless Systems: A Survey", *IEEE Communications Magazine*, vol. 49, no. 12, pp. 182-191, 2011.

[30] Farsi, Saeed, et al. "Mutual Coupling Reduction Between Planar Antennas by Using a Simple Microstrip U-Section", *IEEE Antennas and Wireless Propagation Letters*, vol. 11, pp. 1501-1503, 2012.

[31] Jiang, Wen, and Wenquan Che, "A novel UWB antenna with dual notched bands for WiMAX and WLAN applications", *IEEE Antennas and Wireless Propagation Letters*, vol. 11, pp. 293-296, 2012.

[32] Bjornson, Emil, et al. "Capacity Limits and Multiplexing Gains of MIMO Channels with Transceiver Impairments", *IEEE Communications Letters*, vol. 17, no. 1, pp. 91-94, 2012.

[33] Meshram, Manoj K., et al. "A novel Quad-Band Diversity Antenna for LTE and Wi-Fi Applications with High Isolation", *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 9, pp. 4360-4371, 2012.

[34] Reza, Audhia, and Joko Suryana, "Design and Realization of 1.8–2.4 GHz MIMO 2×2 Antenna for Handset Application", *IEEE International Conference on Communication Systems* (ICCS), IEEE, 2012.

[35] Yang, Xin Mi, et al. "Reduction of Mutual Coupling Between Closely Packed Patch Antennas Using Waveguided

Metamaterials", *IEEE Antennas and Wireless Propagation Letters*, vol. 11, pp. 389-391, 2012.

[36] Li, Zhengyi, et al. "Reducing Mutual Coupling of MIMO Antennas with Parasitic Elements for Mobile Terminals", *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 2, pp. 473-481, 2011.

[37] Lee, Jae-Min, et al. "A Compact Ultrawideband MIMO Antenna with WLAN Band-Rejected Operation for Mobile Devices", *IEEE Antennas and Wireless Propagation Letters*, vol. 11, pp. 990-993, 2012.

[38] Zhang, Shuai, et al. "Adaptive quad-Element Multi-Wideband Antenna Array for User-Effective LTE MIMO Mobile Terminals", *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 8, pp. 4275-4283, 2013.

[39] Saito, Keisuke, et al. "Field Experiments on 1-Gbps Data Transmission Using 4-by-2 Multi-User MIMO with Cross-Polarized Linear Antenna Array in LTE-Advanced Downlink", *2013 IEEE 77th Vehicular Technology Conference (VTC Spring)*, IEEE, 2013.

[40] M. G.N. Alsath, M. Kanagasabai, and B. Balasubramanian, "Implementation of Slotted Meander-Line Resonators for Isolation Enhancement in Microstrip Patch Antenna Arrays", *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 15-18, 2012.

[41] F. Rusek *et al.*, "Scaling up MIMO: Opportunities and Challenges with Very Large Arrays", *IEEE Signal Processing Magazine*, vol. 30, no. 1, pp. 40-60, 2012.

[42] Z. Qamar *et al*., "Slot Combined Complementary Split Ring Resonators for Mutual Coupling Suppression in Microstrip Phased Arrays", *IET Microwaves, Antennas & Propagation*, vol. 8, no. 15, pp. 1261-1267, 2014.

[43] B. P. Chacko, G. Augustin, and T. A. Denidni. "Uniplanar Slot Antenna for Ultrawideband Polarization-Diversity Applications", *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 88-91, 2013.

[44] P. Gao *et al*., "Compact Printed UWB Diversity Slot Antenna with 5.5-GHz Band-Notched Characteristics", *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 376-379, 2014.

[45] E. G. Larsson et al., "Massive MIMO for Next Generation Wireless Systems", *IEEE Communications Magazine*, vol. 52, no. 2, pp. 186-195, 2014.

[46] L. Liu, S. W. Cheung, and T. I. Yuk, "Compact MIMO Antenna for Portable UWB Applications with Band-Notched Characteristic", *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 5, pp. 1917-1924, 2015.

[47] G. Zhai, Z. N. Chen, and X. Qing, "Enhanced Isolation of a Closely Spaced Four-Element MIMO antenna System Using Metamaterial Mushroom", *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 8, pp. 3362-3370, 2015.

[48] A. Purwar, J. Malik, and M. V. Kartikeyan, "Tri-Band Printed MIMO Antenna Working on 1.7, 2.7 and 3.7 GHz", *2015 National Conference on Recent Advances in Electronics & Computer Engineering (RAECE)*, Roorkee, India, 2015, pp. 237-239.

[49] H. Qi *et al*., "Mutual Coupling Suppression Between Two Closely Spaced Microstrip Antennas with an Asymmetrical Coplanar Strip Wall", *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 191-194, 2015.

[50] H. Qi *et al*., "Improving Isolation Between Closely Spaced Patch Antennas Using Interdigital Lines", *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 286-289, 2015.

[51] A. Peristerianos et al., "Dual-band Fractal Semi-Printed Element Antenna Arrays for MIMO Applications", *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 730-733, 2015.

[52] B. Roy *et al*., "Wideband Snowflake Slot Antenna Using Koch Iteration Technique for Wireless and C-band Applications", *AEU - International Journal of Electronics and Communications*, vol. 70, no. 10, pp. 1467-1472, 2016.

[53] A. Dadgarpour *et al*., "Mutual Coupling Reduction in Dielectric Resonator Antennas Using Metasurface Shield for 60-GHz MIMO Systems", *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 477-480, 2016.

[54] K.-L. Wu *et al*., "Array-Antenna Decoupling Surface", *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12, pp. 6728-6738, 2017.

[55] M. Akbari *et al*., "Spatially Decoupling of CP Antennas Based on FSS for 30-GHz MIMO Systems", *IEEE Access*, vol. 5, pp. 6527-6537, 2017.

[56] R. Karimian *et al*., "Low-Mutual-Coupling 60-GHz MIMO Antenna System with Frequency Selective Surface Wall", *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 373-376, 2016.

[57] H. M. El Misilmani and A. M. El-Hajj, "Massive MIMO Design for 5G Networks: An Overview on Alternative Antenna Configurations and Channel Model Challenges", *2017 International Conference on High Performance Computing & Simulation (HPCS)*, Genoa, Italy, 2017, pp. 288-294.

[58] S. Nandi and A. Mohan, "A Compact Dual-Band MIMO Slot Antenna for WLAN Applications", *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 2457-2460, 2017.

[59] A. Bhattacharya *et al*., "Design and Analysis of a Koch Snowflake Fractal Monopole Antenna for Wideband Communication", *The Applied Computational Electromagnetics Society Journal (ACES*), vol. 32, no. 6, pp. 548-554, 2021.

[60] I. Gnanaharan and R. Anbazhagan, "Review on the Design of the Isolation Techniques for UWB-MIMO Antennas", *Advanced Electromagnetics*, vol. 7, no. 4, pp. 46-70, 2018.

[61] R. Hussain, M. S. Sharawi, and A. Shamim, "4-Element Concentric Pentagonal Slot-Line-Based Ultra-Wide Tuning Frequency Reconfigurable MIMO Antenna System", *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 8, pp. 4282-4287, 2018.

[62] K. R. Jha and S. K. Sharma, "Combination of MIMO Antennas for Handheld Devices [Wireless Corner]", *IEEE Antennas and Propagation Magazine*, vol. 60, no. 1, pp. 118-131, 2018.

[63] F. Faraz *et al*., "Mutual Coupling Reduction for Linearly Arranged MIMO Antenna", *2019 Cross Strait Quad-Regional Radio Science and Wireless Technology Conference (CSQRWC)*, Taiyuan, China, 2019, pp. 1-3.

[64] F. Wang *et al*., "High Isolation Millimeter-Wave Wideband MIMO Antenna for 5G Communication", *International Journal of Antennas and Propagation*, vol. 2019, Article ID 4283010, 12 pages.

[65] M. Irshad Khan *et al*., "Design and Investigation of Modern UWB-MIMO Antenna with Optimized Isolation", *Micromachines*, vol. 11, no. 4, 432, 2020.

[66] H. Tang *et al.*, "A Low-Profile Flexible Dual-Band Antenna with Quasi-Isotropic Radiation Patterns for MIMO System on UAVs", *IEEE Antennas and Wireless Propagation Letters*, vol. 22, no. 1, pp. 49-53, 2022.

[67] R. S. Kshetrimayum, M. Mishra, S. Aïssa, S. K. Koul and M. S. Sharawi, "Diversity Order and Measure of MIMO Antennas in Single-User, Multiuser, and Massive MIMO Wireless Communications", *IEEE Antennas and Wireless Propagation Letters*, vol. 22, no. 1, pp. 19-23, Jan. 2023, doi: 10.1109/LAWP.2022.3200483.

[68] O. Sokunbi, H. Attia, A. Hamza, A. Shamim, Y. Yu and A. A. Kishk, "New Self-Isolated Wideband MIMO Antenna System

for 5G mm-Wave Applications Using Slot Characteristics", *IEEE Open Journal of Antennas and Propagation*, vol. 4, pp. 81-90, 2023, doi: 10.1109/OJAP.2023.3234341.

[69] Y. Qin, L. Zhang, C.-X. Mao and H. Zhu, "A Compact Wideband Antenna With Suppressed Mutual Coupling for 5G MIMO Applications", *IEEE Antennas and Wireless Propagation Letters*, vol. 22, no. 4, pp. 938-942, April 2023, doi: 10.1109/LAWP.2022.3229020.

[70] L. Kong and X. Xu, "A Compact Dual-Band Dual-Polarized Microstrip Antenna Array for MIMO-SAR Applications", *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 5, pp. 2374-2381, 2018.

[71] S. Tripathi, A. Mohan, and S. Yadav, "A Compact Koch Fractal UWB MIMO Antenna with WLAN Band-Rejection", *IEEE Antennas and Wireless Propagation Letters*, vol. 14, pp. 1565-1568, 2015.

[72] T. K. Roshna *et al.*, "A Compact UWB MIMO Antenna with Reflector to Enhance Isolation", *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 4, pp. 1873-1877, 2015.

[73] A. Ramachandran *et al.*, "A Four-Port MIMO Antenna Using Concentric Square-Ring Patches Loaded with CSRR for High Isolation", *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 1196-1199, 2015.

[74] X. Zhao, S. Riaz, and S. Geng, "A Reconfigurable MIMO/UWB MIMO Antenna for Cognitive Radio Applications", *IEEE Access*, vol. 7, pp. 46739-46747, 2019.

[75] C.-X. Mao and Q.-X. Chu, "Compact Coradiator UWB-MIMO Antenna with Dual Polarization", *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 9, pp. 4474-4480, 2014.

[76] J.-F. Li *et al.*, "Compact Dual Band-Notched UWB MIMO Antenna with High Isolation", *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 9, pp. 4759-4766, 2013.

[77] G. Srivastava and A. Mohan, "Compact MIMO Slot Antenna for UWB Applications", *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 1057-1060, 2015.

[78] Z. Li, C. Yin, and X. Zhu, "Compact UWB MIMO Vivaldi Antenna with Dual Band-Notched Characteristics", *IEEE Access*, vol. 7, pp. 38696-38701, 2019.

[79] D. Sipal, M. P. Abegaonkar, and S. K. Koul, "Easily Extendable Compact Planar UWB MIMO Antenna Array", *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 2328-2331, 2017.

[80] M. Li, B. G. Zhong, and S. W. Cheung, "Isolation Enhancement for MIMO Patch Antennas Using Near-Field Resonators as Coupling-Mode Transducers", *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 2, pp. 755-764, 2018.

[81] Z. Niu *et al.*, "Isolation Enhancement in Closely Coupled Dual-Band MIMO Patch Antennas", *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 8, pp. 1686-1690, 2019.

[82] S. Shoaib *et al.*, "MIMO Antennas for Mobile Handsets", *IEEE Antennas and Wireless Propagation Letters*, vol. 14, pp. 799-802, 2014.

[83] A. Bhattacharya and B. Roy, "Investigations on an Extremely Compact MIMO Antenna with Enhanced Isolation and Bandwidth", *Microwave and Optical Technology Letters*, vol. 62, no. 2, pp. 845-851, 2020.