Analysis of Isolation Techniques for Mutual Coupling Reduction in MIMO Antennas

Ahmed Read Al-tameemi, Goh Chin Hock, Tiong Sieh Kiong, Taha Raad Al-Shaikhli, Mohammed S. Al Ani, and Mohammad A. K. Al Ani

Original scientific article

***Abstract*—This paper presents a comprehensive review of isolation enhancement techniques for MIMO systems, emphasizing their role in minimizing mutual coupling for modern wireless communication applications. Seven main reduction couplings are found, such as neutralization lines (NL) structures, metamaterials that included electromagnetic band gap (EBG) and meta-surfaces, parasitic elements (PE), defected ground structures (DGS), decoupling networks (DN), and hybrid isolation techniques. Each technique has been discussed and analyzed based on design geometry, methods, and reduction coupling performance. Depending on the results of using these techniques, the study found there was a good enhancement of isolation, ECC and other antenna performance. In addition, this work draws attention to the effectiveness of combining methods for compact and high-performance antennas. Also, the composition of the previous studies was deeply analyzed in terms of size, isolation, bandwidth, distance and value of isolation enhancement. This work covered the published papers for 5G communication bands to be a base station for designing MIMO antennas with high isolation.**

***Index terms*—MIMO, mutual coupling, isolation, hybrid isolation technique.**

I. INTRODUCTION

Multiple-input multiple-output (MIMO) is a sophisticated method that increases the capacity of a wireless link by employing more than one antenna at both the transmitter and receiver ends to generate multipath propagation [1]. This technology enables data streams over the same radio channel using different antennas on the same geometry and without losing extra power, particularly in environments with significant signal scattering [2].

Manuscript received June 10, 2025; revised July 10, 2025. Date of publication July 22, 2025. Date of current version July 22, 2025. The associate editor prof. Miroslav Joler has been coordinating the review of this manuscript and approved it for publication.

A. R. Al-tameemi, G. C. Hock and T. S. Kiong are with the Universiti Tenaga Nasional, Kajang, Malaysia (e-mails: PE21149@student.uniten.edu.my, {chinhock, Siehkiong}@uniten.edu.my).

T. R. Al-Shaikhli is with the University of Technology, Baghdad, Iraq (e-mail: taha.r.khaleel@uotechnology.edu.iq).

M. S. Al Ani is with the Al-Farahidi University, Baghdad, Iraq (e-mail: mr.muhammed.salim@uoalfarahidi.edu.iq).

M. A. K. Al Ani is with the Al-Nisour University College, Baghdad, Iraq (e-mail: mohammed.itm@nuc.edu.iq).

Digital Object Identifier (DOI): 10.24138/jcomss-2025-0091

MIMO, regarded as a cutting-edge wireless communication technology, enhances system reliability and increases the capacity of channels via multiple antennas. Initially, it was introduced in the early 1990s to address the data rate limitations of traditional single antenna elements. MIMO has since been widely adopted across various networks to boost capacity, improve reliability and accelerate data transfer by optimizing the efficiency of wireless communication systems [3]. Despite its benefits, MIMO systems may encounter challenges related to multipath propagation because of high correlation between each element [4], [5]. Furthermore, when antennas are placed closer together in MIMO setups, mutual coupling can intensify, negatively affecting antenna performance, which has an effect on the accuracy of carrier frequency offset estimation and SINR [6], [7]. While using multiple antennas for both sending and receiving significantly enhances data throughput and system performance, the trend toward more compact MIMO systems has made mutual coupling a more prominent concern [8], [9]. To address this, various mitigation techniques have been developed. Each technique offers distinct advantages and is selected based on the specific needs of the antenna configuration.

The main contributions of this study are:

- To conduct a comprehensive survey of isolation techniques used over the past five years, providing an overview of the state of the art in mutual coupling reduction.
- To perform a detailed analysis of the employed isolation techniques, examining their working principles and how they isolate MIMO antenna elements.
- To compile and present data on the distance among elements and the corresponding improvements in isolation (in dB) achieved after applying each technique.

The arrangement of this paper is as follows: Section II explains the concept of mutual coupling, its working principles, and causes, and briefly reviews the reduction coupling techniques that have been used over the last five years. Section III presents a survey of the isolation methods employed in recent literature. Finally, Section V summarizes the main conclusions of the study.

II. MUTUAL COUPLING

Mutual coupling is a key phenomenon in antenna arrays particularly in closely spaced configurations. It refers to the energy absorbed by nearby antenna elements when one element is active. This interaction affects antenna elements such as s-parameters, efficiency, and radiation of the array elements [10]. Therefore, it can degrade overall system performance, leading to unwanted interference, reduced gain, and beam distortion. Mutual coupling is influenced by factors such as array geometry, element spacing, and excitation methods. To support theoretical analysis, several empirical models of antenna coupling have been presented in the previous studies [11]. These models help predict the extent of interaction and guide the design of mitigation techniques. Reducing mutual coupling is essential for improving isolation between elements. Techniques like decoupling structures, defected ground planes, and electromagnetic bandgap materials are commonly used. Proper management of mutual coupling ensures enhanced array performance and reliability [12]:

$$MC_{ij} = \exp\left(a - \frac{2d_{ij}}{\lambda}(i + j\pi)\right) \quad i \neq j \qquad (1)$$

Here, a represents the number of array elements, denotes the distance between the first and other antenna radiators, and the coupling level is governed by a regulating parameter. Mutual coupling is influenced not only by the geometric arrangement of the array but also by the excitation of the individual elements. It is commonly expressed in decibels (dB). Moreover, the specific method of mutual coupling is significantly affected by whether the system operates in transmitting or receiving mode [12].

Alternatively, mutual coupling can be calculated by using the S-parameters, specifically the transmission coefficient, by the equation below [12]:

$$MC_{ij} = 20log_{10}|S_{21}| \qquad (2)$$

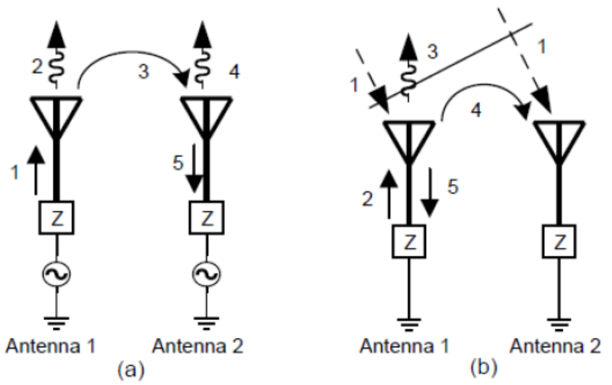


Fig. 1. Antenna array's mutual coupling: a) for the transmitting array, b) for the receiving array [10].

Fig. 1 (a) and (b) illustrate the scenario when Antenna 1 is energized and generates an electromagnetic wave. A segment of this energy, referred to as Energy 2, is instantly emitted into free space. Another segment, known as Energy 3, is transferred to the adjacent Antenna 2 through coupling. Upon receiving Energy 3, Antenna 2 generates a current and subsequently radiates a portion of it into space as Energy 4. At the same time, Energy 5 travels back into the signal source, where it combines with the energy emitted by Antenna 2. In this context, Energy 3 from Antenna 1 can also be considered as Energy 5. This coupling leads to impedance mismatch, which degrades the antenna system's overall performance [10]. Fig. 2 presents the common isolation techniques that are discussed in this survey paper.

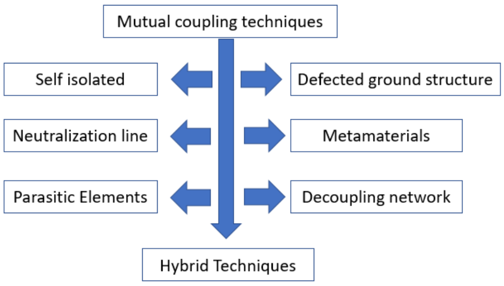


Fig. 2. Mutual coupling reduction techniques.

Fig. 2 shows different techniques have been utilized to improve the MIMO isolation in the recent five years. Self-isolated elements are designed with inherent isolation properties through careful shaping or layout [13], [21]. Defected ground structures (DGS) involve etching geometric shapes on the ground plane to reduce surface current and propagation energy [22], [35]. Neutralization lines are transmission lines connecting antenna elements to cancel induced currents [36], [48]. Metamaterials are engineered materials that exhibit unique electromagnetic properties, helping to block or redirect coupled energy [51], [62]. Parasitic elements placed between active antennas can redirect or absorb coupled energy to improve isolation [63], [75]. Decoupling networks use circuit-based solutions, such as reactive components, to suppress mutual coupling paths [76], [84]. Lastly, hybrid isolation techniques combine two or more of the above methods to achieve enhanced performance across broader frequency ranges and compact structures [85], [97].

III. MUTUAL COUPLING REDUCTION TECHNIQUES

This section will present a review of various decoupling techniques aimed at minimizing mutual coupling. The research will concentrate on key design parameters including bandwidth, isolation, efficiency, distance, enhancement isolation value and size. It also explores different MIMO antenna designs and isolation methods. Additionally, a review of MIMO antennas reported by researchers over the past five years is included. Various decoupling techniques have been documented in the literature for this topic and this study categorizes them into seven distinct groups as outlined above. In the following section, each isolation technique will be briefly discussed and highlighting its fundamental principles. Subsequently, we will review the previous works related to each technique individually. Additionally, a table has been prepared to summarize the previous studies, presenting the results of each work in order to compare the validation of the different techniques.

1) Self-isolated: Antennas can be designed to inherently reduce mutual coupling through their geometric configurations. By carefully shaping and structuring the antennas, engineers can minimize interaction between elements, thus improving isolation by optimizing the spacing between them. In [4], a UWB antenna is introduced featuring a jug-shaped patch and coplanar waveguide as a feeder to achieve a wide bandwidth, as shown in Fig. 3. This MIMO antenna incorporates four radiating elements arranged in an orthogonal configuration to reduce mutual coupling without using any additional decoupling techniques. The overall operating frequency is 3-11 GHz and the lowest isolation is below -20 dB. Although straightforward in design, it can be further improved by applying decoupling methods. The distance among the radiating patches is 5.5 mm, and despite the disconnected ground plane, the symmetrical layout ensures consistent performance and system reliability.

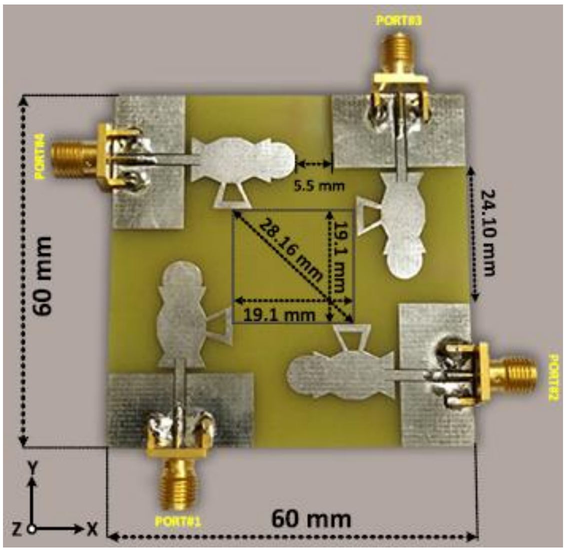


Fig. 3. Jug-shaped patch MIMO antenna presented in [4].

A MIMO antenna operating within the 28 to 37.5 GHz frequency band is presented in [14]. The antenna consists of four rectangular patches located close to each other with a spacing of 0.2 mm. This design achieves a maximum isolation of -18 dB without using any external isolation structures. Various antenna parameters were explored to obtain wide bandwidth and minimal spacing while still preserving high isolation performance.

Additionally, this paper [16] presents a compact triple operating frequency MIMO antenna incorporating multiple stubs and fed by a CPW. The elements of the antenna were located with a distance of just 4 mm. However, it achieves maximum isolation below −30 dB and an ultra-low ECC of 0.0001, ensuring minimal inter-element interference. The 4-port configuration is optimized for future 5G/6G devices with measured results closely matching simulations. Despite its small footprint (60 mm × 60 mm), the antenna maintains high gain and broad coverage. These isolation characteristics make it highly suitable for high-performance, dense communication environments, and it stands out as a robust solution for 5G wireless systems. Table I presents a comparison of the results from previous studies that used self-isolated techniques.

TABLE I
COMPARISON OF SELF-ISOLATED-RELATED WORKS

Ref.	Bandwidth (GHz)	Isolation (dB)	Size (mm^3)	Dis. (mm)	NO.
[4]	3-11	<-20	60 ×60×1.6	5.5	4
[13]	4.48-3.63	<-20	92.06 × 6 × 1.6	5.6	4
[14]	28-37.5	<-18	38×16×1.6	0.2	4
[15]	3.3-6	<-20	150×80×7	20	8
[16]	2.2-3.5 4.8-6.2 7.8-9.8	<-30	60×60×0.79	20	4
[17]	2-2.3 3.3-3.8 3.9-5.7	<-11	20×30×1.6	------	2
[18]	3.4-3.6	<-13	75×150×7	39.27	8
[19]	3.35 -3.53	<-15	75×150×7	-------	10
[20]	3.37-3.56	<-20	150 × 75 × 0.8	20.8	8
[21]	0.88–1.0, 3.11–4.63	<-15	48×27×1.6	5	2

For more details on the previous studies listed in Table I, we observe that different methods of self-isolation techniques were used. However, not all antennas succeeded in achieving high isolation. For instance, studies such as [14], [17], [19], and [21] reported a maximum isolation of around –18 dB, even with antenna spacings greater than 20 mm. In contrast, other studies such as [4], [13], [15], [16], and [20] achieved isolation levels better than –20 dB with spacing distances of less than 10 mm. This variation may be attributed to strong surface currents on the antenna that were not effectively suppressed, indicating that self-isolation techniques alone are not always sufficient to improve isolation.

2) Defected ground structure (DGS): This method involves creating intentional defects or disruptions in the antenna's ground plane. Known as a Defected Ground Structure (DGS), it alters the current distribution, thereby reducing coupling between antenna elements. Among the commonly reported isolation techniques in previous studies, DGS is widely used due to its ability to suppress surface waves and minimize mutual coupling. Additionally, it significantly improves isolation between antenna ports [22]. By modifying the ground plane, the surface current generated can be redirected or suppressed, reducing its tendency to couple with nearby elements and thereby enhancing the isolation performance in MIMO antennas.

In [23], two identical square patch antennas were placed at a relatively large distance from each other on a common ground plane, designed to operate at 5.8 GHz. The achieved isolation without any decoupling techniques was approximately –14 dB. To reduce mutual coupling, a zigzag groove was etched at the center of the ground plane to serve as a Defected Ground Structure (DGS), as shown in Figure 4. The results demonstrated a significant reduction in mutual coupling, with isolation improved to below –22 dB even in the worst-case scenario.

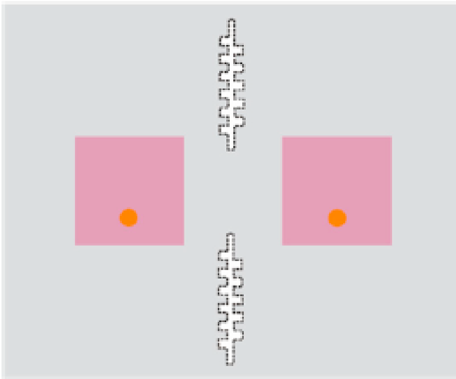


Fig. 4. Square patch antenna with zigzag groove proposed in [23].

A simple rectangular microstrip MIMO antenna with a conventional ground plane designed for body-centric applications is presented in [25]. Initially, the antenna did not exhibit any resonance frequency. To enable operation at 2.45 GHz and enhance isolation, wide and narrow rectangular slots, along with a semi-circular slot, were etched into the ground plane. These modifications resulted in improved isolation, achieving values below –21 dB under flat conditions and around –20 dB under bent conditions.

Finally, the study in [26] introduces a quad-element circular patch MIMO antenna with two rectangular slots on the left and right sides, sharing a common ground plane and fabricated on a Rogers RT/5880 substrate for millimeter-wave applications. To enhance isolation, square slots with dimensions of 1 mm were etched along the ground plane. This decoupling method effectively improves isolation and overall MIMO performance. With a wide bandwidth of 3.52 GHz and a high gain of 7.1 dBi, it maintains a low envelope correlation coefficient. Through iterative optimization of the DGS, the design achieves excellent channel diversity and significantly reduces inter-element interference.

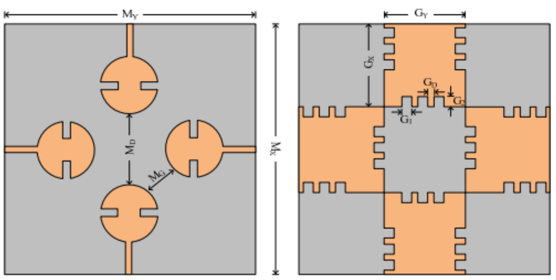


Fig. 5. Modified circular MIMO antenna with DGS enhancement presented in [26].

Table II presents a comparison of results from previous studies that employed DGS techniques in terms of bandwidth, isolation, antenna size, element spacing, isolation improvement after applying the technique, and the number of elements. Table II referred to the previous studies of using DGS. We note that the studies [2], [26], [28], [29], [30] and [34] achieved a good isolation below -20 dB. But at the same time, the distance among them and the size are large, which does not meet the needs of compact size for new compact devices. However, studies [23], [24], [27], [31], [33] obtained isolation below -20 with a maximum distance of 10 mm. Which proves that using the DGS method has a positive effect on coupling reduction.

TABLE II
COMPARISON OF DGS TECHNIQUE-RELATED WORKS.

Ref.	BW (GHz)	Iso. (dB)	Size (mm^3)	Iso. Imp. (dB)	Dis. (mm)	NO.
[22]	2.4-2.7,4.7-5.2,6.6-7,8.7-9.4	<-18	50×70×1.6	4	>20	2
[23]	5.8	<-28	45×55.6×1.546	10	2.6	2
[24]	3.1-3.92	<-72	25×38×1.6	4	3	2
[25]	2.45	<-22	40×90×0.8	8	------	2
[26]	27	<-30	30×30×1.6	15	14	4
[27]	5–13.5	<-21	20×29×1.6	6	10	2
[28]	5.5–9.2, 13.2–17.9, 11.5–14.6	<-25	-----	7	------	4
[29]	26-30	<-15	30 × 35 × 0.76	5	------	4
[30]	2.3-2.6	<-20	50×80×1.6	6	40	2
[31]	5–13.5	<-21	20 × 29 × 1.6	-----	10	2
[32]	2.4 -2.6, 3.3 – 5.0,5.15 -5.75	<-20	------	6	10	4
[33]	5.725 - 5.825	<-25	36.9 × 24×1.6	18	4	2
[34]	5.1-6	<-25	100 × 50	13	40	2
[35]	2.46-2.49	<-40	29.4×22.2 ×0.6	20	1	2

3) Neutralization Line (NL): A neutralization line is a conductor positioned between two antennas to mitigate mutual coupling. It functions by generating an opposing electromagnetic field that cancels out the coupling effects between the antennas, thereby enhancing overall system performance. In MIMO antenna design, NL is a narrow metallic structure used to enhance isolation among antenna elements and address the coupling issues. The dimensions, positioning, and geometry of the NL are customized based on the particular antenna setup. Although the structure is straightforward and easy to fabricate, achieving an effective design and seamless integration of the NL can be complex [36].

In [38], a two-element MIMO antenna is proposed. The design starts by placing the two elements side by side and uses a CPW feeding method to enhance return loss. The antenna operates at triple bands for sub-6 GHz 5G applications but exhibits strong mutual coupling. To address this, the authors introduced a simple NL connected to the CPW of each element. The obtained results show a significant improvement in terms of isolation from –10 dB to below –17 dB by suppressing current flow between the radiating elements.

Reference [40] presents a four-dipole MIMO antenna for sub-6 of 5G communication. Each inverted two-element was printed on the top and bottom sides of the substrate. Plus-shaped metal strips of NL and a circular loop were used to reduce mutual coupling, which achieves isolation of around -21 dB at 2.45 GHz and -35 dB at 5.8 GHz. Furthermore, the inclusion of periodic and defected ground structures helps to further reduce mutual coupling. These combined techniques enable stable MIMO performance with minimal interference across both frequency bands. The antenna also offers wide bandwidth and omnidirectional radiation patterns, making it well-suited for high-efficiency WLAN applications.

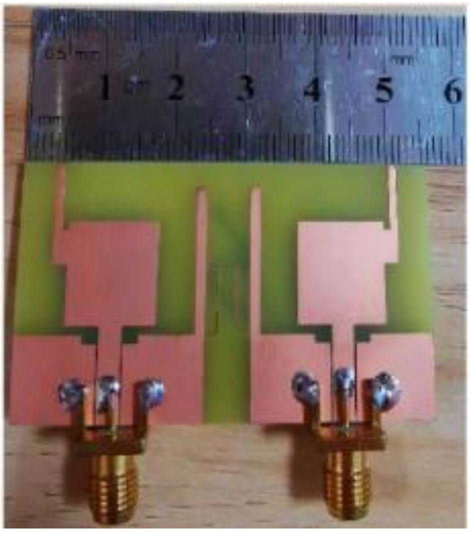


Fig. 6. Fabricated two element MIMO antenna in [38].

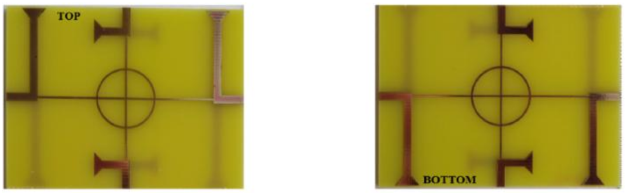


Fig. 7. Fabricated four element MIMO antenna in [40].

Another NL-based decoupling technique is explored in [41]. The study proposes a four-element U-shaped MIMO system for 5G applications with a focus on inter-element isolation. By incorporating decoupling structures, the design achieves isolation levels exceeding -14 dB over the operating band (3.20 to 3.86 GHz), even with closely spaced elements on a 36 × 36 mm² substrate. The orthogonal arrangement and monopole design promote pattern diversity, reduce coupling and ensure efficient performance. The achieved isolation supports stable MIMO for sub-6 of 5G communication.

Table III presents a comparison of the results from previous studies that used NL techniques in terms of bandwidth, isolation, size, distance between elements, isolation improvement after the applied technique, and number of elements. Table III referred to previous studies of MIMO antennas with the NL technique. For more comparison between the previous studies of NL effectiveness in terms of isolation improvement value. We found studies [37], [41] where the value of isolation enhancement was below 10 dB for the strongest coupling. While studies such as [42], [44] and [45] achieved enhancement isolation values above 9 dB. The confirm that NLs has a significant effect on the correlation among antennas.

TABLE III
COMPARISON OF NL TECHNIQUE-RELATED WORKS

Ref.	BW (GHz)	Iso. (dB)	Size (mm^3)	Iso. Imp. (dB)	Dis. (mm)	No.
[37]	3.44-4.68	<-15	-------	4	6.6	6
[38]	2.38–2.52, 3.28–3.63, 5.05–6.77	<-18, <-16, <-17	56×30×1.6	6	6	2
[39]	3.21–3.28	<-22	50×100×0.8	7	44	4
[40]	2.09–2.68, 4.73–6.33	<-21	60×45×1.6	---	31	4
[41]	3.2-3.84	<-14	36×36×1.6	---	---	4
[42]	4.3–15.63	<-20	30×18×1.6	10	10	2
[43]	2.4-2.7, 4.4-6.7	<-15	36×33.5×1.6	6	3	2
[44]	2.3,3.5,5.7	<-18	38×49×1.6	9.8	4	2
[45]	5.62-5.92	<-15.5	30×35×0.8	10	5	2
[46]	3.4–12.1	<-16	21.5×28×1.6	---	3.5	2

4) Metamaterials (MTM): Metamaterials are artificial structures engineered to manipulate electromagnetic waves in ways that natural materials cannot. The two main types include Electromagnetic Band Gap (EBG) structures, which suppress specific frequency bands to reduce mutual coupling. While metasurfaces can control wave direction, phase, and polarization [44]. These structures enhance MIMO systems by improving gain, efficiency, and isolation, while enabling compact and reconfigurable antenna designs. Metasurfaces also support advanced functionalities like smart beam steering and dynamic signal control [49].

Despite their advantages, metamaterials often face limitations such as narrow bandwidth, high fabrication complexity, and increased cost. They may also introduce signal losses, particularly at higher frequencies. Nevertheless, these methods offer considerable potential for current and next-generation communications [50].

A quad-element MIMO antenna featuring a G-shaped slot is introduced in [51]. The elements are arranged orthogonally to minimize unwanted coupling. Additionally, an S-shaped EBG structure is printed in the free space among the four elements, as seen in Fig. 8, to enhance isolation below –18 dB with an enhancement value of isolation of 10 dB.

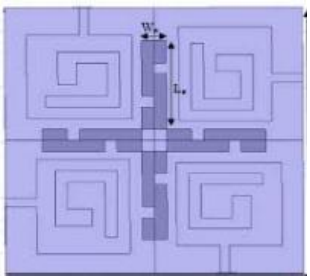


Fig. 8. Compact four-element MIMO antenna with S-shaped EBG.

In [3], a wideband MIMO antenna operating from 3.1 to 11 GHz is presented. It consists of two identical rectangular patch antennas printed on an FR-4 substrate with a partial ground plane. To address strong coupling caused by the 8 mm spacing between elements, small rectangular EBG unit cells are arranged vertically with a 5 mm periodicity, and a vertical slot is etched in the center of the EBG structure. This configuration improves isolation significantly, reducing coupling from –12 dB to below –25 dB.

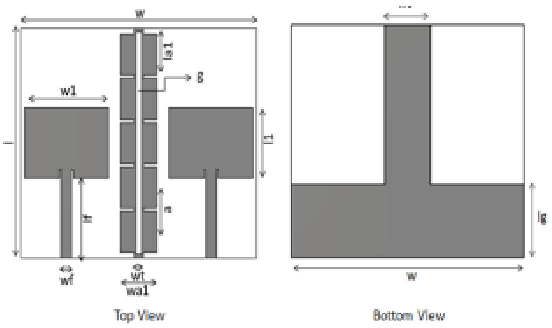


Fig. 9. Compact four-element MIMO antenna with S-shaped EBG [3].

Finally, [54] presents a two-element MIMO antenna enhanced by a single-layer metamaterial (MTM) superstrate for 5G applications. The metasurface, arranged in a periodic pattern, significantly reduces mutual coupling, improving isolation from 5.7 dB to –45 dB. V-shaped slots on the patch are incorporated to optimize bandwidth, covering 4.74 to 4.95 GHz. With a maximum gain of 7.7 dB at 4.9 GHz. The antenna demonstrates strong radiation characteristics. This compact and efficient design is particularly suitable for indoor 5G MIMO systems.

Table VI presents a comparison of the results from previous studies that used MTM techniques in terms of bandwidth, isolation, size, distance between elements, isolation improvement after the applied technique, and number of elements. Table IV referred to the previous studies of MIMO with MTM (EBG and meta-surfaces); it can be noted that some of these EBG and meta-surface structures have positive effects on the isolation, such as [3], [50], [53], [55], [57] and [60], which achieved a high isolation below -20 dB. On the other hand, published work, such as [49], [56], and [59], has not obtained high isolation (above -20 dB). Nevertheless, distance among antennas also has a significant effect on correlation between antennas. The distance in [3] and [54] was just 8 and 13 mm, respectively. However, the EBG in [3] was more effective than the EBG in [54] despite the operating bandwidths of both studies being close to each other. But isolating in [3] is better than this study [54].

5) Parasitic Elements (PE): Parasitic components are passive elements added to antenna arrays to modify the distribution of the electromagnetic field. By absorbing or redirecting energy, these elements help reduce coupling between active antennas, thereby enhancing isolation [63]. In [63], a high isolation MIMO microstrip monopole antenna array is proposed, incorporating an innovative composite parasitic element. This element consists of a T-shape with an isolated branch on the ground plane, which together generate a novel 3D weak electric field that effectively minimizes mutual coupling. The resulting antenna achieves up to a 26 dB improvement in isolation, demonstrating the effectiveness of the PE.

TABLE IV
COMPARISON OF MTM TECHNIQUE-RELATED WORKS

Ref.	BW (GHz)	Iso. (dB)	Size (mm^3)	Iso. Imp. (dB)	Dis. (mm)	NO.
[49]	3.3-3.7	-10.5	48×48×1.6	5	-------	4
[3]	3.1-11	-25	26×31×0.8	22	8	2
[50]	3-5	-20	75 × 134 × 0.8	3	31	6
[51]	3.1–11.8	-20	54×54×1.54	12	14	4
[52]	4.78 - 5.08	-20	34×45×13	13	2	2
[53]	2.4-3.8,4.6-5.6, 23-25.3,26.8-29	-22	80×80×0.51	9	5	6
[54]	3–12	-15	30×60 × 1.6	-----	13	2
[55]	8.2-12	-27	40 × 40 × 0.8	20	----	2
[56]	3 – 6	-16	66×36×1.6	4	42.8	2
[57]	25.25–29.85	-47	25 × 10 × 1.52	10	10	2
[58]	3.2–4.4	-17	50×50×1.6	5	6.8	4
[59]	2.34–2.46, 3.66–6.00	-15	185 × 111 × 4.21	6	30	2
[60]	20.22 - 30.65	-20	26 × 14.5×0.508	10	7	2

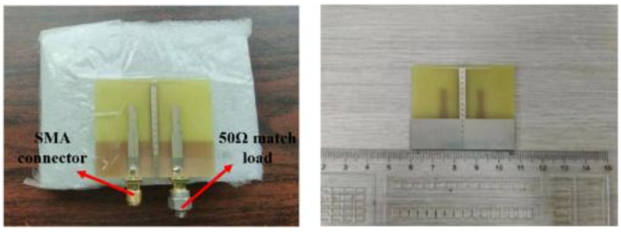


Fig. 10. Microstrip monopole antenna with enhanced isolation via PE [63].

In [64], a compact MIMO antenna is proposed for microwave and mm-wave systems, operating across 2.4 GHz and 28 GHz. A semi-circular slotted monopole combined with quarter-wavelength metallic stubs facilitates multi-band performance with -10 dB impedance bandwidths. In the initial design, the coupling among antennas was strong. Therefore, decoupling structure based on a combination of parasitic elements was employed to enhance isolation. The obtained results after using PE show there is a good enhancement in terms of isolation (maximum isolation achieved is -28 dB). The antenna exhibits radiation efficiency above 85% in microwave bands and 95% in mm-wave bands. Additionally, a low-pass filter is integrated to support simultaneous band operation. The design offers high diversity performance in a compact form factor, making it suitable for emerging 5G and IoT systems.

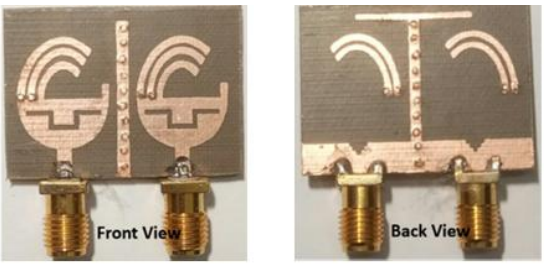


Fig. 11. Fabricated two-port MIMO antenna for microwave and mmWave proposed in [64].

The study in [65] presents a MIMO antenna designed based on a fractal shape tailored for Sub-6 5G communications. To improve isolation between antenna elements, the design incorporates a T-shaped stub along with triangular slots positioned between the radiators. Additional enhancement of isolation is accomplished through the use of split-ring resonators (SRRs). These strategies ensure isolation levels above -15 dB, while also maintaining low ECC and high diversity gain. The antenna achieves efficient performance across a broad bandwidth with high radiation efficiency.

Table V presents a comparison of the results from previous studies that used PE techniques in terms of bandwidth, isolation, size, distance between elements, isolation improvement after the applied technique, and number of elements.

TABLE V
COMPARISON OF PE TECHNIQUE-RELATED WORKS

Ref.	BW (GHz)	Iso. (dB)	Size (mm^3)	Iso. Imp. (dB)	Dis. (mm)	NO.
[63]	3.1-3.8	-19.5	40×47.5×1.6	19	13	2
[64]	0.55, 0.66, 0.51, 1.26, 4.37	<-19	32×22×1.6	8	4	2
[65]	3.3–6.0	<-15	72×72×1.6	9	23	2,8
[66]	1.2 -3, 4.5 - 5.7	<-16	171×95×0.68	4	50	2
[67]	2.42-7.45	<-12	35×35 × 1.6	5	15	4
[68]	3.34-3.87	<-20	20 × 35 × 0.8	10	9	2
[69]	4.4-5	<-30	55×46.1.6	8	--	2
[70]	3.7-4.3	<-25	40.29×35.14×1.6	5	24	2
[71]	3.3-3.9	<-32	146×146×1.6	15	57.9	4
[72]	2.28–2.47,3.34–3.73,4.57–6.75	<-20	44 × 31 × 1.6	19	13	2
[73]	26.5–31.5,36–41.7	<-50	28 × 28 × 0.79	8	4	2
[74]	3.2-5.75	<-22	40 ×40 ×1.6	9	23	2,8
[75]	5-5.8	<-20	80 ×50× 1.6	4	50	2

Table V referred to the previous studies of MIMO with PE technique; it can be noted that some of these PE structures have positive effects on the isolation, such as [68] and [75], which achieved a high isolation below -20 dB. On the other hand, published work such as [63] and [67] has not obtained high isolation (above -20 dB). However, studies like [63] achieved high isolation improvement of more than -12 dB. While studies such as [68], [70], [73], and [75] achieved isolation improvement values below -10 dB for the worst situation.

6) Decoupling network (DN): The decoupling network isolation technique involves integrating a network of passive components such as metal strips, stubs, loops, or additional circuit elements between antenna elements to minimize mutual coupling [78]. These networks function by rerouting or neutralizing surface currents and electromagnetic fields that contribute to interference between MIMO antenna ports [79]. Properly designed decoupling networks can significantly enhance isolation, improve impedance matching, and maintain radiation efficiency without increasing antenna size. This technique is widely used in compact MIMO systems, especially for mobile and WLAN applications, due to its simplicity and effectiveness [80].

In [77], circularly polarized MIMO antennas with two- and four-port configurations are introduced to operate from 2.41 to 2.47 GHz with high coupling about -9 dB due to the small distance between each antenna. A band-stop filter-based decoupling network was utilized to reduce the strong coupling as seen in Figure 12. This method improved isolation to over -30 dB isolation as the best result, while the worst isolation was below -17. However, the enhancement isolation value after introducing the band-stop filter was 6 dB as a minimum value. That proves a significantly improving MIMO system performance.

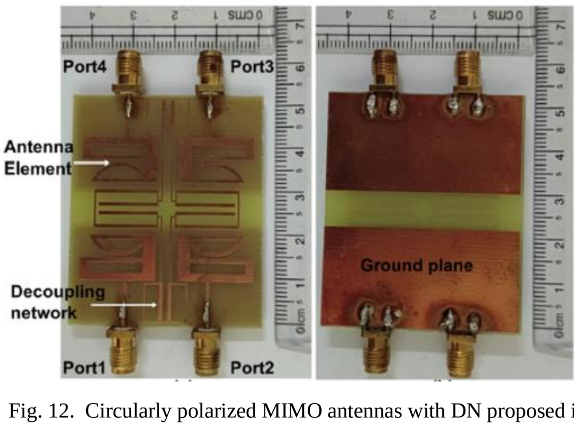


Fig. 12. Circularly polarized MIMO antennas with DN proposed in [77].

A quad-element MIMO antenna system designed for mmWave applications is presented in [78]. Each element consists of a meandering V-shaped radiating structure with a microstrip line. The presented antenna has a wideband behavior (20–32 GHz). To improve isolation between horizontally adjacent elements, all antenna elements are connected to the same ground plane by using a circular stub to achieve isolation over -20 dB. The system offers an impedance bandwidth from 20.2 to 32 GHz and a maximum gain of 6.6 dBi at 28 GHz. In addition, ECC achieved 0.0055, which confirms that the antenna has good isolation.

Finally, a compact, conformal monopole MIMO antenna designed for smart vehicle communication is proposed in [79]. Each element consists of a U-shaped monopole with a loaded meander strip on the top right corner and a CPW as a feeder. To reduce mutual coupling, a pair of circular rings loaded with four open-ended U-shaped stubs. After this edition, the mutual coupling improved from -19 to -29 at the worst situation over 5.37 to 7.34 GHz. Although the distance between each element was only 4 mm.

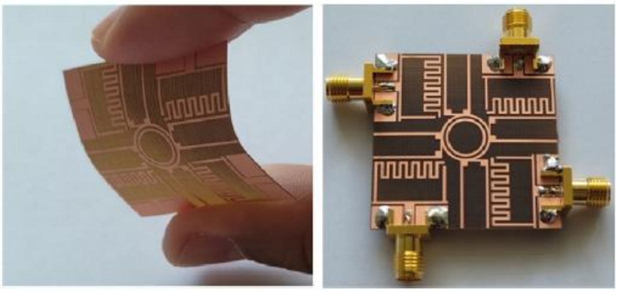


Fig. 13. conformal monopole MIMO antenna for V2X proposed in [79].

TABLE VI
COMPARISON OF DN TECHNIQUE-RELATED WORKS

Ref.	BW (GHz)	Iso. (dB)	Size (mm^3)	Iso. Imp. (dB)	Dis. (mm)	NO.
[76]	7.4-11.8	<-26	30×30×1.6	20	18	2
[77]	2.78–2.93	<-15	44×22×1.6	4	8.25	2
[77]	2.41–2.47	<-15	44×52×1.6	6	12	4
[78]	20–32	<-20	24× 32×0.254	0.0055	8	4
[79]	5.53–7.32	<-29	37×37×0.508	10	7	4
[80]	698-960,1.47-2.7	<-10	19.1× 15× 65	-----	----	2
[81]	1.95–2.72	<-15	100 × 50 × 38.6	4	-----	2
[82]	1.6-1.8,2.3-2.5	<-15	40 ×40× 0.508	4	15	4
[83]	1.8 – 9.9	<-20	40 × 46 × 2	6	12	4
[84]	1.85-2.1	<-22	-----	15.5	-----	2

Table VI referred to previous studies of MIMO antennas with DN technique. For more comparison between the previous studies of DN effectiveness in terms of isolation improvement value. We found studies [76], [77], [82] and [83] value of isolation enhancement was below 10 dB for the strongest coupling. While studies such as [78], [81] and [84] achieved enhancement isolation values above 9 dB, which proves that some DN structures have a significant effect on the correlation among antennas.

7) Hybrid Techniques: Combine two or more decoupling methods, such as NL and DGS, EBG structures, and PE, or other combinations of different isolation techniques to achieve superior isolation in complex MIMO antenna systems. These integrated approaches address the limitations of individual methods and are particularly effective for modern wireless systems with compact form factors and multi-band requirements [88].

Study [86] presents a MIMO design composed of two rectangular microstrip patch antennas operating in the sub-5 5G communications. Due to a small 8 mm separation between elements, mutual coupling is initially high. To mitigate this, a NL is introduced between elements to oppose current flow, improving isolation to –12 dB. An asymmetric open slot etched on the ground plane further reduces coupling, achieving isolation better than –17 dB.

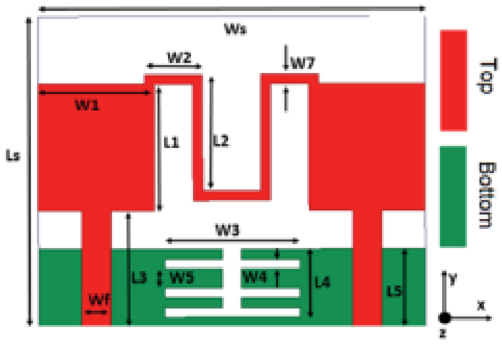


Fig. 14. Rectangular microstrip patch antennas with PE and NL presented in [86].

In [87], a novel ultra-wideband (UWB) MIMO antenna is developed using a modified base design to address the close proximity of antenna elements. The study integrates two techniques of NL and split ring resonator. NL reduces coupling by more than -15 dB, while SRR metamaterial contributes an additional -20 dB of isolation. The hybrid approach preserves radiation characteristics and operating bandwidths, making it suitable for 5G and modern communication systems.

Article [89] introduces a reconfigurable dual-band MIMO antenna for 5G (3.5 GHz) and ISM (5.2 GHz) bands. The design includes a partial ground plane DGS (PGP-DGS) and pin diode-controlled branch lines for dynamic frequency tuning. To enhance isolation, a mushroom-inspired EBG structure is integrated with the DGS. The isolation achieved was below -25 dB after the insertion of the hybrid technique. Experimental results confirm strong isolation and effective frequency reconfigurability, supporting diverse practical applications in wireless communication.

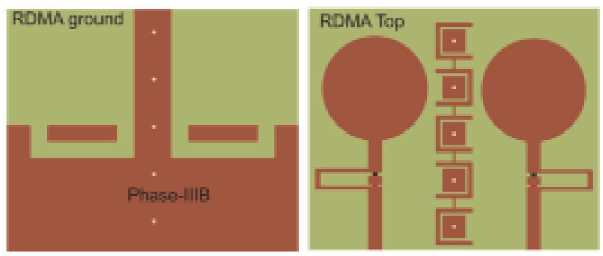


Fig. 15. Reconfigurable MIMO antenna used DGS and EBG in [89].

Table VII presents a comparison of the results from previous studies that used hybrid techniques in terms of bandwidth, isolation, distance between elements, isolation improvement after the applied technique, number of elements and used techniques.

TABLE VII
COMPARISON OF HYBRID TECHNIQUE-RELATED WORKS

Ref.	BW (GHz)	Iso. (dB)	Iso. Imp. (dB)	Dis. (mm)	NO.	Tech.
[85]	4.9-5.06	<-20	6	-----	2	DGS & NL
[86]	4.9-5.5	<-17	8	7	2	NL & PE
[87]	3.2-17.7	<-15	6	2.8	4	MTM & NL
[88]	5.2–5.7, 11.8–17.3, 23.4–37.3	<-20	7	16.7		DGS & PE
[89]	2.8-3.6, 4.7-5.6	<-25	9	11.5	2	DGS & EBG
[90]	1.92-6.1	<-15	8	12	2	PE & DGS
[91]	2.45,5.25	<-36	18	6.8	2	PE & DGS
[92]	3.8 – 5.4	<-19	7	-----	2	NL & DGS
[93]	3.35-3.68	<-16.5	5		2	NL & DGS
[94]	3.45-3.7	<-20	6	-----	8	Self-isolated & PE
[95]	3.1–12.5	<-22	12	6	4	NL &DGS
[96]	1.6–4.4	<-15	------	11	4	
[97]	2.82 - 14.45	<-22	6	-----	2	DGS & NL

V. CONCLUSION

Effective isolation between antenna elements is critical for enhancing the performance of MIMO systems in increasingly compact and complex environments. This review demonstrates that various techniques ranging from passive structures like parasitic elements and EBGs to advanced solutions like metamaterials can significantly reduce mutual coupling. Among them, hybrid techniques show the greatest potential by leveraging the strengths of individual methods. Neutralization lines and DGS remain popular due to their ease of integration and performance consistency. Metamaterial-based designs offer superior control over electromagnetic behavior but often suffer from fabrication complexity. The reviewed literature confirms that isolation improvements of 15–45 dB are achievable with proper technique selection. Furthermore, low ECC and stable radiation patterns are consistently maintained across the proposed designs. Future research should focus on reconfigurable and adaptive isolation techniques for dynamic wireless environments. This study provides a solid foundation for designing next-generation high-isolation MIMO antennas.

REFERENCES

[1] S. Kumar, A. S. Dixit, R. R. Malekar, H. D. Raut, and L. K. Shevada, "Fifth generation antennas: A comprehensive review of design and performance enhancement techniques," IEEE Access, vol. 8, pp. 163568–163593, 2020, doi: 10.1109/ACCESS.2020.3020952.

[2] H. Yon et al., "Development of c-shaped parasitic mimo antennas for mutual coupling reduction," Electron., vol. 10, no. 19, 2021, doi: 10.3390/electronics10192431.

[3] A. Khan, S. Bashir, S. Ghafoor, and K. K. Qureshi, "Mutual Coupling Reduction Using Ground Stub and EBG in a Compact Wideband MIMO-Antenna," IEEE Access, vol. 9, pp. 40972–40979, 2021, doi: 10.1109/ACCESS.2021.3065441.

[4] S. Ahmad et al., "A Compact CPW-Fed Ultra-Wideband Multi-Input-Multi-Output (MIMO) Antenna for Wireless Communication Networks," IEEE Access, vol. 10, pp. 25278–25289, 2022, doi: 10.1109/ACCESS.2022.3155762.

[5] P. Sharma, R. N. Tiwari, P. Singh, P. Kumar, and B. K. Kanaujia, "and Applications," 2022.

[6] A. S. Adesoye, J. J. Popoola, and A. O. Fadamiro, "Mutual Coupling in a Collocated Dipole Antenna Setup: A Comprehensive Review," vol. 8, no. 9, pp. 14565–14585, 2021.

[7] T. Pei, L. Zhu, J. Wang, and W. Wu, "A low-profile decoupling structure for mutual coupling suppression in mimo patch antenna," IEEE Trans. Antennas Propag., vol. 69, no. 10, pp. 6145–6153, 2021, doi: 10.1109/TAP.2021.3098565.

[8] M. M. Hassan et al., "Two element MIMO antenna with frequency reconfigurable characteristics utilizing RF MEMS for 5G applications," J. Electromagn. Waves Appl., vol. 34, no. 9, pp. 1210–1224, 2020, doi: 10.1080/09205071.2020.1765883.

[9] C. Rhee et al., "Pattern-reconfigurable MIMO antenna for high isolation and low correlation," IEEE Antennas Wirel. Propag. Lett., vol. 13, pp. 1373–1376, 2014, doi: 10.1109/LAWP.2014.2339012.

[10] H. T. Chattha, M. K. Ishfaq, B. A. Khawaja, A. Sharif, and N. Sheriff, "Compact Multiport MIMO Antenna System for 5G IoT and Cellular Handheld Applications," IEEE Antennas Wirel. Propag. Lett., vol. 20, no. 11, pp. 2136–2140, 2021, doi: 10.1109/LAWP.2021.3059419.

[11] P. Kaur, S. Malhotra, and M. Sharma, "A Review of Isolation Techniques for 5G MIMO Antennas," J. Telecommun. Inf. Technol., 2024, doi: 10.26636/jtit.2024.3.1490.

[12] I. Nadeem and D. Y. Choi, "Study on Mutual Coupling Reduction Technique for MIMO Antennas," IEEE Access, vol. 7, no. c, pp. 563–586, 2019, doi: 10.1109/ACCESS.2018.2885558.

[13] F. Ghawbar, A. S. Jumadi, H. A. Majid, F. A. Saparudin, A. S. A. Ghafar, and B. A. F. Esmail, "Compact self-Isolated MIMO antenna system with low mutual coupling for 5G mobile applications," 2020 IEEE Student Conf. Res. Dev. SCOReD 2020, no. September, pp. 200–205, 2020, doi: 10.1109/SCOReD50371.2020.9250998.

[14] 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 J. Antennas Propag., vol. 4, no. January, pp. 81–90, 2023, doi: 10.1109/OJAP.2023.3234341.

[15] S. Nithya and V. Seethalakshmi, "MIMO Antenna with Isolation Enrichment for 5G Mobile Information," Mob. Inf. Syst., vol. 2022, no. February, 2022, doi: 10.1155/2022/1802352.

[16] M. Hussain, W. A. Awan, M. S. Alzaidi, and D. H. Elkamchouchi, "Self-decoupled tri band MIMO antenna operating over ISM, WLAN and C-band for 5G applications," Heliyon, vol. 9, no. 7, p. e17404, 2023, doi: 10.1016/j.heliyon.2023.e17404.

[17] S. H. Ghadeer, S. K. Sharul, and T. A. Elwi, "Solar Panel Integrated 3D MIMO Antenna Array for Modern Communication Systems," 2021 Int. Conf. Adv. Comput. Appl. ACA 2021, pp. 112–115, 2021, doi: 10.1109/ACA52198.2021.9626802.

[18] M. Y. Muhsin, A. J. Salim, and J. K. Ali, "A Compact Self-Isolated MIMO Antenna System for 5G Mobile Terminals," Comput. Syst. Sci. Eng., vol. 42, no. 3, pp. 919–934, 2022, doi: 10.32604/csse.2022.023102.

[19] D. Abbasi et al., "Higher Order MIMO Antenna Design Using Capacitively Coupled Meandered Loop Element for 5G Smartphone Applications," IEEE Trans. Circuits Syst. II Express Briefs, vol. 70, no. 8, pp. 2889–2893, 2023, doi: 10.1109/TCSII.2023.3253427.

[20] A. Zhao and Z. Ren, "Size Reduction of Self-Isolated MIMO Antenna System for 5G Mobile Phone Applications," IEEE Antennas Wirel. Propag. Lett., vol. 18, no. 1, pp. 152–156, 2019, doi: 10.1109/LAWP.2018.2883428.

[21] N. Kaur, J. Kaur, and S. Sharma, "MIMO Antenna System with Self Isolation Characteristics for GSM and sub - 6 GHz 5G Applications," Wirel. Pers. Commun., no. 0123456789, 2021, doi: 10.1007/s11277-021-08500-5.

[22] G. DIvya, K. Jagadeesh Babu, and R. Madhu, "Quad-band hybrid DRA loaded MIMO antenna with DGS for isolation enhancement," Int. J. Microw. Wirel. Technol., vol. 14, no. 2, pp. 247–256, 2022, doi: 10.1017/S1759078721000519.

[23] H. Xing et al., "Efficient isolation of an mimo antenna using defected ground structure," Electron., vol. 9, no. 8, pp. 1–13, 2020, doi: 10.3390/electronics9081265.

[24] G. Naga Jyothi Sree and S. Nelaturi, "Design and experimental verification of fractal based MIMO antenna for lower sub 6-GHz 5G applications," AEU - Int. J. Electron. Commun., vol. 137, no. February, p. 153797, 2021, doi: 10.1016/j.aeue.2021.153797.

[25] A. Gupta and V. Kumar, “DGS-based wideband MIMO antenna for on–off body communication with port isolation enhancement operating at 2.45 GHz industrial scientific and medical band,” J. Electromagn. Waves Appl., vol. 35, no. 7, pp. 888–901, 2021, doi: 10.1080/09205071.2020.1865209.

[26] M. Hussain et al., “Design and Characterization of Compact Broadband Antenna and Its MIMO Configuration for 28 GHz 5G Applications,” Electron., vol. 11, no. 4, pp. 1–14, 2022, doi: 10.3390/electronics11040523.

[27] S. B. Kempanna, R. C. Biradar, P. Kumar, P. Kumar, S. Pathan, and T. Ali, “Characteristic-Mode-Analysis-Based Compact Vase-Shaped Two-Element UWB MIMO Antenna Using a Unique DGS for Wireless Communication,” J. Sens. Actuator Networks, vol. 12, no. 3, p. 47, 2023, doi: 10.3390/jsan12030047.

[28] U. D. Yalavarthi, “Reconfigurable orthogonal quad-port MIMO antenna for DSRC, WLAN, RADAR and Ku-band applications,” AEU - Int. J. Electron. Commun., vol. 136, p. 153766, 2021, doi: 10.1016/j.aeue.2021.153766.

[29] M. Khalid et al., “4-port MIMO antenna with defected ground structure for 5G millimeter wave applications,” Electron., vol. 9, no. 1, 2020, doi: 10.3390/electronics9010071.

[30] R. Hussain, M. U. Khan, and M. S. Sharawi, “A dual PIFA based MIMO and tunable DGS MIMO antenna system,” IET Conf. Publ., vol. 2018, no. CP741, pp. 3–6, 2018, doi: 10.1049/cp.2018.0569.

[31] C. Güler and S. E. Bayer Keskin, “A Novel High Isolation 4-Port Compact MIMO Antenna with DGS for 5G Applications,” Micromachines, vol. 14, no. 7, p. 1309, 2023, doi: 10.3390/mi14071309.

[32] J. Kulkarni, T. Y. Han, J. S. Row, and C. Y. D. Sim, “Multiband 4-Port DGS MIMO Antenna with DR Isolating Element for Wireless Applications,” 2021 IEEE Int. Symp. Antennas Propag. North Am. Radio Sci. Meet. APS/URSI 2021 - Proc., no. mm, pp. 1021–1022, 2021, doi: 10.1109/APS/URSI47566.2021.9704610.

[33] Y. Tang, S. Deng, R. Gao, and S. Liu, “Shape optimization method for curved-groove DGS of MIMO antenna-array based on the trigonometric function expansion,” AEU - Int. J. Electron. Commun., vol. 139, p. 153904, 2021, doi: 10.1016/j.aeue.2021.153904.

[34] M. Kaur and H. S. Singh, “Design and analysis of high isolated super compact 2 × 2 MIMO antenna for WLAN application,” Int. J. RF Microw. Comput. Eng., vol. 31, no. 11, pp. 1–14, 2021, doi: 10.1002/mmce.22864.

[35] P. Kim-Thi and T. Pham-Danh, “Compact and high isolated microstrip patch antenna system for full-duplex/MIMO applications,” Heliyon, vol. 10, no. 19, p. e38980, 2024, doi: 10.1016/j.heliyon.2024.e38980.

[36] A. M. Ibrahim, I. M. Ibrahim, and N. A. Shairi, “Review isolation techniques of the MIMO antennas for Sub-6,” Prz. Elektrotechniczny, vol. 97, no. 1, pp. 3–9, 2021, doi: 10.15199/48.2021.01.01.

[37] M. Mishra, S. Chaudhuri, R. S. Kshetrimayum, and H. Chel, “Low mutual coupling six-port planar antenna for the MIMO applications,” Int. J. RF Microw. Comput. Eng., vol. 30, no. 12, pp. 1–10, 2020, doi: 10.1002/mmce.22439.

[38] C. Du, Z. Zhao, X. Wang, and F. Yang, “A compact cpw-fed triple-band mimo antenna with neutralization line decoupling for wlan/wimax/5g applications,” Prog. Electromagn. Res. M, vol. 103, no. July, pp. 129–140, 2021, doi: 10.2528/PIERM21042301.

[39] K. N. Patil, G. Akshay, T. Chaitanya, A. K. Dwivedi, N. K. Narayanaswamy, and V. Singh, “A Two-element MIMO Antenna with a Small Footprint for 5G Connectivity,” Proc. 2022 Work. Microw. Theory Tech. Wirel. Commun. MTTW 2022, pp. 110–113, 2022, doi: 10.1109/MTTW56973.2022.9942621.

[40] A. Birwal, S. Singh, B. K. Kanaujia, and S. Kumar, “MIMO/Diversity Antenna with Neutralization Line for WLAN Applications,” Mapan - J. Metrol. Soc. India, vol. 36, no. 4, pp. 763–772, 2021, doi: 10.1007/s12647-020-00427-9.

[41] N. Agrawal, M. Gupta, and S. Chauhan, “Design and Simulation of MIMO antenna for low frequency 5G band application,” 2021 2nd Glob. Conf. Adv. Technol. GCAT 2021, pp. 1–4, 2021, doi: 10.1109/GCAT52182.2021.9587860.

[42] W. Mu et al., “A Flower-Shaped Miniaturized UWB-MIMO Antenna with High Isolation,” Electron., vol. 11, no. 14, 2022, doi: 10.3390/electronics11142190.

[43] A. M. Saleh, T. A. Nagim, R. A. Abd-Alhameed, J. M. Noras, and C. H. See, “Mutual coupling reduction of dual-band uni-planar MIMO system using neutralization line technique,” Appl. Comput. Electromagn. Soc. J., vol. 35, no. 2, pp. 167–175, 2020.

[44] A. Nur et al., “Textile MIMO Antenna Using Viscose-Wool Felt,” 2022.

[45] D. Saxena, A. Kumar, R. K. Verma, and P. Jha, “Metamaterial Inspired Dual band MIMO antenna with Open-Ended Slot and Neutralized Line for Isolation Enhancement,” Proc. 10th Int. Conf. Signal Process. Integr. Networks, SPIN 2023, vol. 2, pp. 727–732, 2023, doi: 10.1109/SPIN57001.2023.10117256.

[46] P. Kumar, T. Ali, and M. P. MM, “Characteristic Mode Analysis-Based Compact Dual Band-Notched UWB MIMO Antenna Loaded with Neutralization Line,” Micromachines, vol. 13, no. 10, 2022, doi: 10.3390/mi13101599.

[47] P. Kumar, T. Ali, and M. M. Manohara Pai, “Two-Port UWB MIMO Antenna Based on the Neutralization Line Approach for Automotive Applications,” 2023 15th Int. Conf. Comput. Autom. Eng. ICCAE 2023, pp. 575–579, 2023, doi: 10.1109/ICCAE56788.2023.10111355.

[48] A. Singh, A. Kumar, and B. K. Kanaujia, “A Compact Low-Profile High Isolation MIMO Antenna For X-Band Applications,” ResearchSquare, 2021.

[49] J. An et al., “Stacked Intelligent Metasurface-Aided MIMO Transceiver Design,” IEEE Wirel. Commun., vol. 31, no. 4, pp. 123–131, 2024, doi: 10.1109/MWC.013.2300259.

[50] W. Li, kun Zhang, R. Pei, and F. Xu, “Composite metamaterial antenna with super mechanical and electromagnetic performances integrated by three-dimensional weaving technique,” Compos. Part B Eng., vol. 273, no. January, p. 111265, 2024, doi: 10.1016/j.compositesb.2024.111265.

[51] G. Tamminaina and R. Manikonda, “Investigation on Performance of Four Port MIMO Antenna Using Electromagnetic Band Gap for 5G Communication,” Prog. Electromagn. Res. M, vol. 119, no. August, pp. 51–62, 2023, doi: 10.2528/PIERM23080303.

[52] A. M. Hediya, A. M. Attiya, and W. S. El-Deeb, “5G MIMO Antenna System Based on Patched Folded Antenna with EBG Substrate,” Prog. Electromagn. Res. M, vol. 109, no. March, pp. 149–161, 2022, doi: 10.2528/PIERM22020101.

[53] A. Abbas et al., “Highly selective multiple-notched UWB-MIMO antenna with low correlation using an innovative parasitic decoupling structure,” Eng. Sci. Technol. an Int. J., vol. 43, p. 101440, 2023, doi: 10.1016/j.jestch.2023.101440.

[54] W. Zhou, C. Yue, and Y. Li, “Metamaterial Promoting 5G MIMO Antenna with Isolation Enhancement,” 2021 Int. Appl. Comput. Electromagn. Soc. Symp. ACES-China 2021, Proc., pp. 1–2, 2021, doi: 10.23919/ACES-China52398.2021.9581860.

[55] S. Jabeen and Q. U. Khan, “An integrated MIMO antenna design for Sub-6 GHz & millimeter-wave applications with high isolation,” AEU - Int. J. Electron. Commun., vol. 153, no. June, 2022, doi: 10.1016/j.aeue.2022.154247.

[56] N. S. Babu, A. Q. Ansari, B. K. Kanaujia, G. Singh, and S. Kumar, “A two-port UWB MIMO antenna with an EBG structure for WLAN/ISM applications,” Mater. Today Proc., vol. 74, pp. 334–339, 2023, doi: 10.1016/j.matpr.2022.08.316.

[57] A. A. Althuwayb, “Low-Interacted Multiple Antenna Systems Based on Metasurface-Inspired Isolation Approach for MIMO Applications,” Arab. J. Sci. Eng., vol. 47, no. 3, pp. 2629–2638, 2022, doi: 10.1007/s13369-021-05720-6.

[58] N. Supreeyatitikul, A. Phungasem, and P. Aeimopas, “Design of Wideband Sub-6 GHz 5G MIMO Antenna with Isolation Enhancement Using an MTM-Inspired Resonators,” 2021 Jt. 6th Int. Conf. Digit. Arts, Media Technol. with 4th ECTI North. Sect. Conf. Electr. Electron. Comput. Telecommun. Eng. ECTI DAMT NCON 2021, pp. 206–209, 2021, doi: 10.1109/ECTIDAMTNCON51128.2021.9425774.

[59] T. Islam, F. Alsaleem, F. N. Alsunaydih, and K. Alhassoon, “Mutual Coupling Reduction in Compact MIMO Antenna Operating on 28 GHz by Using Novel Decoupling Structure,” Micromachines, vol. 14, no. 11, 2023, doi: 10.3390/mi14112065.

[60] M. Bose and V. Karuppiah, “Metamaterial inspired superstrate loaded miniaturized quad port MIMO antenna for 5G C-band applications,” Opt. Commun., vol. 574, no. July 2024, p. 131123, 2025, doi: 10.1016/j.optcom.2024.131123.

[61] B. Kumkhet, P. Rakluea, N. Wongsin, and P. Sangmahamad, “International Journal of Electronics and Communications SAR reduction using dual band EBG method based on MIMO wearable antenna for WBAN applications,” AEUE - Int. J. Electron. Commun., vol. 160, no. January, p. 154525, 2023, doi: 10.1016/j.aeue.2022.154525.

[62] O. Elalaouy et al., “International Journal of Electronics and Communications DNG metamaterial loaded dual wideband MIMO antenna with mitigated mutual coupling for 5G n257 / n258 / n260 / n261 NR networks,” AEUE - Int. J. Electron. Commun., vol. 195, no. March, p. 155775, 2025, doi: 10.1016/j.aeue.2025.155775.

[63] Y. Liu, Z. Yang, P. Chen, J. Xiao, and Q. Ye, “Isolation Enhancement of a Two-Monopole MIMO Antenna Array with Various Parasitic Elements for

Sub-6 GHz Applications," Micromachines, vol. 13, no. 12, 2022, doi: 10.3390/mi13122123.
[64] S. Ghosh, G. S. Baghel, and M. V. Swati, "A dual-port, single-fed, integrated microwave and mm-wave MIMO antenna system with parasitic decoupling mechanism for 5G-enabled IoT applications," AEU - Int. J. Electron. Commun., vol. 176, no. November 2023, p. 155122, 2024, doi: 10.1016/j.aeue.2024.155122.
[65] T. Addepalli, M. S. Kumar, C. R. Jetti, N. K. Gollamudi, B. K. Kumar, and J. Kulkarni, "Fractal Loaded, Novel, and Compact Two- and Eight-Element High Diversity MIMO Antenna for 5G Sub-6 GHz (N77/N78 and N79) and WLAN Applications, Verified with TCM Analysis," Electron., vol. 12, no. 4, 2023, doi: 10.3390/electronics12040952.
[66] J. Wani, P. Camacho, R. S. Malfajani, and M. S. Sharawi, "Design and Fabrication of a multi-band 2Element MIMO Antenna for Sub-6 GHz Applications," 2021 IEEE Indian Conf. Antennas Propagation, InCAP 2021, pp. 198–200, 2021, doi: 10.1109/InCAP52216.2021.9726512.
[67] S. K. Mahto, A. K. Singh, R. Sinha, M. Alibakhshikenari, S. Khan, and G. Pau, "High Isolated Four Element MIMO Antenna for ISM/LTE/5G (Sub-6GHz) Applications," IEEE Access, vol. 11, no. August, pp. 82946–82959, 2023, doi: 10.1109/ACCESS.2023.3301185.
[68] A. K. Saurabh and M. K. Meshram, "Compact sub-6 GHz 5G-multiple-input-multiple-output antenna system with enhanced isolation," Int. J. RF Microw. Comput. Eng., vol. 30, no. 8, pp. 1–11, 2020, doi: 10.1002/mmce.22246.
[69] Y. Liu, P. Chen, J. Tian, J. Xiao, S. Noghanian, and Q. Ye, "International Journal of Electronics and Communications Hybrid ANN-GA optimization method for minimizing the coupling in MIMO antennas," AEUE - Int. J. Electron. Commun., vol. 175, no. September 2023, p. 155068, 2024, doi: 10.1016/j.aeue.2023.155068.
[70] H. H. Tran, T. T. L. Nguyen, H. N. Ta, and D. P. Pham, "A Metasurface-Based MIMO Antenna With Compact, Wideband, and High Isolation Characteristics for Sub-6 GHz 5G Applications," IEEE Access, vol. 11, no. July, pp. 67737–67744, 2023, doi: 10.1109/ACCESS.2023.3292303.
[71] H. Askari, "Isolation Enhancement of a Metasurface-Based MIMO Antenna Using Slots and Shorting Pins," pp. 73533–73543, 2021, doi: 10.1109/ACCESS.2021.3079965.
[72] S.- Ghz et al., "A Compact MIMO Antenna with Improved Isolation for ISM ," pp. 1–10, 2022.
[73] M. Hussain et al., "Isolation Improvement of Parasitic Element-Loaded Dual-Band MIMO Antenna for Mm-Wave Applications," 2022.
[74] A. A. Megahed, M. Abdelazim, E. H. Abdelhay, and H. Y. M. Soliman, "Sub-6 GHz Highly Isolated Wideband MIMO Antenna Arrays," IEEE Access, vol. 10, pp. 19875–19889, 2022, doi: 10.1109/ACCESS.2022.3150278.
[75] H. U. Y. H. Tran and N. Nguyen-trong, "Performance Enhancement of MIMO Patch Antenna Using Parasitic Elements," vol. 9, 2021, doi: 10.1109/ACCESS.2021.3058340.
[76] D. Wen, Y. Hao, M. O. Munoz, H. Wang, and H. Zhou, "A Compact and Low-Profile MIMO Antenna Using a Miniature Circular High-Impedance Surface for Wearable Applications," IEEE Trans. Antennas Propag., vol. 66, no. 1, pp. 96–104, 2018, doi: 10.1109/TAP.2017.2773465.
[77] H. Islam et al., "Compact circularly polarized 2 and 4 port multiple input multiple output antennas with bandstop filter isolation technique," Alexandria Eng. J., vol. 66, pp. 357–376, 2023, doi: 10.1016/j.aej.2022.11.029.
[78] H. Elmannai et al., "Design and characterization of a meandered V-shaped antenna using characteristics mode analysis and its MIMO configuration for future mmWave devices," AEU - Int. J. Electron. Commun., vol. 186, 2024, doi: 10.1016/j.aeue.2024.155477.
[79] U. F. Azimov, A. Abbas, S. W. Park, N. Hussain, and N. Kim, "A 4-port flexible MIMO antenna with isolation enhancement for wireless IoT applications," Heliyon, vol. 10, no. 11, p. e32216, 2024, doi: 10.1016/j.heliyon.2024.e32216.
[80] A. Michel, R. K. Singh, and P. Nepa, "A Low-Profile Cellular Antenna Module for Vehicular Applications," 17th Eur. Conf. Antennas Propagation, EuCAP 2023, pp. 1–4, 2023, doi: 10.23919/EuCAP57121.2023.10133010.
[81] V. Tashvigh and M. Kartal, "International Journal of Electronics and Communications Regular paper A dual-sense CP MIMO antenna using decoupling structure with improved isolation," AEUE - Int. J. Electron. Commun., vol. 175, no. December 2023, p. 155065, 2024, doi: 10.1016/j.aeue.2023.155065.
[82] Mamta and V. Nath, "L-shaped reconfigurable band decoupling assisted dual band four port MIMO antenna for 5G and IoT application," AEU - Int. J. Electron. Commun., vol. 179, no. April, p. 155295, 2024, doi: 10.1016/j.aeue.2024.155295.
[83] P. Kumar, T. Ali, S. Pathan, N. Kumar Shetty, Y. Bommenahalli Huchegowda, and Y. Nanjappa, "Design and analysis of ultra-wideband four-port MIMO antenna with DGS as decoupling structure for THz applications," Results Opt., vol. 13, no. October, p. 100573, 2023, doi: 10.1016/j.rio.2023.100573.
[84] C. Y. Lau and K. K. M. Cheng, "Pattern-Reconfigurable 2-element MIMO Antenna Design by using Novel Switchable Decoupling and Matching Network," Asia-Pacific Microw. Conf. Proceedings, APMC, vol. 2021-Novem, no. 4, pp. 247–249, 2021, doi: 10.1109/APMC52720.2021.9661900.
[85] S. K. Sharma and A. Wang, "Two Elements MIMO Antenna for Tablet Size Ground Plane with Reconfigurable Lower Bands and Consistent High Band Radiating Elements," 2018 IEEE Antennas Propag. Soc. Int. Symp. Usn. Natl. Radio Sci. Meet. APSURSI 2018 - Proc., vol. 2, pp. 25–26, 2018, doi: 10.1109/APUSNCURSINRSM.2018.8608838.
[86] A. Kumar, C. Tyagi, D. Saxena, and P. Jha, "Miniaturized Two-element MIMO Antenna with neutralization line and an asymmetric open slot for WLAN and IOT applications," 2023 Int. Conf. Artif. Intell. Smart Commun. AISC 2023, pp. 227–231, 2023, doi: 10.1109/AISC56616.2023.10085167.
[87] C. Abdelhamid and H. Sakli, "Mutual reduction in the coupling of the MIMO antenna network applied to the broadband transmission," Adv. Sci. Technol. Eng. Syst., vol. 5, no. 2, pp. 338–343, 2020, doi: 10.25046/AJ050244.
[88] A. Ali, M. E. Munir, M. M. Nasralla, M. A. Esmail, A. J. A. Al-Gburi, and F. A. Bhatti, "Design process of a compact Tri-Band MIMO antenna with wideband characteristics for sub-6 GHz, Ku-band, and Millimeter-Wave applications," Ain Shams Eng. J., vol. 15, no. 3, p. 102579, 2024, doi: 10.1016/j.asej.2023.102579.
[89] P. B. Nikam, J. Kumar, V. Sivanagaraju, and A. Baidya, "Dual-band reconfigurable EBG loaded circular patch MIMO antenna using defected ground structure (DGS) and PIN diode integrated branch-lines (BLs)," Meas. J. Int. Meas. Confed., vol. 195, no. March, p. 111127, 2022, doi: 10.1016/j.measurement.2022.111127.
[90] X. Liu, M. Amin, and J. Liang, "Wideband MIMO antenna with enhanced isolation for wireless communication application," IEICE Electron. Express, vol. 15, no. 22, pp. 1–9, 2018, doi: 10.1587/elex.15.20180948.
[91] L. S. Yahya, L. S. Yahya, and K. H. Sayidmarie, "Dual-Band Folded Monopole MIMO Antennas with Enhanced Isolation," Appl. Comput. Electromagn. Soc. J., vol. 36, no. 12, pp. 1569–1578, 2021, doi: 10.13052/2021.ACES.J.361208.
[92] N. R. Kamil, A. G. Waddy, and A. H. Al-nakkash, "A Design of Fractal Hilbert MIMO Antenna for 5G Mobile," vol. 4, no. 1, pp. 29–38, 2022.
[93] A. H. Mousa, M. Azlishah, B. I. N. Othman, M. Z. Abidin, and A. M. Ibrahim, "Fractal H-Vicsek MIMO Antenna for 5G Communications," no. 6, pp. 15–20, 2021, doi: 10.15199/48.2021.06.03.
[94] M. Cholavendan and V. Rajeshkumar, "Dual-Feed Orthogonally Polarized Compact 8-Element MIMO Antenna Using Metallic Stub and Decoupling Unit for Isolation Enhancement of Sub-6 GHz 5G Application," Prog. Electromagn. Res. Lett., vol. 116, no. January, pp. 105–111, 2024, doi: 10.2528/PIERL23121104.
[95] P. Kumar et al., "Results in Engineering A quad port dual band notch UWB MIMO antenna using hybrid decoupling structure," Results Eng., vol. 23, no. July, p. 102551, 2024, doi: 10.1016/j.rineng.2024.102551.
[96] G. Shankar Das, B. Bikash Chamuah, Y. Beria, P. Protim Kalita, and A. Buragohain, "Compact four elements SUB-6 GHz MIMO antenna for 5G applications," Mater. Today Proc., no. xxxx, pp. 5–9, 2023, doi: 10.1016/j.matpr.2023.06.344.
[97] T. Addepalli and V. R. Anitha, "A Very Compact and Closely Spaced Circular Shaped UWB MIMO," AEUE - Int. J. Electron. Commun., p. 153016, 2019, doi: 10.1016/j.aeue.2019.153016.

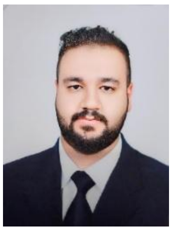
Ahmed Raed Al-tameemi received the Bachelor Degree in Computer techniques engineering from dijlah University, Iraq, in 2011 and Master in Nano electronics from Mordovia national university, Russia in 2018. He is Assistant lecturer with the Department of computer techniques Engineering, Al-Nisour University. In the same time, He is manager of IT department in Al-Nisour university. His work and research interest includes, utility communication technology, electromagnetic technology.

Goh Chin Hock received the Bachelor Degree in Electrical and Electronics Engineering in 2004 as well as Master and PhD in Electrical Engineering in 2008 and 2012 respectively from Universiti Tenaga Nasional, Malaysia. He is currently an Associate Professor with the Department of Electrical and Electronics Engineering, Universiti Tenaga Nasional. He is the Professional Engineer of BEM, Energy Professional of MEPA and Corporate Member of IEM. Besides that, he is Certified Energy Manager (CEM), Certified Professional in Measurement and Verification (CPMV) as well as Registered Electrical Energy Manager (REEM).

Sieh Kiong Tiong (Senior Member, IEEE) received the B.Eng. (Hons.), M.Sc., and Ph.D. degrees in electrical, electronics and system engineering from the National University of Malaysia (UKM), in 1997, 2000, and 2006, respectively. He is currently a Professor with the College of Engineering, Universiti Tenaga Nasional, where he is also the Director of the Institute of Sustainable Energy (ISE). His research interests include renewable energy, artificial intelligence, data analytics, microcontroller systems, and communication systems. He is currently a Professional Engineer registered with the Board of Engineers Malaysia (BEM).

Taha Raad Al-Shaikhli currently works at University of technology. Taha does research in, Antennas, Filters Telecommunications Engineering.

Mohammed S. Al Ani received the Bachelor Degree in Computer techniques engineering from dijlah University, Iraq, in 2011 and Master in Nano electronics from Mordovia national university, Russia in 2018. Now, he is an Assistant lecturer at AlFarahidi University.



Mohammad A. K. Al Ani received the Bachelor Degree in Computer techniques engineering from University of baghdad, Iraq, in 2015 and Master in electronics from University of baghdad, Baghdad, Iraq in 2018. He is Assistant lecturer at the Department of computer techniques Engineering, Al-Nisour University.