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

***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 coupling are founded: neutralization lines (NL), structures, metamaterials which included elctomegnitc band gap (EBG) and meta-sufaces, parasitic elements (PE), defected ground structures (DGS), decoupling networks (DN), and hybrid isolation techiques. Each technique has been dicussed and analyzed based on design geometery, methods, and redcuction coupling preformance. depanding on results of using these techiques, we found there a good enhancement of isolation, ECC and othar antenna preformance . In additon, This work draws attention to effectiveness of combining methods for compact and high-performance antennas. Also the compasition between the previus studies deeplly analyzied in ordor to size, isolation, bandwidth, distance and vlue of isolation enhacment. This work covered the published papers for 5G communication bands to be a base station for designing a high isolation techiques and preformance**

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

I. INTRODUCTION

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

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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).

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MIMO, regarded as a cutting-edge wireless communication technology, enhances system reliability and increases capacity of channels via multiple antennas. Initially introduced in the early 1990s to address the data rate limitations of traditional single antenna element, 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 elements [4], [5]. Furthermore, when antennas are placed closer together in MIMO setups, mutual coupling can intensify, negatively affecting antenna performance which is 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 offering distinct advantages and 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 as follows: section II explains the concept of mutual coupling, its working principles, 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].

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

where, a represents the number of array elements, d_{ij} denotes the distance among the first and others antenna radiator, 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 S_{21}, by equation below [12]:

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

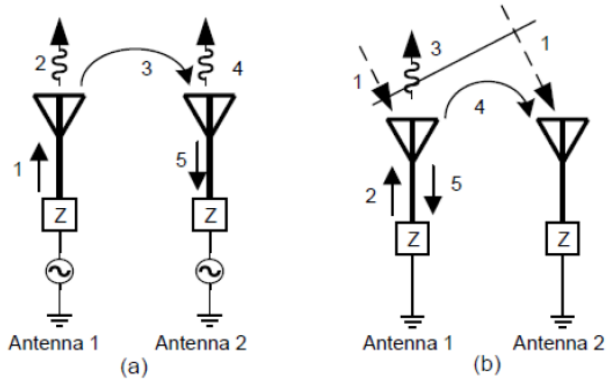

Fig. 1. Antenna arrays' mutual coupling: a) for the transmitting array, b) for the receiving array [10].

Figs. 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]. Figure 2 presents the common isolation techiques which is discussed in this survey paper. Figure 2 illustrates the techniques for reducing mutual coupling that are examined in this review.

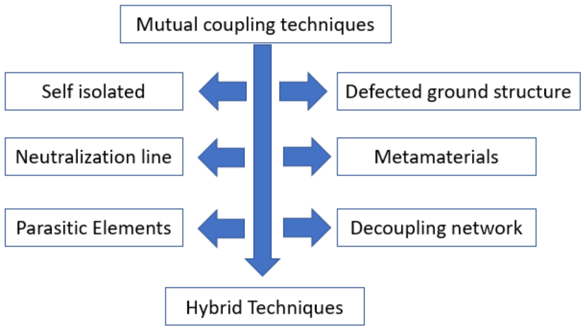

Fig. 2. Mutual coupling reduction techniques.

Fig 2 shows different techniques have been utilized to improve the MIMO isolation in 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 out 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 for have been documented in the literature for this topic, and this study categorizes them into seven distinct groups as outlined below. In the following section, each isolation technique will be briefly discussed, 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 achieving a wide bandwidth as shown in fig. 3. This MIMO antenna incorporates four radiating elements arranged in an orthogonal configuration, to reducing mutual coupling without the using any additional decoupling techniques. The overall operating frequency is 3-11 GHz and lowest isolation 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.

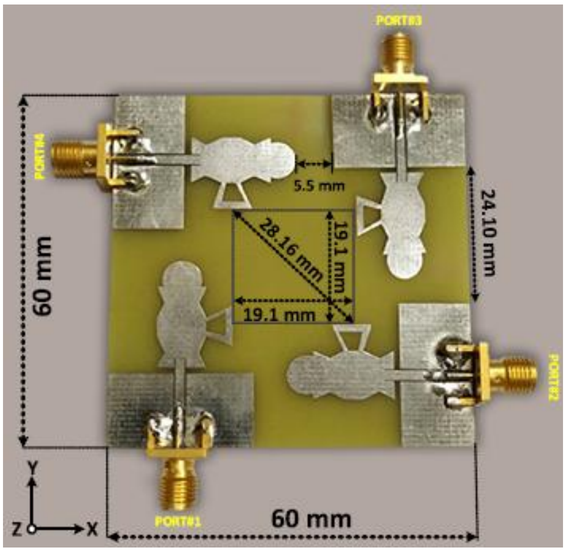

Fig. 3. jug-shaped patch MIMO antenna presented in [4].

A MIMO antenna operating within the 28 to 37.5 GHz frequency band is presented in [14]. Antenna consists of four rectangular patch located close to each with a spacing of 0.2 mm. This design achieves a maximum isolation of -18 dB, all 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, [16] presents a compact triple operating frequency MIMO antenna, incorporating multiple stubs and fed by a CPW. The elements of antenna was located with distance of just 4 mm. However, It achieves maximum isolation below −30 dB and an ultra-low ECC 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 1 presents a comparison of the results from previous studies that used self-isolated techniques.

TABLE I
COMPARISON OF SELF ISOLATED TECHNIQUE RELATED IN RELATED WORK

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 detail of previous studies which sites in table I, we conclude that different method of self isolated technique used.However, not all antenna successed to obtain high isolation such as [14], [17]-[19] and [21] which achieved above -18 dB as maximum isolation. Although, some of these studies has a distance more than 20 mm. On the other hand, some of studies achieved like [4],[13],[15],[16] and [20] obtaianed isolation below -20 dB with maximum distance of 10 dB. This difference can happen because of there was a strong current on antenna which not effectively reduces the coupling and the self isolated was not always enough to improve isolation.

2) Defected ground structure: This method involves creating intentional defects or disruptions in the antenna's ground plane. Known as DGS, it alters the current distribution in the ground plane, thereby reducing coupling between antennas. Commonly isolation techiques has been reported in previus study was DGS due to ablitty to reduce the coupling wave between antennas. Additionally, this method makes a significant improvement in the isolation between antenna parts [22]. By altering the ground plane, the current generated at a ground plane can lessen its tendency to couple with nearby elements, which reduces isolation in the MIMO antenna.

In [23], two identical square patch antennas was located with high diatnce between them with commond ground plane, specified to operate at 5.8 GHz. The achieved isolation without any decoupling techiqniues was -14 dB. To reduce mutual coupling, a zigzag groove is etched at the center of the ground plane, serving as the DGS as seen in Figure 4. The results shows a significant reduction in mutual coupling below -22 dB at the worst stuation.

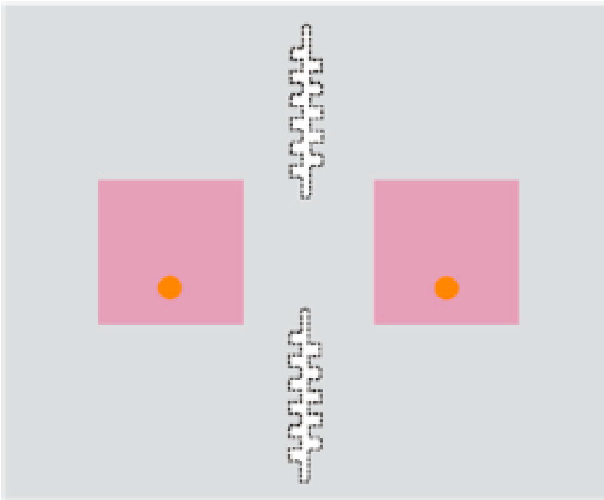

Fig. 4. Square patch antenna with zigzag groove proposed in [23].

A simple rectangular microstrip MIMO antenna with conventional ground plan designed for body-centric applications is presented in [25], firstly, there was no resonance frequency. Next, wide and small rectangulars with another semi-circular slot have bween etched on ground ground planeto make antenna operate at 2.45 GHz with enhanced isolation significantly. This editions yields isolation below 21 dB and 20 dB under flat and bent conditions, respectively.

Finally, [26] introduces a quad identical circular with two rectangular slots on right and left with common ground plane printed on Rogers RT/5880 substrate for mm-wave. To enhance isolation, square slots with dimentions of 1 mm etched along the ground plane. This decoupling method effectively enhances isolation and overall MIMO performance. With a wide bandwidth of 3.52 GHz and a high gain of 7.1 dBi, the antenna maintains low envelope correlation. Through iterative DGS optimization, the design achieves excellent channel diversity and reduced inter-element interference.

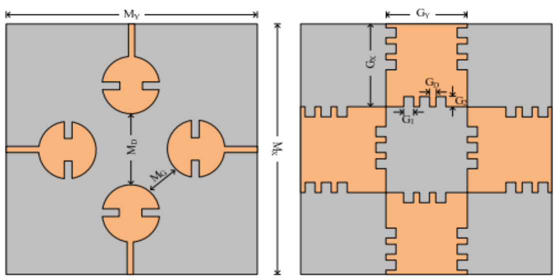

Fig. 5. Modified circular MIMO antenna with DGS enhancement presented in [26].

Table II presents a comparison of the results from previous studies that used DGS techniques interm of bandwidth, isolation, size, distance between elements, isolation improvement after applied technique and number of elements. Table II refers 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 in same time, distance among and size is large which not meeting meeting the needs of compact size for new compact devices. However, studies [23], [24], [27], [31]-[33] obtained isolation below -20 with maximum distance 10 mm. which prove that used 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, the 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 elements 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 CPW of each element. The obtained results shows a good improvement interm of isolation –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 elements was printened on top and bottm side of substrate. Plus-shaped metal strips of NL and a circular loop was 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.

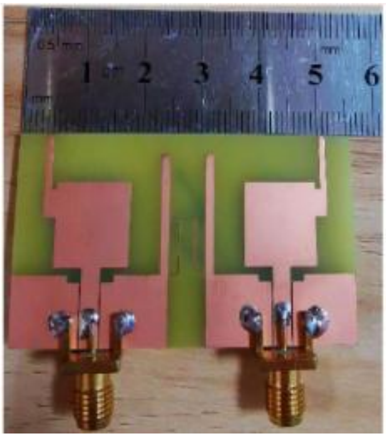

Fig. 6. Fabricated two elements MIMO antenna in [38].

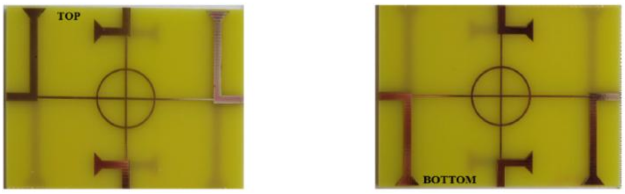

Fig. 7. Fabricated two elements MIMO antenna in [40].

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 and reduce coupling and ensuring 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 interm of bandwidth, isolation, size, distance between elements, isolation improvement after applied technique and number of elements.

Table III refers to previous studies of MIMO antenna with NL technique. For more comparison between the previous studies in term of NL effectiveness in term isolation improvement value. We found, studies [37]-[41] value of isolation enhancement was below 10 dB for strongest coupling. While, studies such as [42], [44] and [45] achieved enhancement isolation value above 9 dB. That confirms that NLs has a signtifcant effects on the correlation among antennas.

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, and metasurfaces, which 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, they offer considerable potential for current and next-generation of communications [50].

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

A quad elements 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 Figure 6 to enhance isolation below –18 dB with enhancement value of isolation was 10 dB .

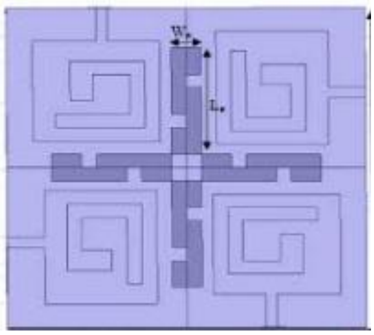

Fig. 8. Compact four-element MIMO antenna with S-shaped EBG.

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.

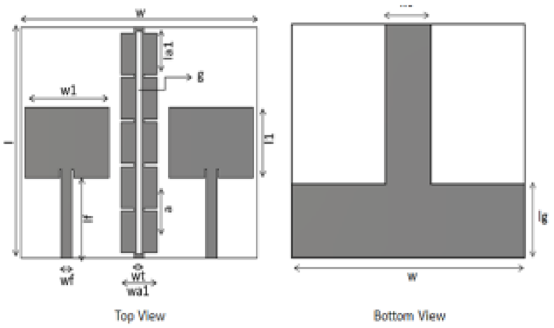

Fig. 9. Compact four-element MIMO antenna with S-shaped EBG [3].

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 IV presents a comparison of the results from previous studies that used MTM techniques interm of bandwidth,isolation,size,distance between elements, isolation improvement after applied technique and number of elements.

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

5) Parasitic Elements: 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-shaped with isolated branch on ground plane, which together generate a novel 3D weak electric field that effectively minimizes mutual coupling. The resulting antenna achieves up to 26 dB improvement in isolation, demonstrating the effectiveness of the PE.

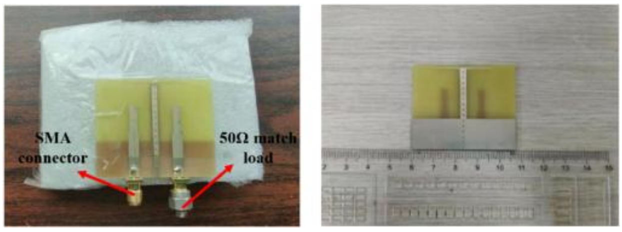

Fig. 10. Microstrip monopole antenna with enhanced isolation via PE [63].

In [64], a compact MIMO antenna is proposed for microwave and mmWave systems, operating across 2.4 GHz to 28 GHz. A semi-circular slotted monopole combined with quarter-wavelength metallic stubs facilitates multi-band performance with -10 dB impedance bandwidths. In 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 used PE show there a good enhancement in term of isolation (maximum isolation achieved -28 dB). The antenna exhibits radiation efficiency above 85% in microwave bands and 95% in mmWave 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.

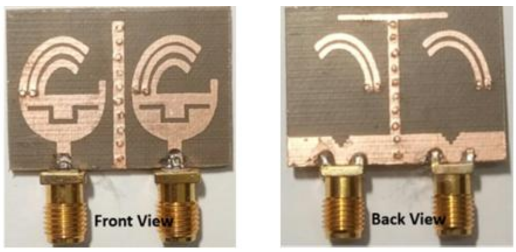

Fig. 11. Fabricated two ports MIMO antenna for microwave and mmWave proposed in [64].

The study in [65] presents a MIMO antenna designed based on fractal-shaped 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 interm of bandwidth, isolation, size, distance between elements, isolation improvement after 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 refers to the previous studies of MIMO with PE technique, its can note that some of these PE strucatures have a positive effects on the isolation such as [68]-[75] which achieved a high isolation below -20dB. On the other hand, published work such as [63]-[67] have not obtained high isolation (above -20 dB). However, studies like [63] achieved high isolation improvement more than 12 dB. While studies such as [68]-[70], [73]-[75] achieved isolation improvement value below 10 dB for the worst stuation.

6) Decoupling network: 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 interfereence 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 operating from 2.41 to 2.47 GHz with high coupling -9 due to small distance between each antenna. A band-stop filter-based decoupling network was utilized to reduce the strong coupling as seen in figure 8. This method improve isolatione over -30 dB isolation as best result, while the worst isolation was below -17. However, enhancement isolation value after introduce band stop filter was 6 dB as a minmum.that prove a significantly improving MIMO system performance.

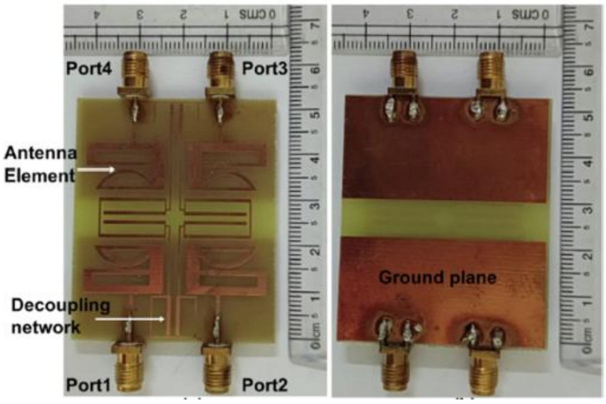

Fig. 12. Circularly polarized MIMO antennas with DN proposed in [77].

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

Finally, a compact, conformal monopole MIMO antenna designed for smart vehicle communication is proposed in [79], using a flexible substrate and metallic stubs. Each elements consist of U-shaped monopole with loaded mander strip on top right corner and 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 improve from -19 to -29 at the worst situation over 5.37 to 7.34 GHz. Althouth, the distance between each elements was only 4 mm.

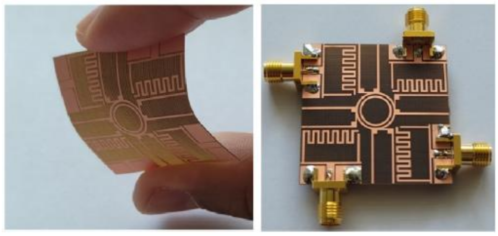

Fig. 13. conformal monopole MIMO antenna for V2X proposed in [79].

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 refers to previous studies of MIMO antenna with DN technique. For more comparison between the previous studies in term of DN effectiveness in term isolation improvement value.We found, studies [76], [77], [82] and [83] value of isolation enhancement was below 10 dB for strongest coupling. While, studies such as [78]-[81] and [84] achieved enhancement isolation value above 9 dB. The prove that some DN structures has a significant effects on the correlation among antennas

7) Hybrid Techniques: combine two or more decoupling methods such as NL and DGS, EBG structures, and PE and othars 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.

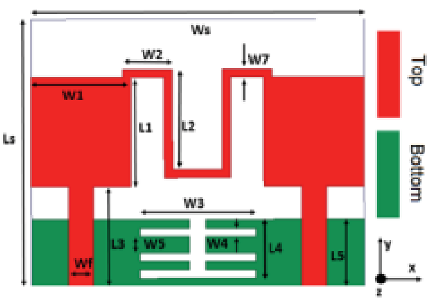

Fig. 14. Rectangular microstrip patch antennas with PE and NL presented in [86].

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: a neutralization line, which reduces coupling by more than 15 dB, and a split ring resonator (SRR) metamaterial, which 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 electromagnetic bandgap (EBG) structure is integrated with the DGS. The isolation achieved over 25 dB after the insertion of hybrid technique. Experimental results confirm strong isolation and effective frequency reconfigurability, supporting diverse practical applications in wireless communication.

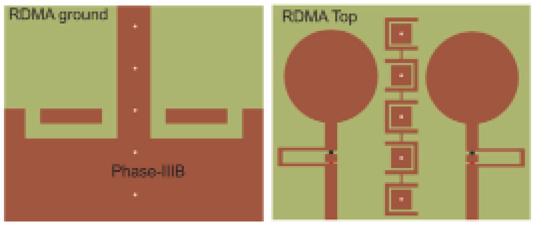

Fig. 15. Reconfigurable MIMO antenna used DGS and EBG in [89].

Table VII presents a comparison of the results from previous studies that used hybrid techniques interm of bandwidth, isolation, distance between elements, isolation improvement after 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.

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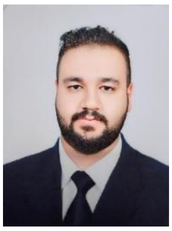
Ahmed Raed Al-tameemi received the Bachelor Degree in Computer techniques engineering from dijlah University, Iraq, in 2011 and Master in Nano electronics from Mordovia national university, Russia in 2018. He is Assistant lecturer with the Department of computer techniques Engineering, Al-Nisour University. 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.