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Synergistic Mitigation of Mutual Coupling in Millimeter-Wave MIMO Arrays: A Hybrid DGS and EBG Paradigm for 5G Systems.

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التخفيف التآزري للاقتران المتبادل في مصفوفات MIMO ذات الموجات المليمترية: نـهج هجين باستخدام DGS وEBG لأنظمة الجيل الخامس (G5)

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Abstract
This paper presents the design and simulation of a 28 GHz MIMO microstrip antenna for 5G millimeter-wave communication. Beginning with design is extended to 1×2 configurations to enhance gain, directivity, return loss, and isolation. Defected Ground Structures (DGS) and Electromagnetic Band Gap (EBG) structures were employed to reduce mutual coupling. Simulations in ANSYS HFSS demonstrate that DGS improves isolation and enhances gain and directivity, while the inclusion of EBG provides further coupling suppression with a slight reduction in gain due to energy losses. These results indicate that combining DGS and EBG is an effective approach for compact 5G MIMO antennas, balancing isolation and radiation efficiency for high-speed wireless systems.

Keywords: MIMO Antennas, 5G, Millet Waves, Microstrip Antennas, Cross-coupling .

الملخص
يقدم هذا البحث تصميم ومحاكاة هوائي ميكروستريب من نوع MIMO يعمل عند تردد 28 جيجاهرتز لتطبيقات الاتصالات بالموجات المليمترية للجيل الخامس (5G). يبدأ التصميم بعنصر واحد ثم يتم تطويره إلى مصفوفة 1×2 بهدف تحسين الكسب، والتوجيهية، وخسارة الإرجاع، والعزل بين العناصر.
تم استخدام تقنيات الهياكل الأرضية المعيبة (DGS) وهياكل فجوة الحزمة الكهرومغناطيسية (EBG) لتقليل الاقتران المتبادل بين عناصر الهوائي.
أظهرت نتائج المحاكاة باستخدام برنامج ANSYS HFSS أن تقنية DGS تُحسن العزل وتعزز الكسب والتوجيهية، بينما يؤدي دمج تقنية EBG إلى تقليل إضافي للاقتران مع حدوث انخفاض طفيف في الكسب نتيجة فقدان الطاقة.
تشير هذه النتائج إلى أن الجمع بين DGS وEBG يُعد حلاً فعالاً لتصميم هوائيات MIMO مدمجة لأنظمة الجيل الخامس، حيث يحقق توازناً بين العزل وكفاءة الإشعاع في أنظمة الاتصالات اللاسلكية عالية السرعة.

الكلمات المفتاحية: هوائيات MIMO، الجيل الخامس، الموجات المليمترية، هوائي ميكروستريب، الاقتران المتبادل.

Introduction

For wireless systems, the antenna is one of the critical components. A good design of the antenna can relax system requirements and improve overall system performance. The wireless systems include a large variety of different kinds, such as radar, navigation, landing systems, direct broadcast TV, satellite communications, mobile communications and so on. An antenna could be as large as 100m by 100m for radio telescope or as small as the order of centimeters in built-in handsets. All of them play an important role in science and daily life. Today we enjoy much benefit from wireless, and the significant contributions of antennas should not be underestimated [1].

An antenna is an electromagnetic transducer, used to convert, in the transmitting mode, guided waves within transmission lines to radiated free-space waves, or to convert, in the receiving mode, free-space waves to guided waves. In 1886, Hertz demonstrated the first wireless electromagnetic system. In 1901, Marconi succeeded in sending signals over large distance from England to Newfoundland.

Antenna Idea

If a parallel-wire transmission line is left open, the electric and magnetic fields escape from the end of the line and radiate into space:

- This radiation is inefficient and unsuitable for reliable transmission or reception.
- The radiation from a transmission line can be greatly improved by bending the transmission-line conductors so they are at a right angle to the transmission line [2].

Basic types of antennas:

- omnidirectional
- semi-directional
- directional

Fifth Generation

In telecommunications, 5G is the fifth generation for broadband cellular networks, which cellular phone companies began deploying worldwide in 2019, and is the planned successor to the 4G networks which provide connectivity to most current cellphones. 5G networks are predicted to have more than 1.7 billion subscribers worldwide by 2025, according to the GSM Association [4].

Pre-fifth Generation

There are generations of new mobile that appear in almost every 10 years since the first generation of the first mobile phone system, appeared in 1981. The first start-up of the 2G system was introduced in 1992, the third-generation 3G system was launched in 2001, and finally the fourth-generation system was in operation in 2012.

Internet of Things

The main logo of the fifth generation is the Internet for everything or what's called the Internet of Things. That is, everyone and everything will be connected to the Internet, any device or device at home or on the street or any place of business will be connected to the Internet, which leads us to the term smart cities, since data is gathered everywhere by any device and by any machine and will be analysed in as little real time as possible to infer timely useful information such as monitoring the health status of sick and the elderly, monitoring sensors and tools at a home and determining whether there is a malfunction or a shortage of a substance, as well as analysing the traffic situation on the streets and warning and alerting the drivers, thus paving the ways for self-driving cars. Here, mobile communications play a central role in enabling the secure transfer of this information from one machine to another (= MACHINE TO MACHINE M2M) without human intervention – to process it and take appropriate action within the minimum delay (less than 1ms). This process takes place at maximum speed and minimum error, and most ambitious future challenges is the huge number of devices and sensors almost everywhere to form a large-scale future network, which must also mobilise further additional high speed, secure mobile and stored information, efficiency and a high degree of secure mobile and stored information.

Aim of the Research

The primary aim of this project is to design and evaluate 28 GHz MIMO microstrip antennas while employing methods to mitigate mutual coupling among the antenna elements, including

EBG and DGS structures, with the goal of improving system performance regarding gain, radiation efficiency, and reduced interference, thereby facilitating contemporary high-speed communication applications such as 5G networks.

MICROSTRIP ANTENNA

Antennas are metallic structures designed for radiating and receiving electromagnetic energy. An antenna acts as a transitional structure between the guiding device and the free space. The official IEEE definition of an antenna as given by Stutsman and Thiele follows the concept "That part of a transmitting or receiving system that is designed to radiate or receive electromagnetic waves" [5].

Feeding techniques of microstrip antennas

Microstrip patch antennas can be fed by a variety of methods. These methods can be classified into two categories: contacting and non-contacting. In the contacting method, the fed line is directly connected to the radiating patch. In the non-contacting scheme, electromagnetic field coupling is done to transfer power between the microstrip line and the radiating patch. The most popular feed techniques are: microstrip line feed, coaxial probe (both contacting schemes), aperture coupling and proximity coupling (both non-contacting schemes) [2].

Losses in Microstrip:

Losses in microstrip antennas can be attributed to several factors, including dielectric losses in the substrate, conductor losses in the metallic patch and ground plane, and surface wave losses. These losses reduce the overall efficiency of the antenna and can impact its performance, especially at higher frequencies. Careful material selection and design optimization are crucial to minimize these losses.

Advances In Multiple Input Multiple Output (Mimo) System Model And Potentials

MIMO (Multiple-Input Multiple-Output) technology has emerged as a cornerstone of modern wireless communication systems, offering significant improvements in data throughput and spectral efficiency without requiring additional bandwidth or transmit power. By employing multiple antennas at both the transmitter and receiver, MIMO systems can exploit spatial diversity and multiplexing to enhance system performance. This chapter delves into the fundamentals of MIMO systems, their advantages, disadvantages, challenges, and key parameters. [7], [8].

Advantages of MIMO

MIMO systems offer several compelling advantages:

- **Increased Data Throughput:** By transmitting multiple data streams simultaneously over different spatial paths, MIMO can significantly increase the data rate within a given bandwidth [9].
- **Improved Spectral Efficiency:** More bits per second per Hertz can be transmitted, making more efficient use of the available spectrum.
- **Enhanced Link Reliability and Diversity Gain:** MIMO can combine multiple received signals to mitigate the effects of fading and interference, leading to a more robust and reliable communication link [10].
- **Reduced Transmit Power:** For a given data rate and reliability, MIMO can achieve this with lower transmit power compared to single-antenna systems.

Disadvantages Of MIMO

Despite its advantages, MIMO technology also presents certain disadvantages and complexities:

- **Increased Hardware Complexity:** MIMO systems require multiple RF chains (antennas, amplifiers, converters) at both the transmitter and receiver, leading to higher hardware costs and power consumption.
- **Larger Physical Size:** The need for multiple antennas can increase the physical size of devices, which can be a challenge for compact mobile devices.
- **Channel State Information (CSI) Requirements:** Optimal MIMO performance often relies on accurate CSI at the transmitter, which can be challenging to obtain and maintain, especially in fast-changing environments.
- **Mutual Coupling:** In compact antenna arrays, mutual coupling between closely spaced antenna elements can degrade performance, affecting radiation patterns and impedance matching.

MIMO Technology

MIMO technology leverages the spatial dimension of wireless channels by employing multiple antennas at both the transmitter and receiver. This creates multiple independent paths for data transmission, which can be utilized in two primary ways: spatial diversity and spatial multiplexing. Spatial diversity improves reliability by sending the same data over different paths, while spatial multiplexing increases data rates by sending different data streams simultaneously. The effectiveness of MIMO largely depends on the richness of the scattering environment, which creates these multiple paths.

Massive MIMO

Massive MIMO is an emerging technology that scales up conventional MIMO by employing a very large number of antennas (e.g., hundreds) at the base station to serve multiple users simultaneously within the same time-frequency resources. A key characteristic is that the number of base station antennas is significantly greater than the number of user terminals. This approach offers substantial benefits, including dramatic increases in spectral efficiency, energy efficiency, and system capacity, along with improved robustness against interference and fading. Massive MIMO simplifies signal processing at the user end and enables highly focused beamforming, leading to better signal quality and coverage [11], [12], [13].

Mutual Coupling Issue of MIMO Systems

In compact MIMO antenna arrays, especially in mobile handsets where antennas are closely packed, mutual coupling is a significant challenge. Mutual coupling occurs when the electromagnetic fields of one antenna element interact with adjacent elements, leading to several detrimental effects:

- **Degradation of Radiation Patterns:** The radiation pattern of individual antennas can be distorted, leading to reduced gain and directivity.
- **Changes in Input Impedance:** Mutual coupling alters the input impedance of the antennas, causing impedance mismatch and reducing radiation efficiency.
- **Reduced Isolation:** It decreases the isolation between antenna ports, meaning power transmitted from one port can couple into another, leading to interference and reduced system performance. [19].
- **Impact on Channel Capacity:** High mutual coupling can reduce the effective channel capacity by increasing correlation between antenna elements.

Methods of Decoupling

To overcome the adverse effects of mutual coupling in MIMO antenna systems, various decoupling methods have been developed. These methods aim to improve isolation between antenna elements and maintain optimal radiation characteristics. They can be broadly classified into circuit-based techniques and antenna/structural modifications:

- **Defected Ground Structures (DGS):** DGS involves etching slots or patterns into the ground plane beneath the microstrip patch. These defects disrupt the surface current distribution, effectively increasing the electrical path length and reducing mutual coupling between adjacent elements. DGS can also improve bandwidth and gain in some cases [21].
- **Electromagnetic Band Gap (EBG) Structures:** EBG structures are periodic arrangements of metallic or dielectric elements that create forbidden frequency bands for electromagnetic wave propagation. When integrated near antenna elements, EBG structures can suppress surface waves, which are a major source of mutual coupling in microstrip antennas, thereby enhancing isolation [22].
- **Neutralization Lines:** These are passive elements connected between antenna ports to cancel out the coupled signals.
- **Decoupling Networks:** External circuits designed to transform the impedance of the coupled antenna system, effectively decoupling the ports.
- **Metamaterial Structures:** Utilizing artificial materials with unique electromagnetic properties to control and reduce mutual coupling [23].
- **Orthogonal Polarization:** Designing adjacent antennas with orthogonal polarizations can inherently reduce coupling.
- **Spatial Separation:** Increasing the physical distance between antenna elements, though often limited by device size constraints.

Combining techniques like DGS and EBG often yields superior mutual coupling reduction, as demonstrated in this project, where both were utilized to achieve high isolation for 28 GHz MIMO microstrip antennas. These methods are essential for realizing compact and high-performance MIMO arrays for 5G millimeter-wave applications.

SIMULATION AND RESULTS

This chapter presents the simulation results for the designed 28 GHz MIMO microstrip antennas, detailing the performance metrics for various configurations. The designs were progressively developed, starting from a single patch element and extending to 1×2 MIMO array, incorporating Defected Ground Structures (DGS) and Electromagnetic Band Gap (EBG) techniques to mitigate mutual coupling. All simulations were performed using ANSYS HFSS software.

Single Microstrip Patch Antenna

The baseline performance was established using a single microstrip patch antenna. This configuration serves as a reference for evaluating the improvements achieved with MIMO arrays and decoupling techniques.
cavity model equations and then optimized in ANSYS HFSS. The exact dimensions of the patch are provided in Table 1.

Table 1 :The exact dimensions of the patch

Parameter	Symbol	Value
Patch Length	Lp	2.43mm
Patch Width	Wp	4.23mm
Substrate Length	Sl	6mm
Substrate Width	Sw	6.2mm
Substrate Hight	Sh	1.6mm

Libyan Open University Journal of Applied Sciences (LOUJAS)
Volume 2 - Issue 1 - 2026 - Pages 259-273

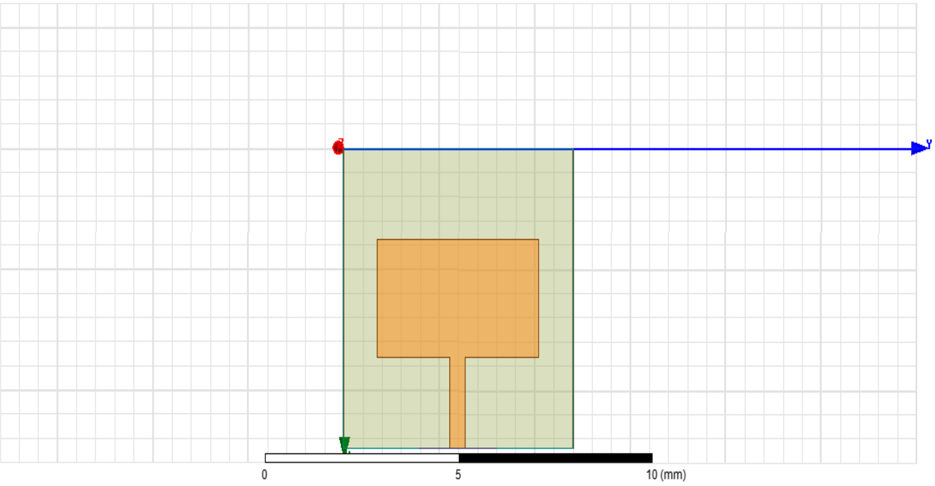


Figure 1: Single Microstrip Patch Antenna

Return Loss (S11): The single microstrip patch antenna exhibited a return loss (S11) of –**15.42 dB** at the operating frequency of 28 GHz. A lower return loss indicates better impedance matching and less reflected power, as shown in fig 2.

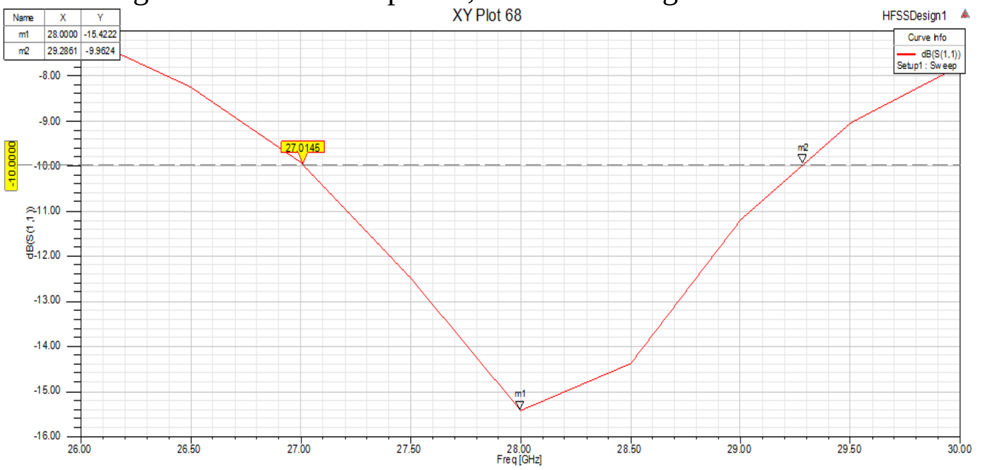


Figure 2: Return Loss of single patch antenna

The Gain: The simulated gain for the single patch antenna was 6.83 dB. as shown in fig 3.

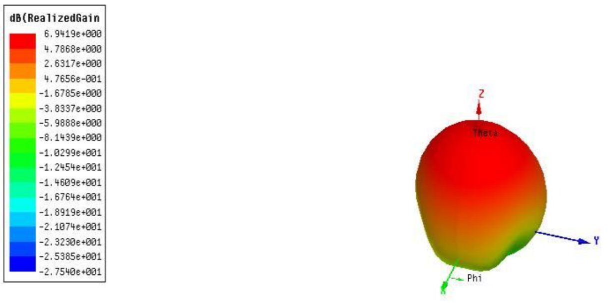


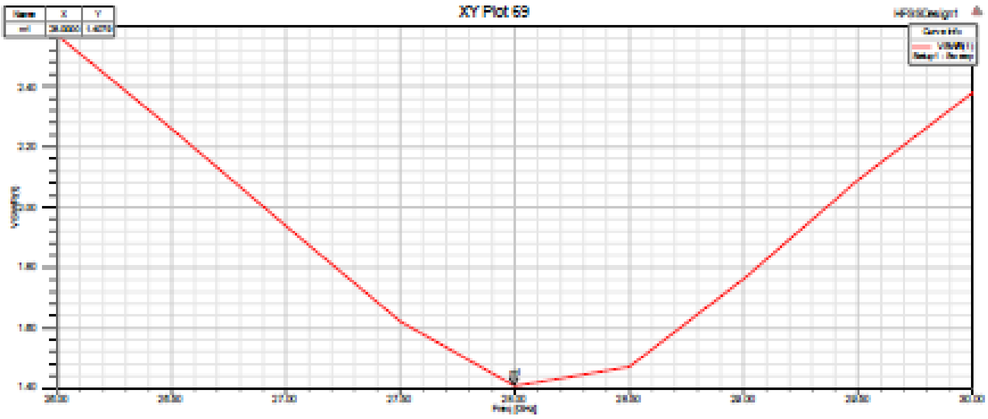
Figure 3: The gain of signal patch

The Directivity: The directivity of the single patch antenna was **6.99 dBi** as shown in fig 4.

Libyan Open University Journal of Applied Sciences (LOUJAS)
Volume 2 - Issue 1 - 2026 - Pages 259-273

Figure 4: The Directivity of single Patch

VSWR: The Voltage Standing Wave Ratio (VSWR) for the single patch antenna was **1.4079**, indicating good impedance matching, as shown in fig 5.



2×1 MIMO Antenna Array: Following the single-element design, a 2×1 MIMO antenna array was configured to investigate the effects of multiple elements without decoupling structures, as shown in fig 6.

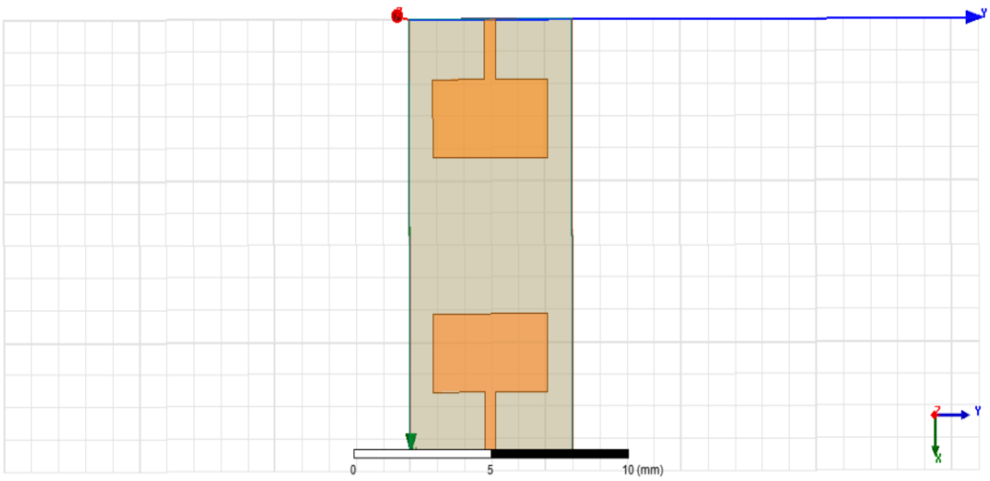


Figure 6: 2x1 MIMO

Return Loss (S11, S22): For the 2×1 MIMO antenna array, the return loss values were **–13.1 dB** for S11 and **–13.32 dB** for S22, as shown in fig 7.

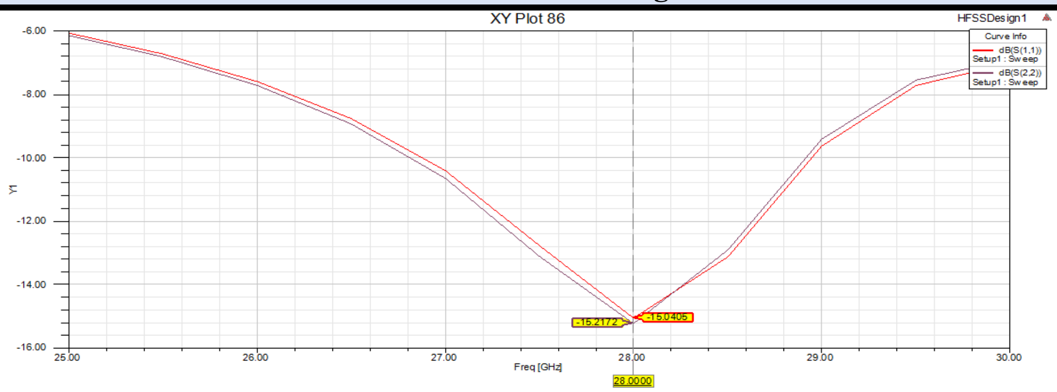


Figure 7: Return Loss (S11, S22)

The Gain: The gain for the 2×1 MIMO antenna array was **9.4 dB**, as shown in fig 8.

Figure 8: Gain of 2x1 MIMO

The Directivity: The directivity for the 2×1 MIMO antenna array was **9.45 dBi**.

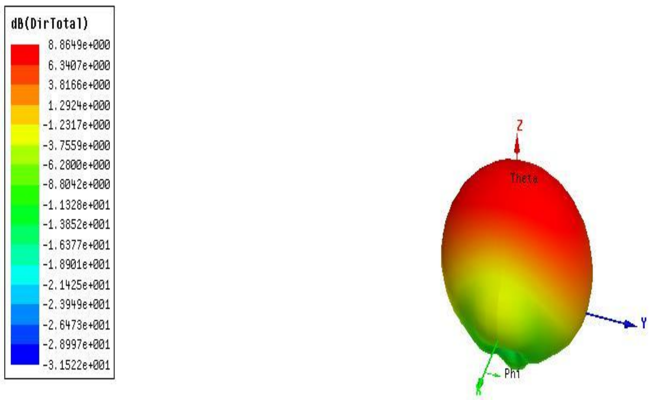


Figure 9: The Directivity of 2x1 MIMO

VSWR: The VSWR for the 2×1 MIMO antenna array was **1.51** for port 1 and **1.57** for port 2, as shown in fig 10.

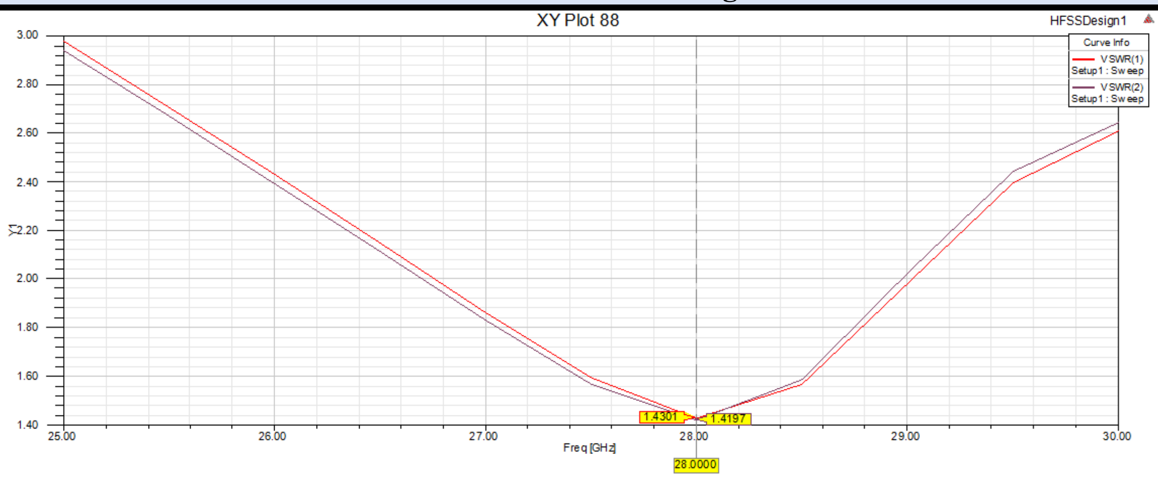


Figure 10: VSWR of 2x1 MIMO

Mutual Coupling (S12,S21): Without decoupling techniques, the mutual coupling (S12, S21) for the 2×1 MIMO array was **–18.2 dB**, as shown in fig 11**.**

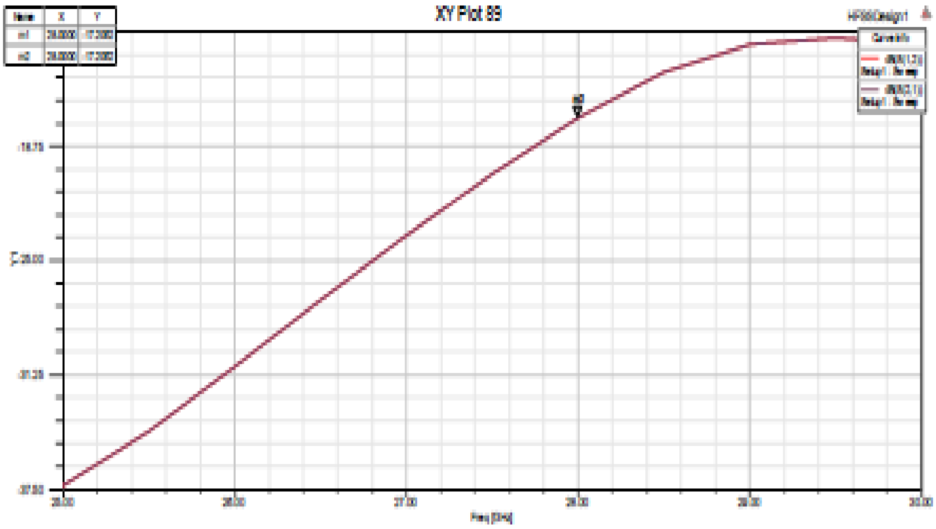


Figure 4.11: Mutual Coupling in 2x1 MIMO

2×1 MIMO Antenna Array with DGS: To address mutual coupling, Defected Ground Structures (DGS) were integrated into the 2×1 MIMO antenna array. This section presents the performance improvements, as shown in fig 12.

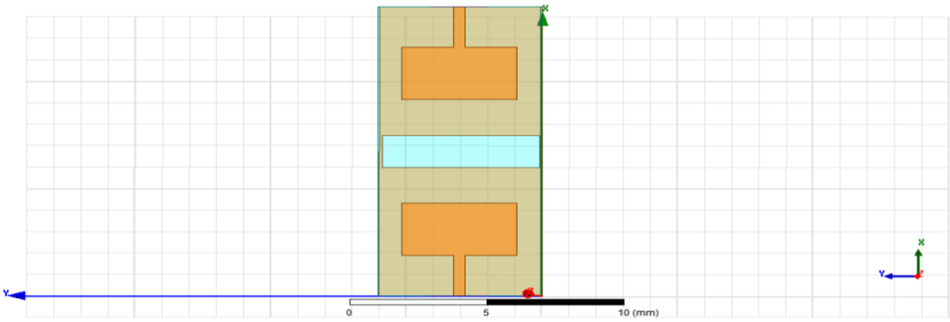


Figure 12: 2×1 MIMO antenna array with DGS

Return Loss (S11, S22): The 2×1 MIMO antenna array with DGS exhibited a return loss of **–17.98 dB** at port 1 (S11) and **–19.33 dB** at port 2 (S22). as shown in fig 13.

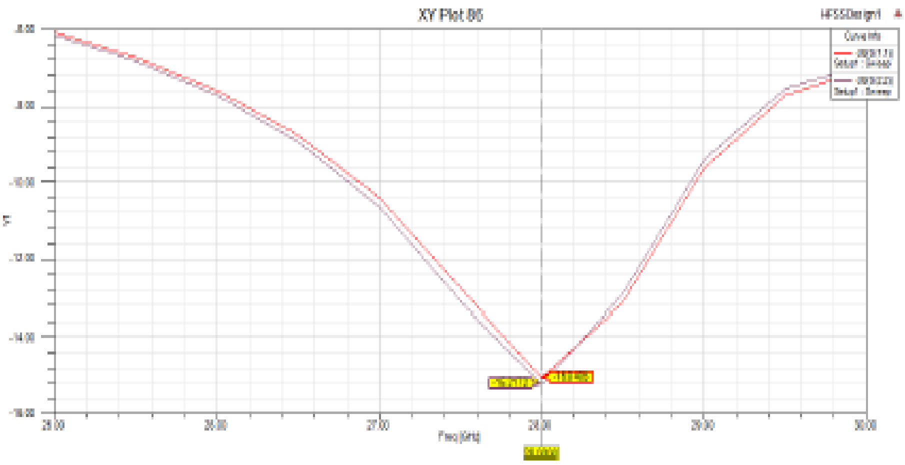


Figure 13: Return Loss of 2×1 MIMO antenna array with DGS

Gain: The gain for the 2×1 MIMO antenna array with DGS was **9.4 dB**, as shown in fig 14.

Figure 14: Gain of 2×1 MIMO antenna array with DGS

The Directivity: The directivity for the 2×1 MIMO antenna array with DGS was **9.45 dBi**, indicating a radiation efficiency of up to 99.4%, as shown in fig 15.

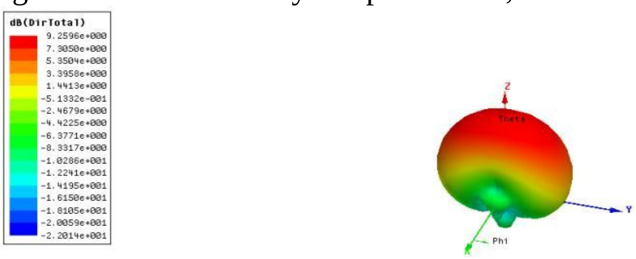


Figure 15: The Directivity of The 1x2MIMO antenna with DGS

VSWR: The VSWR for the 2×1 MIMO antenna array with DGS was **1.2887** at port 1 and **1.2419** at port 2, as shown in fig 16.

Libyan Open University Journal of Applied Sciences (LOUJAS)
Volume 2 - Issue 1 - 2026 - Pages 259-273

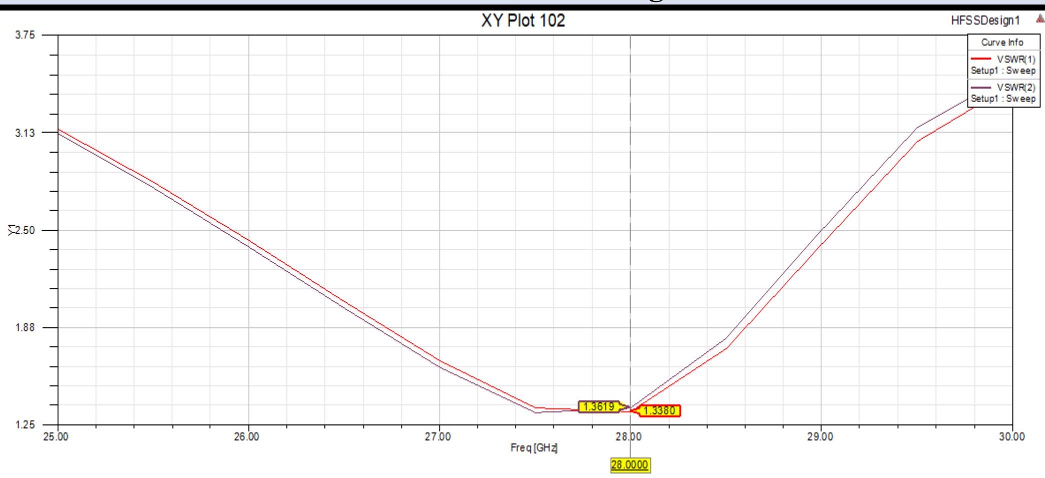


Figure 16: VSWR of 2×1 MIMO antenna array with DGS

Mutual Coupling (S12,S21): The mutual coupling between port 1 and port 2 for the 2×1 MIMO antenna array with DGS was significantly improved to **–22.85 dB**. as shown in fig 17.

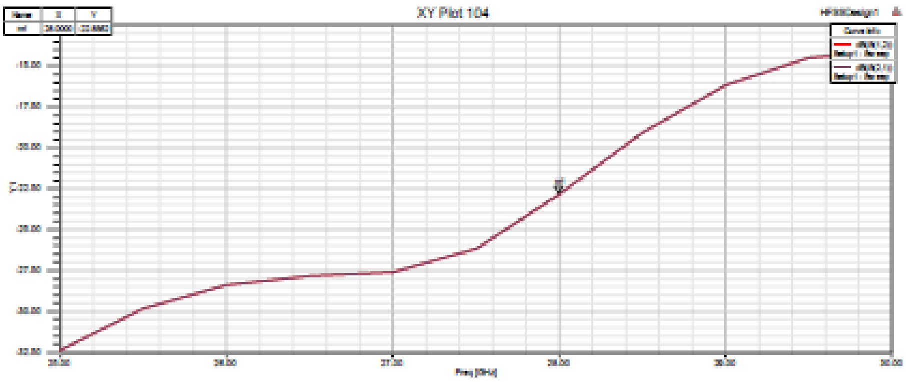


Figure 17: Mutual Coupling in 2x1 MIMO with DGS

2×1 MIMO with DGS + EBG: Further enhancement was achieved by combining DGS with Electromagnetic Band Gap (EBG) structures in the 2×1 MIMO configuration to provide additional coupling suppression, as shown in fig 18.

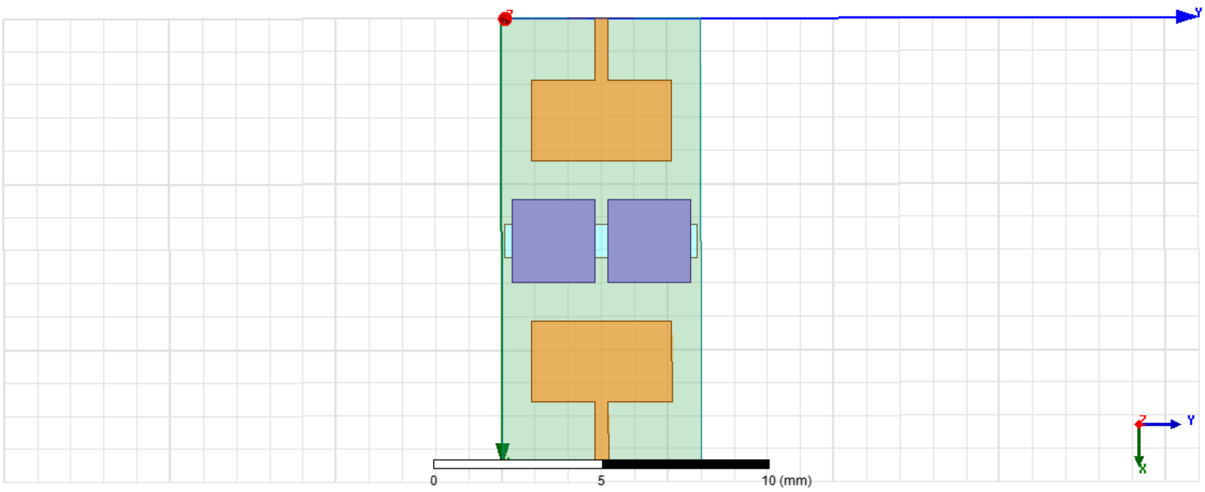


Figure 18: 2×1 MIMO with DGS + EBG

Return Loss (S11, S22): The 2×1 MIMO antenna array with DGS and EBG exhibited a return loss of **–16.79 dB** at port 1 (S11) and **–16.29 dB** at port 2 (S22), as shown in fig 19.

Libyan Open University Journal of Applied Sciences (LOUJAS)
Volume 2 - Issue 1 - 2026 - Pages 259-273

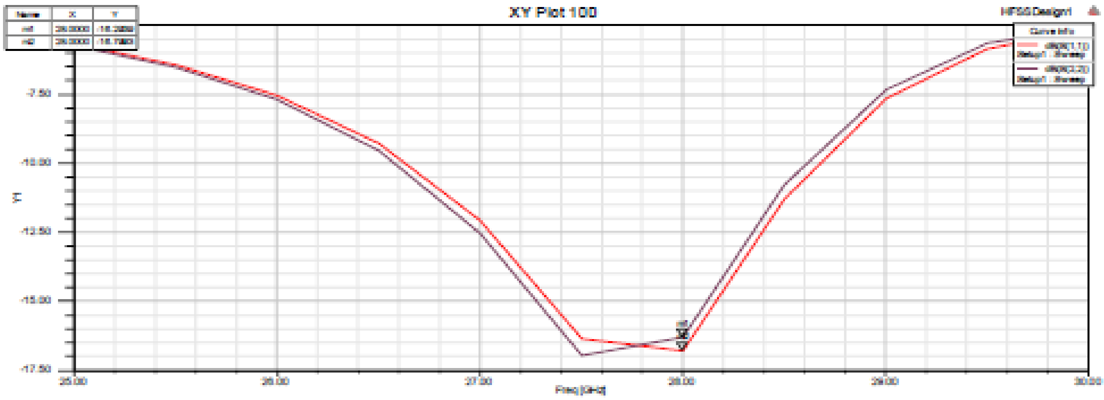


Figure 19: Return Loss of 2×1 MIMO antenna array with DGS+EBG

The Gain: The gain for the 2×1 MIMO antenna array with DGS and EBG was **9.21 dB**, as shown in fig 20.

Figure 20: Gain of 2×1 MIMO antenna array with DGS and EBG

The Directivity: The directivity for the 2×1 MIMO antenna array with DGS and EBG was **9.26 dBi**, indicating a radiation efficiency of up to 99.46%, as shown in fig 21.

Figure 21: The Directivity of 2×1 MIMO antenna array with DGS and EBG

VSWR: The VSWR for the 2×1 MIMO antenna array with DGS and EBG was **1.338** at port 1 and **1.3619** at port 2, as shown in fig 22.

Libyan Open University Journal of Applied Sciences (LOUJAS)
Volume 2 - Issue 1 - 2026 - Pages 259-273

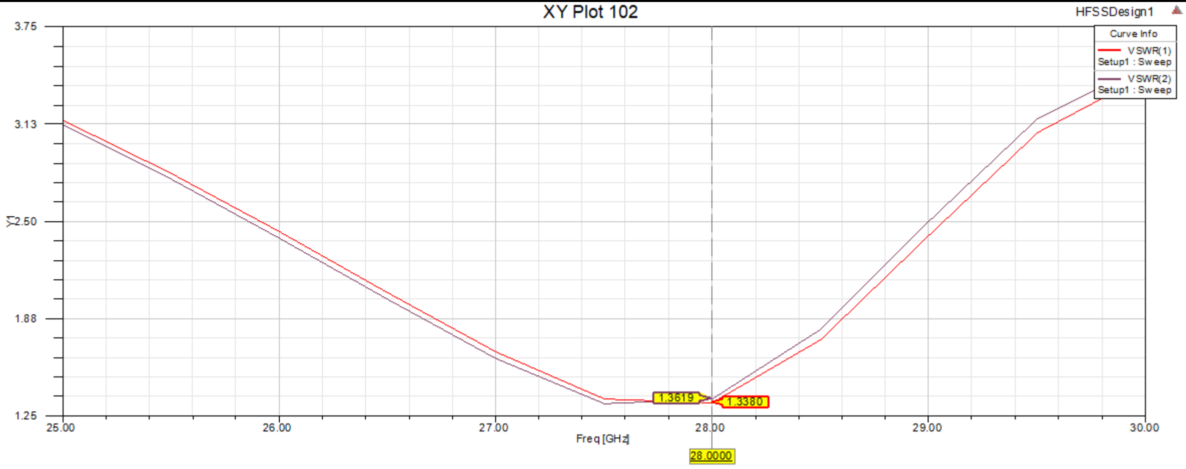


Figure 22: VSWR of 2×1 MIMO antenna array with DGS and EBG

Mutual Coupling (S12,S21): The mutual coupling for the 2×1 MIMO antenna array with DGS and EBG was further reduced to **–24.5175 dB**, as shown in fig 23.

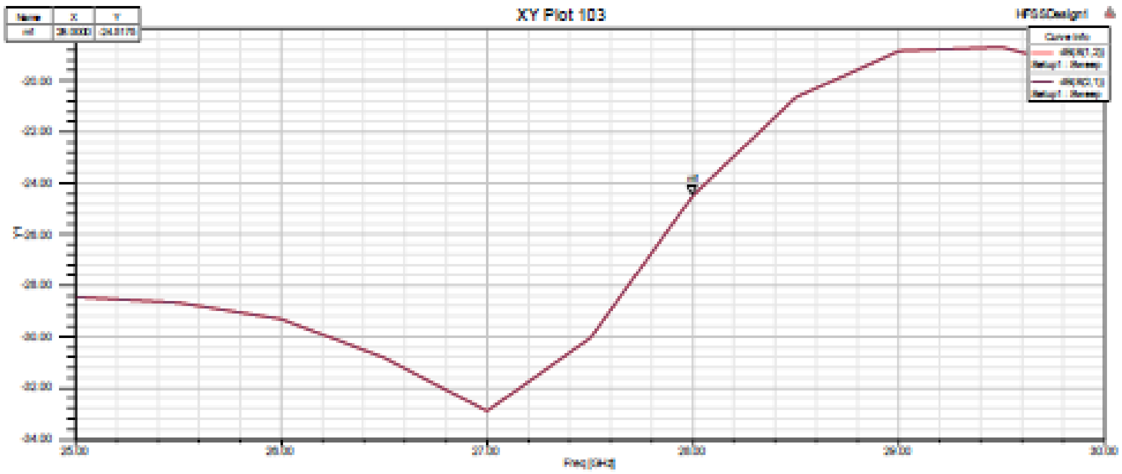


Figure 23: Mutual Coupling in 2×1 MIMO antenna array with DGS and EBG

Discussion

The antenna design was developed progressively from a single-element microstrip patch to a 1×2 MIMO system integrated with DGS and EBG structures. A summary of the key parameters at each stage is provided below:

- **Single-element antenna:**
  - Gain: 6.83 dB
  - Directivity: 6.99 dBi
  - Return Loss: –15.42 dB
  - VSWR: 1.4079
- **1×2 MIMO with DGS:**
  - Gain: 9.4 dB (↑ from 6.83 dB)
  - Directivity: 9.45 dBi (↑ from 6.99 dBi)
  - Return Loss: –17.98 dB (Port 1), –19.33 dB (Port 2)
  - VSWR: 1.28 (Port 1), 1.24 (Port 2)
  - Mutual Coupling: –22.85 dB
- **1×2 MIMO with DGS + EBG:**
  - Gain: 9.21 dB (↓ from 9.4 dB)
  - Directivity: 9.26 dBi (↓ from 9.45 dB)

- Return Loss: –16.79 dB (Port 1), –16.29 dB (Port 2)
- VSWR: ~1.3
- Mutual Coupling: –24.52 dB (improved by ~1.67 dB)

Analysis

Moving from a single-element to 1×2 MIMO with DGS increased gain by ~2.57 dB and directivity by ~2.46 dBi, while mutual coupling improved to –22.85 dB. Adding EBG to the 1×2 MIMO further reduced mutual coupling to –24.52 dB, but caused a slight decrease in gain and directivity due to additional energy losses introduced by the EBG structures.

CONCLUSION

In this project, a 28 GHz MIMO microstrip antenna system was designed and analyzed progressively, starting from a single-element patch antenna and expanding to 1×2 and 2×2 MIMO configurations. Techniques such as Defected Ground Structures (DGS) and Electromagnetic Band Gap (EBG) structures were applied to reduce mutual coupling and improve isolation between antenna elements.

The numerical results indicate that:

- The single-element antenna provided a baseline performance with acceptable gain, directivity, and return loss.
- The 1×2 MIMO with DGS significantly improved isolation, gain, and directivity compared to the single-element design.
- Adding EBG structures to the 1×2 MIMO further enhanced isolation (mutual coupling reduced from –22.85 dB to –24.52 dB) while causing a slight decrease in gain and directivity due to energy losses introduced by EBG.

Overall, the combination of DGS and EBG proved effective in mitigating mutual coupling, improving diversity, and enabling the MIMO antenna system to meet 5G millimeter-wave requirements.

References

1. Zeng, D.L. (2010). *Antenna theory and microstrip antenna*. Taylor & Francis Group.
2. Balanis, C.A. (2016). *Antenna theory: Analysis and design* (2nd ed.). John Wiley & Sons.
3. Eudacadenic.net. (n.d.). Some background on antennas. Retrieved from https://eudacadenic.net/some-background-on-antennas
4. Wikipedia. (n.d.). 5G. Retrieved from https://en.wikipedia.org/wiki/5G
5. Saoud, H.A., & Abdalla, A.Z. (2020). Design and simulation of rectangular microstrip patch antenna with coplanar ground to 5G band for satellite applications. *College of Electronic Technology*.
6. Johnson, D.L., & Thiele, G.A. (2003). *Antenna theory and design* (2nd ed.). John Wiley & Sons, Inc.
7. Tse, D., & Viswanath, P. (2005). *Fundamentals of wireless communication*. Cambridge University Press.
8. Goldsmith, A. (2005). *Wireless communications*. Cambridge University Press.
9. Heath, R.W., & Lozano, A. (2018). *Foundations of MIMO communication*. Cambridge University Press.
10. Foschini, G.J. (1996). Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas. *Bell Labs Technical Journal, 1*(2), 41–59.
11. Telatar, E. (1999). Capacity of multi-antenna Gaussian channels. *European Transactions on Telecommunications, 10*(6), 585–595.
12. Marzetta, T.L., et al. (2016). *Fundamentals of massive MIMO*. Cambridge University Press.
13. Xiang, T. (2014). Massive MIMO in next generation environments.
14. Ren, J., Mi, D., & Yin, Y. (2018). Compact ultra-wideband MIMO antenna with WLAN/UWB band coverage. *Congress in Electromagnetic Research*.
15. Roque, G. (2021). MIMO antenna for mobile terminals.
16. Larsson, G. (2018). *Massive MIMO in next generation wireless systems*. Linköping University Press.

17. Sun, C.W. Deshun. (2016). Analysis and design of 4×4 MIMO-antenna systems in mobile phone. *Journal of Computer and Communications*.
18. Chen, Z.N., et al. (2018). A review of mutual coupling in MIMO systems. *IEEE Access*, *6*, 24706–24719.
19. Islam, S.S., et al. (2019). Mutual coupling reduction in MIMO antennas using defected ground structures and EBG. *IEEE Transactions on Antennas and Propagation*, *67*(9), 5852–5863.
20. Ali, T., et al. (2023). Mutual coupling reduction in MIMO antennas using metamaterial structures. *Sensors, 23*(18), 7720. MDPI.