REGULAR ARTICLE

Pattern-Diversity Four-Element MIMO Antenna with Enhanced Isolation for Millimeter-Wave 5G Applications

D. Haimoune[1,*], B. Guenad[2], H.A. Bakir[2], A. Zidour[3], H.A. Benghenia[4]

[1] *Department of Electronics, Faculty of Technology, Signals, Systems and Artificial Intelligence Laboratory (2SAIL), Hassiba Benbouali University of Chlef, Algeria*
[2] *Department of Electronics, Faculty of Technology, Hassiba Benbouali University of Chlef, Algeria*
[3] *Department of Electrical Systems Engineering, Faculty of Technology, LIST Laboratory, M'hammed Bougara University, Boumerdes 35000, Algeria*
[4] *Department of Electronics and Telecommunications, Faculty of Science and Technology, Belhadj Bouchaib University of Ain Temouchent, Algeria*

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In this work, we present a compact four-port MIMO antenna designed for millimeter-wave 5G systems. The antenna operates across the 34.8 to 48.6 GHz frequency range, providing an impedance bandwidth of roughly 28.36 %. It was fabricated on a Rogers RT/Duroid 5880 substrate (*r* = 2.2, thickness 0.787 mm, tan = 0.0009), which keeps losses very low while maintaining strong performance. Our measurements show that the antenna reaches a peak gain of 9.9 dB and exhibits excellent impedance matching, with a return loss of – 46 dB at 43 GHz. The MIMO configuration performs reliably: inter-element isolation exceeds 20 dB, ECC stays below 0.05, and the Mean Effective Gain (MEG) is – 3.0103 dB. This confirms that signals are received consistently and evenly across all ports. One of the things that stands out about this design is its simplicity. Unlike antennas that rely on multiple layers or decoupling techniques, this planar structure is easy to fabricate and integrate directly into 5G hardware. Even with a compact footprint of just 28 × 36 mm^2, it delivers excellent efficiency and stable broadband performance. Altogether, this antenna provides a practical and reliable solution for next-generation mmWave MIMO communication, offering wideband operation, strong isolation, and pattern diversity all packed into a small, easy-to-build design.

Keywords: MIMO, Pattern diversity, Millimeter-wave (mmWave), High isolation, Antenna design, Fifth-Generation (5G).

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1. INTRODUCTION

The constant drive to improve terminal installations and infrastructure development has drawn a lot of interest from researchers in Fifth Generation (5G) technology [1]. Although 5G networks are currently in operation, continued research and development remain critical to fulfill the expanding demand For extremely high data throughput, very low latency, massive device connectivity, and efficient spectrum utilization [2], the steadily rising demand for mobile data together with the rapid growth of platforms offering high-quality video delivery, cloud computing, immersive augmented and virtual reality, and the Internet of Things (IoT) is creating the urgency for continual advancement in wireless system architectures [3]. Currently, 5G networks utilize sub-6 GHz frequency bands to provide broad coverage, and millimeter-wave (mmWave) bands are being developed to support local area connectivity and short-range indoor connectivity [4]. The vast bandwidth of mmWave frequencies allows for the possibility of multi-gigabit data rates, which may greatly improve the communication performance as compared to traditional sub-6 GHz bands [5]. The mmWave region of the electromagnetic spectrum, ranging from 30 to 300 GHz has the largest amount of bandwidth resources available for 5G in the greater range of 5G frequency options [6].In order to develop their national 5G standards, many countries have selected certain mmWave frequency bands which include Japan: 27.5-28.8 GHz, Korea: 28 GHz, and China: 24.2-27.5/37-43.5 GHz [7]. In October 2015, the Federal Communications Commission (FCC) recommended the comprehensive study of the 28, 37, 39, and 64-71 GHz bands. Therefore, it has become essential to design devices to operate in these frequencies to facilitate the advancement of 5G communication systems [8]. To satisfy the increasing demand of next-generation wireless networks, new antenna technology such as multipleinput multiple-output (MIMO) systems have emerged as effective options for increasing gift capacity, reliability, and data throughput [9].

The millimeter wave (mmWave) spectrum is an attractive area for 5G, offering significant bandwidth assets, while posing unique propagation challenges. As a key technology in fifthgeneration (5G) mobile networks, mmWave is an important enabler for the increasing volume of data traffic. However, mmWave has

* Correspondence e-mail: d.haimoune@univ-chlef.dz

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higher carrier frequencies and shorter wavelengths, leading to greater attenuation through the path loss and physical barriers than sub-6 GHz bands. Based on the Friis transmission eq. [10]. Moving communications to the mmWave frequencies results in greater free-space attenuation, which presents new challenges; however, some of these challenges can be solved or compensated for by using an array of high-gain antennas to improve the signal strength and performance of the entire system [11].

5G technology is critically advantageous, but a notable challenge is signal degradation during communication since it can have a limited penetration ability. A solution to the penetration issue is to use multiple input multiple output 2 (MIMO) technology, where multiple antenna elements are used at the transmitter and receiver to improve the rate of data transmission and communication. Here the research community continues to focus on improving radiation characteristics and developing performance metrics for the massive MIMO mmWave antenna and it has yielded many benefits for 5G systems [12]. In [13], A dielectric resonator antenna (DRA) was proposed for MIMO-based 5G millimeter-wave (mmWave) systems, showing improved port isolation. The configuration utilizes two rectangular DRA elements on a dielectric substrate, excited by microstrip-fed slots to achieve efficient coupling and optimized radiation. In [14], the authors proposed a new technique to enhance isolation by adding two orthogonal cross-shaped apertures in the ground plane. Additionally, a decoupling structure with slotted rings placed between the radiating elements was used to reduce mutual coupling, achieving significantly improved isolation. The authors in [15], to improve isolation, slotted-ring decoupling structures were positioned between the radiating elements, and two orthogonal cross-shaped apertures were added to the ground plane. The authors in [16], a single-layer MIMO antenna for the 28 GHz 5G band is proposed. It uses a Rogers5880 substrate, achieves about 6.1 dBi gain with over 90 % efficiency, and has a low ECC (< 0.16). The authors in [17], for mmWave MIMO systems, a multi-arc radiating element was proposed. It provides 23.5-38 GHz impedance bandwidth and 23 dB isolation through an orthogonal setup, though the overall antenna size is still relatively oversized. In summary, MIMO technology presents a number of obstacles in addition to its many advantages. Optimizing several MIMO performance parameters is necessary to achieve the best results.

In contrast to many previously reported designs, the proposed four-port MIMO antenna offers a compact, low-cost, and fabrication-friendly solution tailored for 5G mmWave applications. The antenna is fabricated on a Rogers RT/Duroid 5880 substrate, featuring a relative permittivity of $\varepsilon_r = 2.2$ and a thickness of 0.787 mm, and an overall footprint of 28 × 36 mm^2. It operates across the 34.8–48.6 GHz frequency range, achieving a wide impedance bandwidth of 28.36 %. The design attains a peak gain of 9.9 dB and exhibits excellent matching performance, with a return loss reaching – 46 dB at 43 GHz.

The proposed MIMO configuration ensures superior diversity performance, with inter-element isolation consistently greater than 20 dB and an Envelope Correlation Coefficient (ECC) below 0.05, guaranteeing minimal coupling and enhanced channel capacity. Moreover, the Mean Effective Gain ((MEG) = – 3.0103 dB), indicating well-balanced signal reception across all ports.

Unlike previously reported works relying on multi-layer structures, metamaterials, or decoupling networks, the proposed antenna employs a simple planar geometry. This approach simplifies fabrication and facilitates seamless integration into 5G hardware platforms. The combination of wideband operation, high gain, and compact structure underscores its potential integration into upcoming mmWave MIMO communication platforms.

2. PROPOSED ANTENNA DESIGN AND METHODOLOGY

The study addresses three architectures: a standalone antenna element, a dual-element MIMO arrangement, and a configuration incorporating four MIMO elements. As the antenna's complexity increases, this methodical methodology makes it possible to systematically assess important performance metrics, including aspects such as impedance bandwidth, mutual coupling, and isolation.

2.1 Single Element Antenna

The configuration of the designed antenna element is shown in Fig. 1. The antenna is printed on a Rogers RT/duroid 5880 substrate, characterized by a dielectric constant of $\varepsilon_r = 2.2$, a loss tangent of 0.0009, and compact overall dimensions of 12 × 18 × 0.787 mm^3. The structure consists of a modified rectangular radiating patch with several etched slots to improve impedance bandwidth and radiation performance. A microstrip feed line of optimized dimensions is used to excite the patch. The ground plane, shown in Fig. 1(b), is a full metallic conductor covering the entire backside of the substrate.

The etched slots in the patch significantly alter the surface current distribution, enabling the antenna to achieve resonance in the millimeter-wave band with enhanced matching. The simulated reflection coefficient ($S11$) of the proposed antenna is shown in Fig. 2. The results reveal a sharp resonance at 43 GHz with a minimum return loss of approximately – 50 dB. In addition, the antenna a broad impedance bandwidth from 33 to 48 GHz is obtained, covering the entire frequency range required for 5G millimeter-wave applications.

Overall, the proposed single-element antenna combines,compact geometry, wideband operation, and excellent impedance matching, which makes it a suitable candidate for integration into multi-element MIMO configurations.

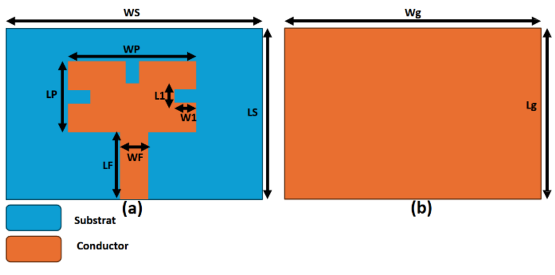


Fig. 1 – Geometry of the proposed patch antenna (a) Front (b) Back

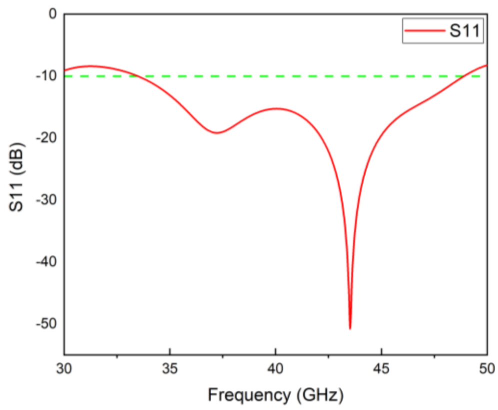


Fig. 2 – Reflection coefficient (*S*11) response of the designed element

2.2 MIMO System with Two Integrated Elements

The proposed antenna design was further developed into,a dual-element MIMO configuration measuring 12 × 36 × 0.787 mm³ overall. Two matching patch elements are arranged side-by-side, with a 12.6 mm gap, a spacing selected to suppress mutual interaction, as depicted in Fig. 3. A Full ground plane covers the underside of the substrate, helping maintain radiation symmetry and consistent performance.

As illustrated in Fig. 4, the simulated *S*-parameter results reveal that the two-port structure operates across 33-48 GHz. Moreover, the transmission coefficients stay below – 35 dB, confirming excellent port isolation and very low coupling, which is summarized in Table 1.

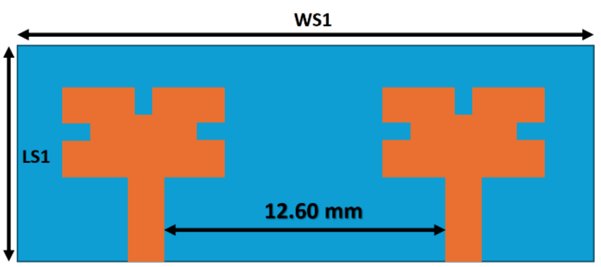


Fig. 3 – Geometry of the two-port MIMO antenna system

Table 1 – Antenna design parameters

Parameter	Value (mm)	Parameter	Value (mm)
WS	18	*WP*	9
LS	12	*LP*	5
WF	2.4	*LF*	4.5
L_1	0.9	W_1	1.5
W_g	18	L_g	12
WS1	36	LS1	12
WS2	36	LS2	28

2.3 Four-Unit MIMO Antenna Structure

After designing the single-element and two-element antenna configurations, the design is extended to a four-element MIMO antenna system, as shown in Fig. 5. In this configuration, the dimensions of each individual antenna element remain the same, while the overall size of the structure is 28 × 36 × 0.787 mm³.

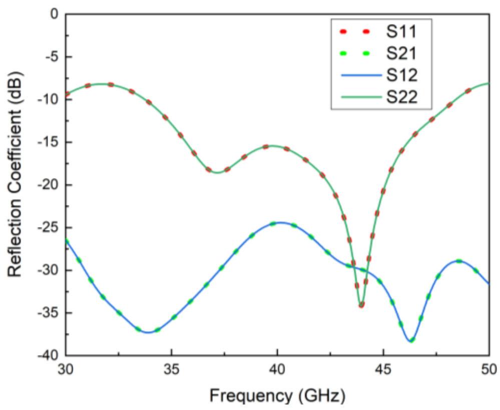


Fig. 4 – *S*-parameter analysis for the dual-element antenna

The four antenna elements are arranged orthogonally, to achieve polarization diversity, and reduce mutual coupling. A full ground plane is employed on the backside of the substrate, to enhance isolation, and improve radiation efficiency, while maintaining compact dimensions suitable for 5G integration.

The simulated scattering parameters (S-parameters), shown in Fig. 6, indicate that the proposed four-element MIMO antenna covers the wide operating band of 34.8–48.6 GHz. In particular, the reflection coefficient (S11) achieves a minimum value below – 46 dB, confirming excellent impedance matching. Furthermore, the transmission coefficients (S_{ij}, $i \neq j$) remain below – 20 dB across the band, demonstrating strong isolation, and minimal coupling between the antenna elements.

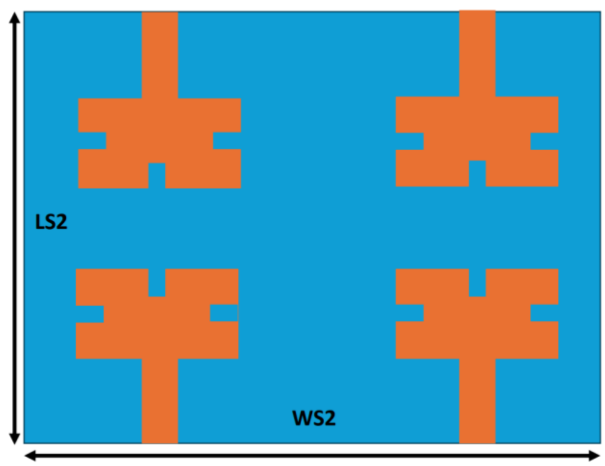
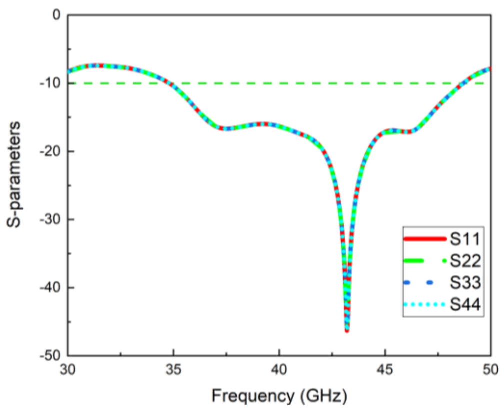


Fig. 5 – Proposed four-antenna MIMO arrangement



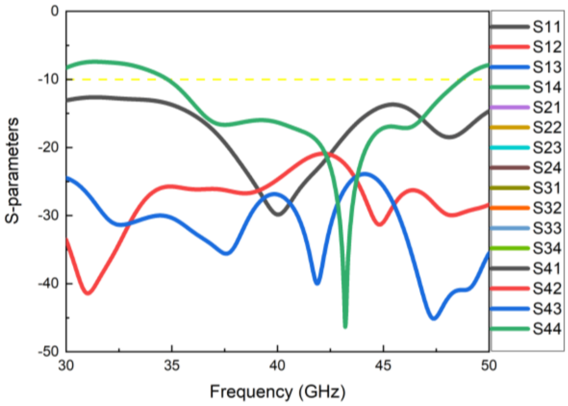


Fig. 6 – Reflection coefficient and *S*-parameter of the proposed 4-port MIMO antenna

Therefore, the proposed four-element MIMO antenna offers a compact size, wide impedance bandwidth, and excellent isolation performance, making it a strong candidate for millimeter-wave 5G wireless communication systems.

The voltage standing wave ratio (VSWR),of the proposed four-element MIMO antenna was evaluated for all four ports, as presented in Fig. 7. The results show that the VSWR values for Ports 1, 2, 3, and 4 remain consistently below 2 across the entire 34.8-48.6 GHz operating band. This indicates excellent impedance matching, and efficient power transfer for each antenna element. Moreover, the nearly identical behavior across all ports, confirms the structural symmetry and balanced performance of the proposed design.

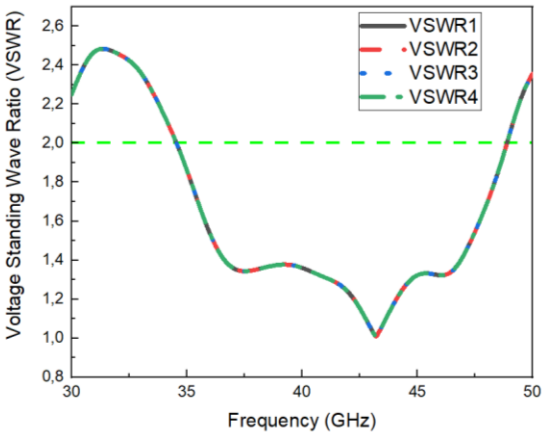


Fig. 7 – VSWR of the proposed four-element MIMO antenna for all four ports

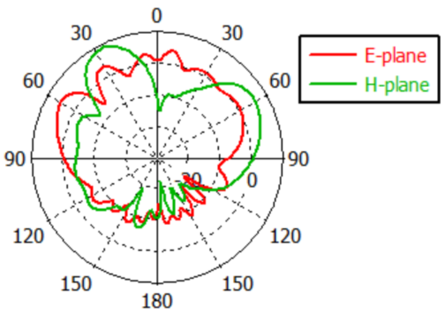


Fig. 8 – Simulated port 1 Radiation at 43 GHz for Principal Planes $\phi = 0°$ (red) and $\phi = 90°$ (green)

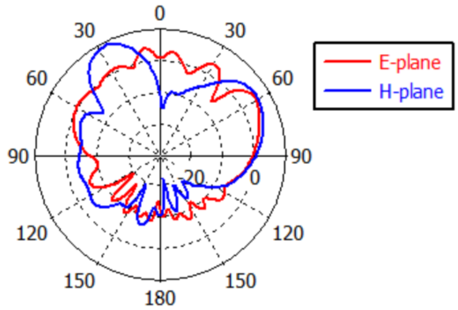


Fig. 9 – Simulated port 2 radiation at 43 GHz for principal planes $\phi = 0°$ (red) and $\phi = 90°$ (blue)

To gain deeper insight into the antenna's radiation behavior, far-field patterns were examined at 43 GHz. Measurements for ports 1 and 2 were extracted across the *E*-plane and *H*-plane, as demonstrated in Fig. 8 and Fig. 9. These patterns demonstrate consistent radiation performance, exhibiting low side-lobe levels and a well-defined main lobe, characteristics that are particularly advantageous for 5G millimeter-wave operation.

3. GAIN AND EFFICIENCY OF THE PROPOSED MIMO ANTENNA

A key feature of the proposed design is its high realized gain,and efficiency. The antenna, fabrication employs Rogers RT/Duroid 5880 substrate, characterized by $\varepsilon_r = 2.2$, and a loss tangent of 0.0009, exhibits excellent radiation performance.

The proposed four-element MIMO antenna achieves, a maximum realized gain of 9.9 dB within the 34.8-48.6 GHz operating band, as illustrated in Fig. 10. Moreover, the simulated total efficiency is consistently above 90 % across the band, confirming the low-loss substrate characteristics and the functional behavior of the antenna.

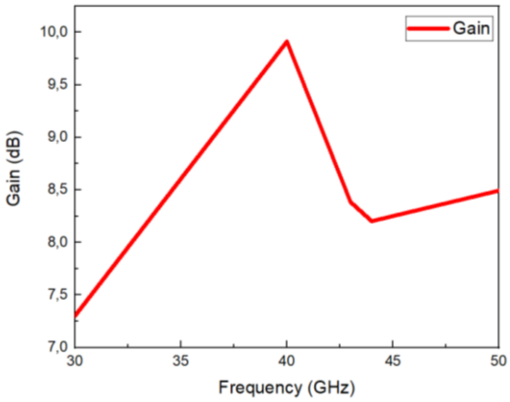


Fig. 10 – Simulated Realized Gain Performance of the Four-Antenna MIMO Configuration

4. EVALUATION PARAMETERS FOR MIMO OPERATION

To comprehensively evaluate the performance of the proposed pattern-diverse quad-element antenna MIMO featuring enhanced isolation for millimeter-wave 5G deployments, several diversity performance metrics are investigated through full-wave simulations in CST Studio Suite.

4.1 Investigation of Envelope Correlation Coefficient (ECC)

The envelope correlation coefficient (ECC) is an important parameter that represents the level of correlation between signals received by different antenna elements in a MIMO system. Lower ECC values, ideally approaching zero, correspond to improved diversity performance and increased channel capacity, while higher ECC values imply stronger signal correlation and degraded diversity. In practice, ECC values below 0.05 are generally considered acceptable [18-19]. In the case of the proposed four-element MIMO antenna, the simulated ECC values remain below this limit across the 34.8-48.6 GHz operating band, as illustrated in Fig. 11. Mathematically, the ECC is defined according to Eq (1) [19]:

$$\mathrm{ECC} = \frac{\left|\iint 4\pi\, M_i(\theta,\phi) M_j(\theta,\phi)\, d\Omega\right|^2}{\left(\iint 4\pi\, |M_i(\theta,\phi)|^2\, d\Omega\right)\left(\iint 4\pi\, |M_j(\theta,\phi)|^2\, d\Omega\right)} \qquad (1)$$

As depicted in Fig. 11, the simulated envelope correlation coefficient (ECC) for antenna pairs (1,2) and (1,3) remains consistently below 0.0025 throughout the 34.8-48.6 GHz frequency range. These results indicate strong inter-element isolation and very low signal correlation, confirming the antenna's suitability for delivering efficient and reliable MIMO operation.

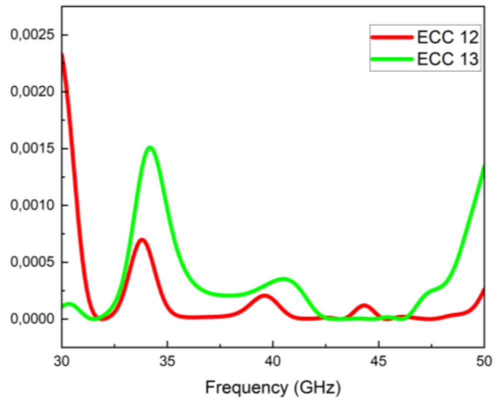


Fig. 11 – Simulated ECC outcomes for antenna pairs (1,2) and (1,3) within the four-element MIMO arrangement

4.2 Investigation of Diversity Gain (DG)

Diversity Gain (DG) is a significant metric that evaluates the capability of a MIMO antenna system to mitigate multipath fading and enhance link reliability. It expresses the improvement achieved when multiple antennas are utilized instead of a single one. There exists a direct relationship between DG and ECC, where the DG can be calculated through the equation given below. [19]:

$$\boldsymbol{DG} = \mathbf{10}\sqrt{\mathbf{1} - |\mathrm{ECC}|^2} \qquad (2)$$

The simulated DG values of the proposed four-port MIMO antenna remain near the optimal reference value of 10 dB over the operating frequency range, demonstrating excellent diversity performance, as illustrated in Fig. 12.

As illustrated in Fig. 12, for element pairs (1,2) and (1,3), the diversity gain (DG) remains above 9.988 dB throughout the entire operating band, demonstrating the outstanding diversity capability of the proposed MIMO antenna configuration.

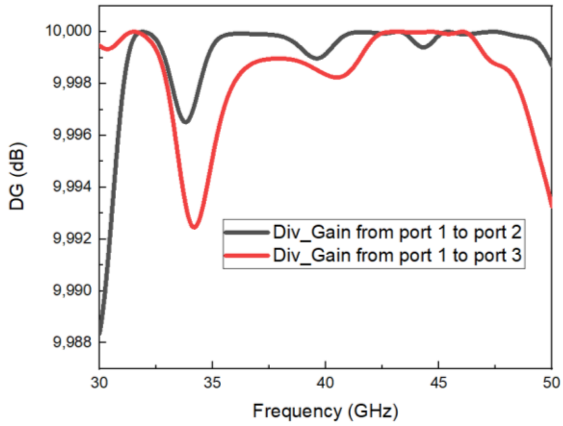


Fig. 12 – Four-element MIMO simulated DG comparison for the (1,2) and (1,3) radiator pairs

4.3 Mean Effective Gain (MEG)

The Mean Effective Gain (MEG) quantifies the average gain of a MIMO antenna relative to an isotropic antenna, providing a measure of how effectively the antenna receives signals in a multipath environment. For optimal performance, MEG values should be below – 3 dB. For a MIMO system with N antenna ports, the MEG of the i-th port is calculated as [20]:

$$\boldsymbol{MEG_i} = \frac{1}{2}\left(\mathbf{1} - \sum_{j=1}^{N}\left|\boldsymbol{S_{ij}}\right|^2\right) \qquad (3)$$

where S_{ii} denotes the reflection coefficient of port i, and S_{ij} ($i \neq j$) represents the mutual coupling between ports. The proposed 4-port MIMO antenna demonstrates excellent MEG performance, as illustrated in Fig. 13.

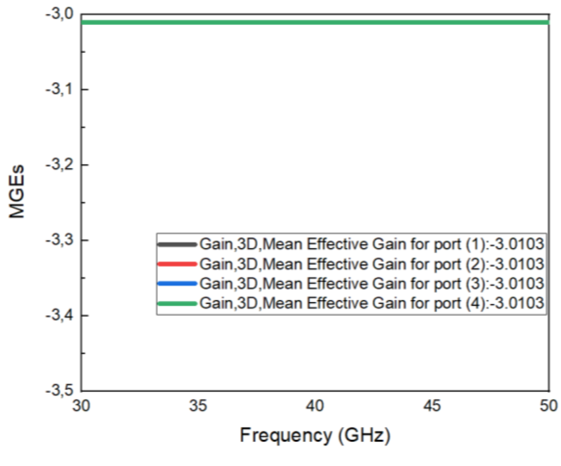


Fig. 13 – Simulated mean effective gain of the presented four-port MIMO antenna

5. COMPARATIVE STUDY WITH ADVANCED 5G MIMO ANTENNAS

The four-port MIMO antenna presented here demonstrates distinctive features that set it apart from recently published designs. A detailed comparison with several contemporary MIMO configurations is given in Table 2, evaluating key factors such as port count, operating bandwidth, and peak gain. To further gauge MIMO behavior, additional aspects – physical footprint.

In addition to evaluating the Envelope Correlation Coefficient (ECC), the investigation highlights interelement isolation. The outcomes confirm that the antenna maintains a compact profile while delivering broad operating bandwidth, considerable gain, and reliable MIMO functionality, positioning it as a strong candidate for mmWave 5G implementations.

Table 2 – Comparative analysis of the presented 5G MIMO antenna with reported 5G designs in the literature

Ref	Ports	Size (mm^3)	Bandwidth (GHz)	Max.Gain (dB)	Isolation (dB)	ECC
[14]	4	158 × 77.8	27.5-40	7.2	> 17	< 0.03
[15]	2	35 × 35	25.5-40	4	28	0.004
[16]	4	30 × 30	27.5-29.5	6.1	26	0.16
[17]	4	11.6 × 12	26.2-27.6/47-50	6	28/25	0.001
[21]	4	25 × 15	26-30	7.8	> 17	< 0.0001
[22]	4	24 × 24	25-40	7	26	< 0.05
This Work	4	28 × 36	34.8-48.6	9.9	> 20	< 0.05

Overall, the proposed antenna design achieves an excellent balance between performance efficiency and practical implementation considerations. The antenna exhibits high interelement isolation, elevated gain, and wide impedance bandwidth, making it superior or highly competitive compared to most contemporary designs across all key performance metrics. Its simple planar geometry and compact substrate integration facilitate practical fabrication and seamless deployment in compact 5G mmWave systems, particularly those requiring high data throughput, multi-channel support, and reliable operation in challenging propagation environments. The combination of high performance, efficiency, and robust isolation establishes the introduced antenna demonstrates outstanding performance characteristics candidate for nextgeneration ultrafast, high-capacity wireless communication networks.

6. CONCLUSION

In this work, a compact four-port MIMO antenna for 5G mmWave applications has been designed, simulated, and analyzed, demonstrating wideband operation across 34.8-48.6 GHz with a peak gain of 9.9 dB and excellent matching performance (return loss of – 46 dB). The antenna is implemented on a Rogers RT/Duroid 5880 substrate with a compact footprint of 28 × 36 × 0.787 mm3 and a relative permittivity of ε_r = 2.2. Its planar and simple geometry facilitates fabrication and seamless integration into 5G hardware platforms, eliminating the need for multilayer structures, metamaterials, or complex decoupling networks. Inspired by high-port MIMO designs, the antenna employs an optimized element arrangement that ensures high interelement isolation (> 20 dB) and low mutual coupling, while offering a 28.36 % impedance bandwidth. Transitioning from a single-element layout to a four-port MIMO architecture markedly improves channel throughput and reliable multistream transmission, supported by low ECC (0.05) and balanced signal reception (MEG = – 3.0103 dB). Furthermore, the antenna delivers superior radiation performance while maintaining a compact size, high efficiency, and structural simplicity. The combination of wideband operation, high gain, robust MIMO functionality, and fabrication-friendly planar geometry establishes this design stands out as a promising solution for future 5G millimeter-wave communications and next-generation wireless systems that require compact yet high-efficiency MIMO implementations.

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Чотириелементна MIMO-антена з рознесенням діаграм спрямованості та покращеною ізоляцією для міліметрових хвиль 5G

D. Haimoune[1], B. Guenad[2], H.A. Bakir[2], A. Zidour[3], H.A. Benghenia[4]

[1] *Department of Electronics, Faculty of Technology, Signals, Systems and Artificial Intelligence Laboratory (2SAIL), Hassiba Benbouali University of Chlef, Algeria*

[2] *Department of Electronics, Faculty of Technology, Hassiba Benbouali University of Chlef, Algeria*

[3] *Department of Electrical Systems Engineering, Faculty of Technology, LIST Laboratory, M'hammed Bougara University, Boumerdes 35000, Algeria*

[4] *Department of Electronics and Telecommunications, Faculty of Science and Technology, Belhadj Bouchaib University of Ain Temouchent, Algeria*

У роботі представлено компактну чотирипортову антену MIMO, розроблену для систем міліметрових хвиль 5G. Антена працює в діапазоні частот від 34,8 до 48,6 ГГц, забезпечуючи смугу пропускання імпедансу приблизно 28,36 %. Вона була виготовлена на підкладці Rogers RT/Duroid 5880 (r = 2,2, товщина 0,787 мм, tan = 0,0009), що забезпечує дуже низькі втрати, зберігаючи при цьому високі характеристики. Вимірювання показують, що антена досягає пікового коефіцієнта підсилення 9,9 дБ і демонструє чудове узгодження імпедансу з втратами на відбиття – 46 дБ на частоті 43 ГГц. Конфігурація MIMO працює надійно: міжелементна ізоляція перевищує 20 дБ, ECC залишається нижче 0,05, а середній ефективний коефіцієнт підсилення (MEG) становить – 3,0103 дБ. Це підтверджує, що сигнали приймаються стабільно та рівномірно на всіх портах. Однією з особливостей цієї конструкції є її простота. На відміну від антен, які використовують кілька шарів або методи розв'язки, цю планарну структуру легко виготовити та інтегрувати безпосередньо в обладнання 5G. Навіть з компактним розміром лише 28 × 36 мм^2, вона забезпечує чудову ефективність та стабільну широкосмугову продуктивність. Загалом, ця антена є практичним та надійним рішенням для зв'язку mmWave MIMO наступного покоління, пропонуючи широкосмугову роботу, міцну ізоляцію та різноманітність діаграм спрямованості, все це в компактному та простому у складанні дизайні.

Ключові слова: MIMO, Різноманітність діаграми спрямованості, Міліметрові хвилі (mmWave), Висока ізоляція, Конструкція антени, П'яте покоління (5G).