International Transaction of Electrical and Computer Engineers System, 2025, Vol. 9, No. 1, 1-5
Available online at http://pubs.sciepub.com/iteces/9/1/1
Published by Science and Education Publishing
DOI:10.12691/iteces-9-1-1

Mathematical Framework for Evaluating Mutual Coupling in MIMO Antennas Across Different Sizes, and Frequencies with Design of a Wearable Antenna on Jeans Substrate

Nassrin Ibrahim Mohamed Elamin[1], Mohammed Gronfula[2,*]

Department of Engineering, Alasala Collages, Dammam, Kingdom of Saudi Arabia
*Corresponding author: nassrin.elamin@alasala.edu.sa

Received August 13, 2025; Revised September 15, 2025; Accepted September 23, 2025

Abstract Recently, MIMO technology has emerged as a crucial component in wireless communication systems, enhancing data rates and channel capacity. Wearable antennas, designed to function while being worn, represent a new generation of clothing that can sense, process, and communicate data. In this paper, a new evaluation method is introduced to assess MIMO antenna system isolation, taking into account mutual coupling, antenna size, and operating frequency. Additionally, a flexible 2-element 3.5 GHz microstrip MIMO antenna system on a jeans substrate is simulated using CST Microwave Studio software and fabricated. Despite the jeans material being an insulator, the antenna achieves a frequency coverage of 3.5 GHz with a VSWR of less than 2.5 (-6 dB) and a gain of 7.35 dB. The MIMO system exhibits high isolation of -34 dB, outperforming expectations given the λ/2 distance between elements. The use of jeans as a substrate results in a flexible, lightweight antenna that matches the 3.5 GHz frequency with high gain and isolation, despite being an unconventional material compared to traditional FR-4 substrates. a new evaluation method is introduced to assess MIMO antenna system isolation, taking into account mutual coupling, antenna size, and operating frequency.

Keywords: *MIMO, Wearable Antenna, Microstrip, Jeans Substrate*

Cite This Article: Nassrin Ibrahim Mohamed Elamin, and Mohammed Gronfula, “Mathematical Framework for Evaluating Mutual Coupling in MIMO Antennas Across Different Sizes, and Frequencies with Design of a Wearable Antenna on Jeans Substrate.” *International Transaction of Electrical and Computer Engineers System*, vol. 9, no. 1 (2025): 1-5. doi: 10.12691/iteces-9-1-1.

1. Introduction

Multiple data streams simultaneously, thereby enhancing the overall throughput and reliability of wireless links. This spatial multiplexing technique allows for significant improvements in spectral efficiency and communication range, particularly in environments with rich multipath propagation [1]. Furthermore, MIMO systems can leverage diversity combining to mitigate fading effects and improve signal-to-noise ratio, ensuring more robust communication channels even under challenging conditions [2]. The advancement of 5G systems further emphasizes the importance of MIMO technology due to its ability to facilitate high-speed data rates, enhanced bandwidth, and reduced latencies [3]. This is particularly crucial for emerging applications such as the Internet of Things, autonomous vehicles, and real-time cloud services, all of which demand robust and high-capacity wireless connectivity [4]. The integration of multiple antennas within compact devices, however, introduces challenges like mutual coupling, which necessitates advanced isolation techniques for optimal performance [5]. The pursuit of enhanced isolation is critical for realizing the full potential of MIMO systems, especially in compact and wearable antenna designs, where physical separation between elements is limited [6,7]. This miniaturization trend, coupled with the growing demand for flexible and wearable electronic devices, has propelled research into non-conventional substrate materials and antenna configurations to maintain performance despite these constraints [8,9]. This paper addresses these challenges by proposing a novel 2-element microstrip MIMO antenna system on a jeans substrate, specifically engineered for wearable technology applications [10]. This design aims to demonstrate the feasibility of achieving high gain and isolation on a flexible, textile-based substrate, which is essential for integrating communication systems directly into clothing without compromising performance.

A simple micro-strip patch antenna consists of a radiating patch on one side of a dielectric substrate and a ground plane on its other side, and it is suitable for body-worn applications because it mainly radiates perpendicularly to the planar structure and the ground plane efficiently shields the body tissues. It is most suitable for integration into clothing because of its various advantages such as low volume, low profile planar configuration, low cost, light weight and almost maintenance free installation but it has a limitation of narrow bandwidth [11]. Presently, a novel that concise the both element of MIMO antenna system is proposed of improved isolation and it resonates at 3.55 GHz. Designed antenna consist of two element array which reduces mutual coupling between the antenna elements due to its structural design and obtained a mutual coupling of –34 dB. Section 2 presents the proposed antenna geometry while Section 3 describes the design of 2×2 MIMO antenna system.

2. Isolation

Potential isolation techniques must be examined to improve the reduction of mutual coupling between antennas and later been employed in our antennas design for the WLAN MIMO application card, and restricted studies must be performed for each cases due to completeness purpose. [12-22]. To mitigate mutual coupling between MIMO antenna elements, an isolation method is necessary when the distance D between elements is less than 0.5λ, where λ is the operating wavelength. The area (A) of the MIMO antenna system is a crucial factor and can be used to evaluate the design's isolation effectiveness. The relationship between D and A can be expressed as:

$$D + 2a = \sqrt{A} \tag{1}$$

where '2a' represents the combined length of the symmetric MIMO antenna elements. A separation distance of:

$$D = 0.5\lambda \tag{2}$$

is considered the worst-case scenario for isolation [23,24]. As illustrated in Figure 1, the antenna positioning zone 26 Z_{26} (0.029, 0.98) indicates high isolation between elements while maintaining a compact size.

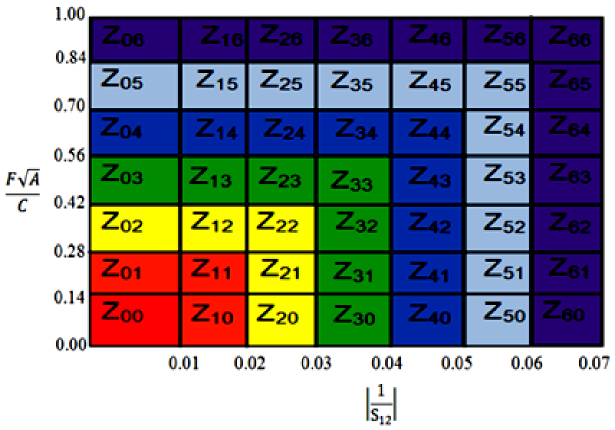

Figure 1. The proposed antenna zone is Z_{26} (0.029, 0.98)

When designing a multiple antenna system, it's crucial to consider antenna isolation, as mutual coupling between antennas can increase port correlation and reduce radiation efficiency, ultimately compromising diversity gain. To achieve high diversity gain, it's essential to minimize correlation between antenna ports. The complex cross-correlation between two signals can be quantified using the mutual coupling between ports [25]. Furthermore, poor isolation between antennas can significantly decrease both capacity and efficiency [26].

3. Antenna Design Steps

In order to identify and verify the improvement for rectangular structure in microstrip antenna, the conventional microstrip antenna design method is used. Designing the patch antenna is to employ the following formulas as an outline for the design procedures [27,28,29,30].

3.1. The Width (W)

$$W = \frac{c}{fr}\sqrt{\frac{2}{\varepsilon r + 1}} \tag{3}$$

Where:
c - Free space velocity of light, 3 x 108 m/s
fr - frequency of operation
ε_r - dielectric constant

3.2. Effective Dielectric constant (ε_r eff)

$$\varepsilon_{reff} = \frac{\varepsilon r + 1}{2} + \frac{\varepsilon r - 1}{2}\left[1 + 12\frac{h}{w}\right]^{-\frac{1}{2}} \tag{4}$$

Where;
ε_r - dielectric constant
h - Height of dielectric substrate
W - Width of the patch

3.3. Effective Length (L_{eff})

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{reff}}} \tag{5}$$

Where
c - free space velocity of light, 3 x 108 m/s
fr - frequency of operation
ε_r eff - Effective dielectric constant

3.4. Patch Length extension (ΔL)

$$\Delta L = 0.412h\frac{\left(\varepsilon_{reff} + 0.3\right)\left(\frac{w}{h} + 0.264\right)}{\left(\varepsilon_{reff} - 0.258\right)\left(\frac{w}{h} + 0.8\right)} \tag{6}$$

3.5. Actual Length of patch (L)

$$L = L_{eff} - 2\Delta L \tag{7}$$

Jeans material has a very low dielectric constant, so that it reduces the surface wave losses and improves the impedance bandwidth of the antenna [12], contrary to the FR-4 substrate, this substrate has a good dielectric that can be observed but not flexible. In this work, we want to obtain a flexible antenna. The proposed MIMO antenna structure is designed as shown in Figure 5. The conductive surfaces and the ground plane of the designed antennas are made out of copper tape with a thickness of T=0.03mm. The simulations were carried out using CST Microwave Studio software and the fabric antennas characteristics were studied. Figure1 below demonstrates CST Model of antenna designs presented in this manuscript showing that the designs of those antennas have been conducted in airspace.

A 50 ohm microstrip feed line was provided for the antenna feed. The antenna is designed to operate at a resonant frequency of 3.55 GHz. The radiation element has a partial ground plane size of 120 mm x 60mm. In addition the jeans substrate has dimensions of 120 mm × 60 mm, with thickness H=3mm, and permittivity ε_r= 1.59. A good impedance matching can be achieved by optimizing the antenna's parameters through the operating band, for WLAN and LTE band 3.55 GHz applications. The proposed MIMO antenna's dimensions are shown in Table 1.

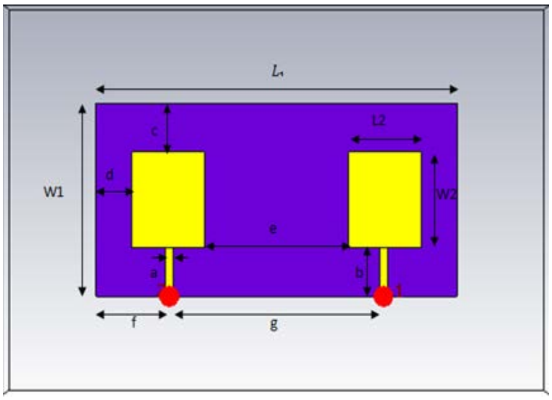

Figure 2. The antenna view of Wearable 2-elements MIMO antenna System

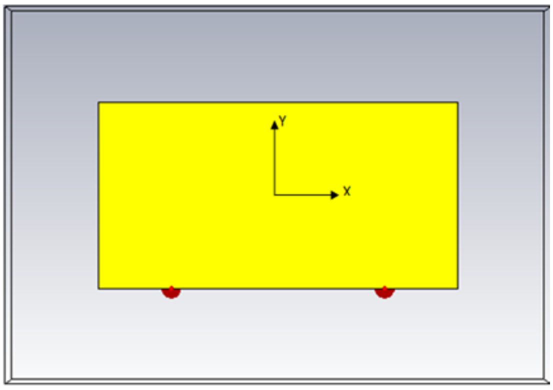

Figure 3. Back view of Wearable 2-elements MIMO antenna System

Table 1. the proposed antenna dimensions (unit: mm)

L_1=120mm	W_1=60mm	a=2.5mm
L_2=24mm	W_2=30mm	b=15mm
c=15mm	d=12mm	e=48mm
f=24mm	g=72mm	

4. Simulation Results

The simulation results depicted in Figure 3 shows that a good isolation higher than -34 dB has been achieved, and that the MIMO antenna system covers WLAN 3.55 GHz application bands under 2.5 VSWR (-6 dB). The simulated return loss and mutual coupling, obtained by using CST Microwave Studio Software, are shown in figure 3. The 3D measured radiation patterns of the 2-elememts at frequency of 3.5GHz are shown in figure 6. So, the gain was a value of 7.38 dB and the directivity was 8.34 dB and good flexible and light weights were observed over the antenna.

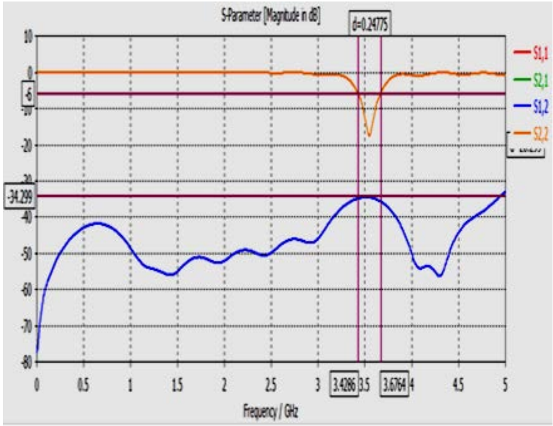

Figure 4. S-parameters of Wearable 2-elements MIMO antenna System

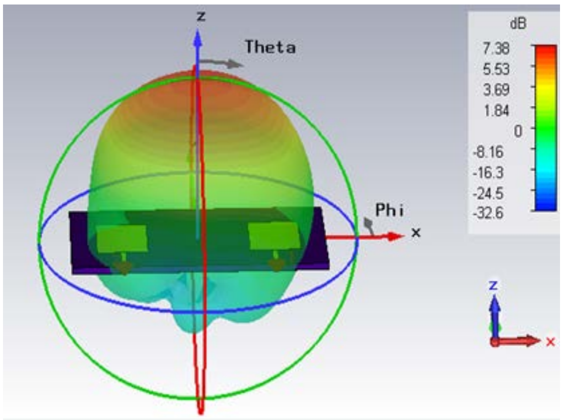

Figure 5. Gain of Wearable 2-elements MIMO antenna System

5. Antenna fabrication

A compact printed planar 2-element MIMO antenna system with good isolation is presented in this path. The antenna is composed of two patch elements as shown in Figure 6. The good isolation achieved, despite the fact that tow antenna elements are printed on a compact MIMO system, is attributable to the three concepts used in the MIMO system design as earlier mentioned. Note that the antenna spacing is less than λ/2 where λ is the free space wavelength at 3.5 GHz.

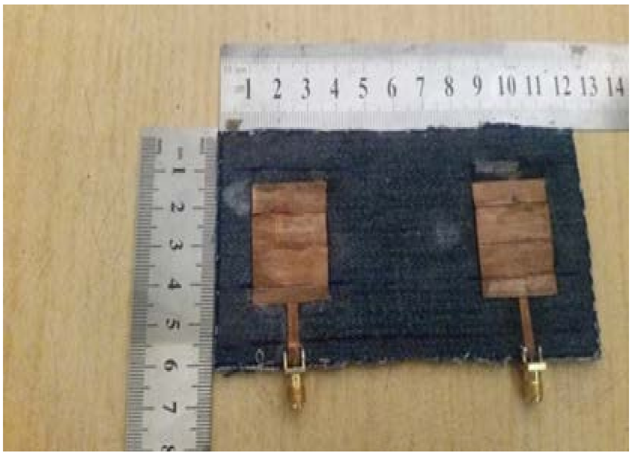

Figure 6. Prototype back view of fabricated 2-element MIMO antenna system

5. Conclusion

This study introduces a pioneering evaluation method for assessing the isolation performance of MIMO antenna systems, taking into account mutual coupling, antenna size, and operating frequency. A novel wearable 2-element microstrip MIMO antenna system is designed on a jeans substrate, operating at 3.5 GHz. The antenna achieves a notable gain of 7.35 dB and a VSWR of 2.5 (-6 dB), attributed to the low dielectric constant of the jeans material. The S-parameters exhibit high isolation between the two elements, with a remarkable value of -34 dB, despite a relatively small distance (λ/2) between them. The antenna's flexible and lightweight design makes it an excellent candidate for wearable applications. This research highlights the potential of utilizing jeans substrate for wearable MIMO antenna design and presents a new approach for evaluating MIMO antenna isolation.

References

[1] Hasan, Md. M., Islam, M. T., Samsuzzaman, M., Baharuddin, M. H., Soliman, M. S., Alzamil, A., Sulayman, I. I. M. A., & Islam, Md. S. (2022). Gain and isolation enhancement of a wideband MIMO antenna using metasurface for 5G sub-6 GHz communication systems. Scientific Reports, 12(1).

[2] Abdelgwad, A. H., & Ali, M. (2020). CAPACITY AND EFFICIENCY IMPROVEMENT OF MIMO ANTENNA SYSTEMS FOR 5G HANDHELD TERMINALS. Progress In Electromagnetics Research C, 104, 269.

[3] Khan, M. A., Harbi, A. G. A., Kiani, S. H., Nordin, A. N., Munir, M. E., Saeed, S. I., Iqbal, J., Ali, E. M., Alibakhshikenari, M., & Dalarsson, M. (2022). mmWave Four-Element MIMO Antenna for Future 5G Systems. Applied Sciences, 12(9), 4280.

[4] Basha, M. M., Pradeep, P., Gundala, S., & Javed, S. (2025). Design of Compact and High Gain Dual-band four-port MIMO antenna array for mm-wave 5G Communications. Results in Engineering, 104153.

[5] Raj, T., Mishra, R., Kumar, P., & Kapoor, A. (2023). Advances in MIMO Antenna Design for 5G: A Comprehensive Review [Review of Advances in MIMO Antenna Design for 5G: A Comprehensive Review]. Sensors, 23(14), 6329. Multidisciplinary Digital Publishing Institute.

[6] Khan, M. K., & Feng, Q. (2022). A Novel Two Ports MIMO Antenna Having Dual Stopped-band Functionality and Enhanced Isolation. Progress In Electromagnetics Research M, 113, 173.

[7] Chu-Anh, T., Kim-Thi, P., Nguyen-Manh, H., & Tran, H. H. (2023). A conformal multi-port MIMO patch antenna for 5G wireless devices. PLoS ONE, 18(12).

[8] Joler, M., & Mihalić, L. (2022). A Subtlety of Sizing the Inset Gap Width of a Microstrip Antenna When Built on an Ultra-Thin Substrate in the S-Band. Sensors, 23(1), 213.

[9] Güler, C., Keskin, S. E. B., & Aymaz, R. B. (2022). The Development of Broadband Microstrip Patch Antenna for Wireless Applications. Bitlis Eren Üniversitesi Fen Bilimleri Dergisi, 11(3), 812.

[10] Abdulbari, A. A., Jawad, M. M., Hanoosh, H. O., Saare, M. A., Lashari, S. A., Sari, S. A., Ahmad, S., Khalill, Y., & Hussain, Y. M. (2021). Design compact microstrap patch antenna with T-shaped 5G application. Bulletin of Electrical Engineering and Informatics, 10(4), 2072.

[11] Priya, Ankita and Kumar, Ayush and Chauhan, Brajlata," A Review of Tetile and Cloth Fabric Wearable Antennas,"Foundation of Computer Science, 2015.

[12] SatyaMitra, YVSS and Kalisha, Sk and Sindhu, G and Kumar, P Raghavendra and Satish, P," DESIGN OF A NOVEL MICROSTRIP MIMO ANTENNA SYSTEM WITH IMPROVED ISOLATION,"JANT Vol.2, No.2, April 2016.

[13] Chou, Hsi-Tseng and Cheng, Hao-Chung and Hsu, Heng-Tung and Kuo, Li-Ruei," Investigations of isolation improvement techniques for multiple input multiple output (MIMO) WLAN portable terminal applications," EMW Publishing, 2008.

[14] Salami, A. F., Zakariyya, S. O., Sadiq, B. O., & Abdulrahman, O. A. (2017). Evaluative Assessment of an X-band Microstrip Patch Antenna for Wireless Systems. arXiv (Cornell University).

[15] Abdelgwad, A. H. (2018). Microstrip Patch Antenna Enhancement Techniques. 12(10), 703.

[16] Nguyen, L. N. (2020). Mutual Coupling Reduction in Microstrip Antennas using Defected Ground Structure. REV Journal on Electronics and Communications, 10.

[17] Bharadwaj, R. (2017). Design of Micro-Strip Patch Antenna Array Using DGS for ISM Band Applications. Global Journal of Research and Review, 4(1).

[18] Qian, J.-F., Gao, S., Sanz-Izquierdo, B., Wang, H., Zhou, H., & Xu, H. (2023). Mutual Coupling Suppression Between Two Closely Placed Patch Antennas Using Higher-Order Modes. IEEE Transactions on Antennas and Propagation, 71(6), 4686.

[19] Sarkar, C., & Ray, S. (2021). SPUR LINE IMPLANTED ORTHOGONAL MICROSTRIP-FED ULTRA WIDEBAND MIMO LINEAR TAPER SLOT ANTENNA WITH WLAN BAND REJECTION. Progress In Electromagnetics Research Letters, 101, 11.

[20] Bhowmik, W., Appasani, B., Jha, A. K., & Srivastava, S. (2022). A Review on Metamaterial Application in Microstrip and Substrate Integrated Waveguide Antenna Designs [Review of A Review on Metamaterial Application in Microstrip and Substrate Integrated Waveguide Antenna Designs]. Progress In Electromagnetics Research B, 96, 87. The Electromagnetics Academy.

[21] Das, G., Sharma, A., & Gangwar, R. K. (2017). Wideband self‐complementary hybrid ring dielectric resonator antenna for MIMO applications. IET Microwaves Antennas & Propagation, 12(1), 108.

[22] Elsheakh, D. M., Iskander, M. F., Abdallah, E. A., Elsadek, H., & El‐Hennawy, H. (2010). MICROSTRIP ARRAY ANTENNA WITH NEW 2D-ELECTROMAGNETIC BAND GAP STRUCTURE SHAPES TO REDUCE HARMONICS AND MUTUAL COUPLING. Progress In Electromagnetics Research C, 12, 203.

[23] Padmasree, R., Dharmapuri, Y. G., Priyanka, K., & Yogesh, V. (2024). Exploring Performance Metrics of a Microstrip Antenna for 6G Millimeter-Wave Communication. Research Square (Research Square).

[24] Prajapati, P. R. (2015). Application of Defected Ground Structure to Suppress Out-of-Band Harmonics for WLAN Microstrip Antenna. International Journal of Microwave Science and Technology, 2015, 1.

[25] Tatomirescu, Alexandru and Pelosi, Mauro and Knudsen, Mikael B and Franek, Ondrej and Pedersen, Gert F," Port isolation method for MIMO antenna in small terminals for next generation mobile networks,"IEEE, 2011.

[26] ShoravKhan,Vinod Kumar singh,Naresh.B S.R. Group of Institutions, Jhansi, India," Textile Antenna Using Jeans Substrate for Wireless Communication Application", IJETSR, Volume 2, Issue 11 November 2015.

[27] Al-Tayyar, H. A., & Ali, Y. E. M. (2023). Compact 28GHz Microstrip Patch Antenna Design with Reduced SAR for 5G Applications. Mathematical Modelling of Engineering Problems,

10(5), 1667-1674. (link unavailable).

[28] Fante, K. A., & Gemeda, M. T. (2021). Broadband Microstrip Patch Antenna at 28 GHz for 5G Wireless Applications. International Journal of Electrical and Computer Engineering, 11(3), 2238-2244. (link unavailable).

[29] Ghazaoui, Y., et al. (2021). A Compact High Gain Wideband Millimeter Wave 1×2 Array Antenna for 26/28 GHz 5G Applications. Circuit World, 48(3), 345-354. (link unavailable).

[30] Nadh, B. P., et al. (2019). Design and Analysis of Dual Band Implantable DGS Antenna for Medical Applications. Sādhanā, 44(5), 1-9. (link unavailable).