Wearable Circularly Polarized MIMO Antenna: Design and Simulation for High-Data Biomedical Sensing Devices

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Abstract. This paper introduces a novel Multi-Input Multi-Output (MIMO) antenna tailored for high-data wearable applications, emphasizing circular polarization. The antenna design is meticulously crafted with two C-shaped patch components, both featuring a specialized ground structure aimed at enhancing circular polarization efficiency. Each component is equipped with 50Ω SMA connectors and integrates L-shaped stubs within the ground plane. One notable feature of the antenna is its remarkable bandwidth, reaching a maximum of 440 MHz (2.32 GHz–2.76 GHz), which effectively covers unlicensed frequencies from 2.4 GHz to 2.48 GHz. Additionally, the antenna showcases outstanding performance metrics: an envelope correlation coefficient below 0.169 signifies minimal correlation between antenna elements, while a diversity gain exceeding 9.46 dB indicates robust diversity performance. Furthermore, the antenna boasts a multiplexing efficiency surpassing −0.85 dB, suggesting efficient data transmission within the MIMO system. Additionally, the channel capacity loss remains below 0.32 bits/s/Hz, indicating minimal loss in communication capacity. With its elevated gain and robust MIMO characteristics, the proposed antenna emerges as a highly promising solution for high-data wearable biomedical devices, particularly in ISM band applications. Its performance metrics position it favourably for reliable and high-speed wireless communication in challenging wearable environments.

Keywords: Multi input-Multi output (MIMO) · Envelop Correlation Coefficient (ECC) · Directive Gain (DG) · Channel Capacity Loss (CCL) · Multiplexing Efficiency (ME) · Total Active Reflection Coefficient (TARC) · Wearable antennas · Defected ground structure · Circular polarization

1 Introduction

Wearable antennas have garnered significant attention from researchers and developers due to their versatile applications in the medical, tracking, and entertainment industries [1, 2]. Efficient operation in human environments, accommodating bending and dynamic movements, necessitates the use of wearable antennas. Wearable circularly

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polarized MIMO antennas, with their orientation flexibility and capability to suppress multi-path interference, emerge as the superior option for such requirements [3–6]. Moreover, employing a multi-element antenna with polarization diversity facilitates the establishment of reliable channel connections and enhances isolation between them. Crucially, there is a growing need to elevate data rates for biomedical devices, enabling the reception and transmission of data at higher speeds. For context, contemporary image sensors can transfer images at rates reaching 78 Mbps. The ISM band stands out as one of the suitable and promising frequency bands for achieving high-data-rate transfers.

In the realm of wearable devices, the operational environment is closely tied to human surroundings. The dynamic movements of individuals can lead to polarization mismatches. Consequently, circularly polarized antennas are favored for such applications due to their adaptability. However, it's worth noting that while circularly polarized antennas excel in adaptability, they may fall short in delivering the high data rates demanded by biomedical sensing applications [7]. Hence, the introduction of a Circularly Polarized (CP) MIMO antenna aims to address this challenge by simultaneously delivering high data rates and mitigating polarization mismatch issues in dynamic environments [6, 8, 9].

Therefore, the research gaps that have been identified encompass the requirement for wearable antennas adept at accommodating dynamic movements, ensuring high data rates in biomedical applications, and addressing polarization mismatches. The introduction of Circularly Polarized MIMO antennas emerges as a prospective solution to these challenges, underscoring the necessity for additional research and development in this domain.

In this work, a novel MIMO wearable antenna is designed specifically for high-data wearable applications. The antenna is constructed using textile materials and comprises two C-shaped patch components, each featuring a defective ground structure to enhance circular polarization. The antenna exhibits a broad bandwidth of 440 MHz. Notably, it attains outstanding performance metrics, featuring an Envelope Correlation Coefficient (ECC) below 0.169, Diversity Gain (DG) surpassing 9.46 dB, Multiplexing Efficiency (ME) exceeding -0.85 dB, and a Channel Capacity Loss (CCL) below 0.32 bits/s/Hz. These attributes render the proposed antenna exceptionally well-suited for high-data wearable biomedical devices, especially in ISM band applications.

2 Design Methodology of MIMO Antenna

Patients with chronic illnesses or those recovering from surgery can benefit from remote patient monitoring systems equipped with MIMO antennas. These antennas enable the transmission of health data from wearable sensors worn by patients to healthcare providers located remotely. This allows healthcare providers to monitor patients' health status without the need for frequent in-person visits. The antenna is constructed on a thin and flexible jeans material, characterized by a permittivity of 1.7 and a tangent loss of 0.025 [10]. The dimensions of the individual antenna element are specified as $0.308\lambda_0 \times 0.308\lambda_0 \times 0.02\lambda_0$, where λ_0 represents the free-space wavelength at 2.4 GHz. The design progression begins with a conventional rectangular radiator resonating at f_0, taking into account well-established equations [11]:

$$W_p = \frac{C}{f_0}\sqrt{\frac{1}{2(1+\varepsilon_r)}} \tag{1}$$

$$L_p = \frac{C}{2f_0\sqrt{\varepsilon_{eff}}} \tag{2}$$

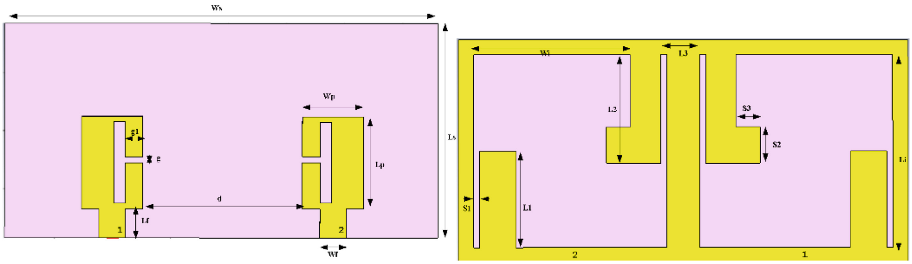
$$\varepsilon_{eff} \approx \frac{\varepsilon_r + 1}{2} \tag{3}$$

where W_p and L_p are the width and length of the traditional patch radiator, ε_{eff} is the effective permittivity of the substrate.

The antenna, designed using these equations, takes on a C-shaped configuration [12–14], achieved by introducing a slot of length L3. This slot enhances the electrical length of the antenna, facilitating miniaturization for resonance at 2.4 GHz. To improve impedance matching, a rectangular-shaped defect is incorporated. Additionally, to support circular polarization, rectangular and L-shaped stubs are printed on the ground plane. Figure 1 illustrates the profile of the presented wearable MIMO antenna, comprising two identical elements arranged in a mirrored fashion. The radiators are excited with a 50Ω microstrip line, and their dimensions are optimized using CST MW Studio. A common ground plane with symmetrical L-shaped stub lines is implemented on the backside of the jeans surface. The mirrored arrangement of the radiating elements ensures stable S12 parameters without the need for external decoupling networks.

3 MIMO Antenna Simulation Explorations

The diversity performance of the MIMO antenna can be evaluated by examining MIMO parameters. All simulations are conducted using CST MW Studio.



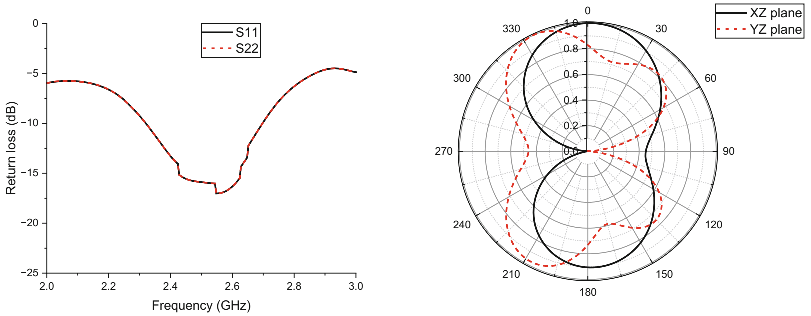
(a) (b)

Fig. 1. Geometrical profile of the anticipated MIMO antenna (a) Radiator (b) Ground layer

The anticipated dimensions are: $W_s = 74.5$ mm, $L_s = 37$ mm, $W_P = 10.5$, $L_P = 16$, $W_f = 4.5$, $L_f = 5$ mm, $d = 27.5$ mm, $g_1 = 3$ mm, $g = 1$ mm, W_i, $L_i = 32$ mm, $L_1 = 16$ mm, $L_2 = 18$ mm, $L_3 = 5.5$ mm, $S_1 = 1$ mm, $S_2 = 6$ mm, $S_3 = 4$ mm.

3.1 S-Parameters and Radiation Pattern

The simulated S-parameters and radiation patterns are depicted in Fig. 2. As observed in Fig. 2(a), the 10 dB bandwidth spans from 2.32 GHz to 2.76 GHz, effectively covering the desired 2.4 GHz range. The isolation between ports 1 and port 2 exceeds 30 dB, ensuring significant decoupling between the two ports. The maximum gain of the system is 3.71 dBi at 2.4 GHz, and the normalized radiation patterns are illustrated in Fig. 2(b).



(a) (b)

Fig. 2. Simulated (a) S_{11}, S_{22} curves (b) Normalized patterns on XZ and YZ planes

3.2 ECC and DG

Understanding the ECC helps in designing MIMO systems to maximize diversity gain or spatial multiplexing gain depending on the application specified. A low ECC implies better diversity and spatial multiplexing capabilities since the antennas are less correlated, while a high ECC suggests that the antennas are highly correlated, which might limit the system's performance. The ECC is the measure of the correlation between the antenna ports. Mathematically, it is expressed as

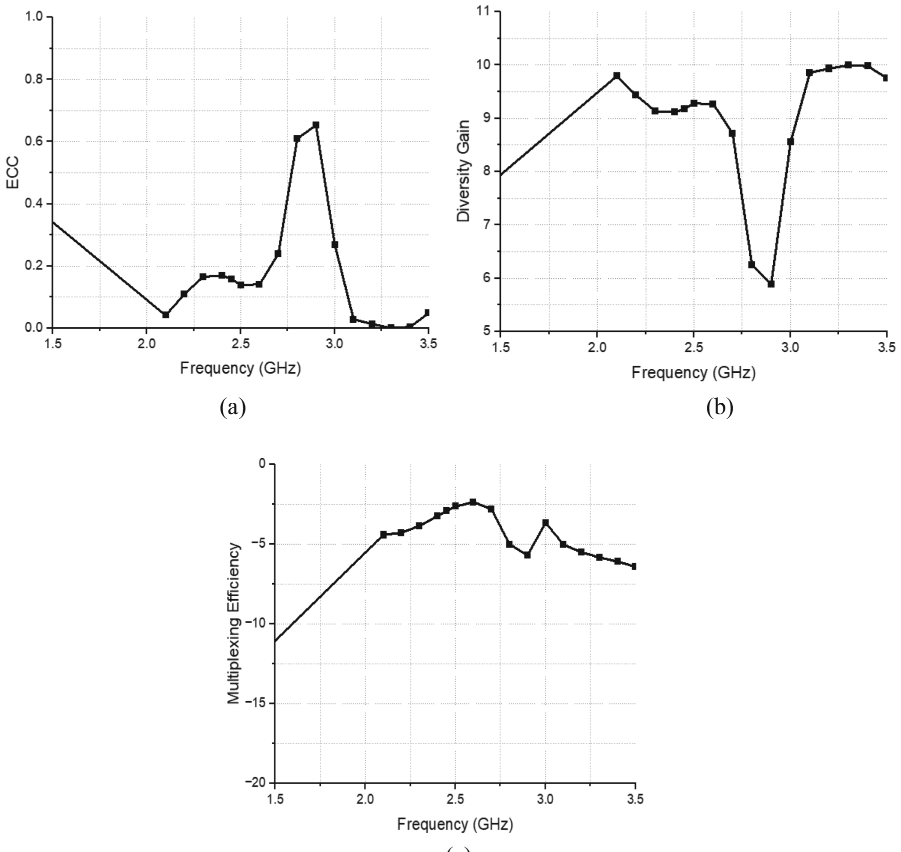
$$ECC = \frac{\left|s_{11}^{*}s_{12} - s_{21}^{*}s_{22}\right|}{\left(1 - |s_{11}|^{2} - |s_{21}|^{2}\right)\left(1 - |s_{22}|^{2} - |s_{12}|^{2}\right)} \quad (4)$$

And the following equation is employed to assess the diversity gain:

$$DG = 10\sqrt{1 - ECC^{2}} \quad (5)$$

Figures 3(a) and (b) depict the computed curves representing the Envelope Correlation Coefficient (ECC) and Diversity Gain (DG) for the proposed antenna. These metrics play a pivotal role in assessing antenna system performance. From Fig. 3, it is evident that the ECC is calculated to be 0.169, while the DG measures 9.46 dB. It is worth noting that in an ideal scenario, the ECC ideally approaches zero, signifying perfect orthogonality among antenna elements. However, in practical scenarios, a value below 0.5 is generally deemed acceptable. The ECC value of 0.169 falls within this acceptable range. On the other hand, Diversity Gain (DG) quantifies the enhancement in the received signal-to-noise ratio (SNR) attributable to multiple antenna elements. In this instance, the DG is determined to be 9.46 dB within the operational band. A higher DG value indicates superior diversity performance and improved signal quality.

Moreover, Fig. 3(c) presents the multiplexing efficiency, a critical parameter in antenna system evaluation. This metric evaluates the antenna system's ability to efficiently manage multiple signals or data streams simultaneously. Therefore, the assessment illustrated by Fig. 3 emphasizes the performance attributes of the proposed antenna design, showcasing its ability to attain acceptable Envelope Correlation Coefficient (ECC) levels, favorable Diversity Gain (DG), and efficient multiplexing within the operational band.



(a)

(b)

(c)

Fig. 3. Simulated (a) Envelope correlation coefficient (b) Directive gain (c) Multiplexing efficiency.

3.3 TARC and CCL

In MIMO (Multiple Input Multiple Output) systems, minimizing reflections from antenna elements is crucial to prevent interference, maintain signal quality, and uphold system performance. The TARC (Total Active Reflection Coefficient) parameter is instrumental in quantifying the total reflected power from all antenna elements in a MIMO array. It serves as a key consideration in antenna design and optimization, ensuring efficient power transmission and reception. The calculation of the TARC parameter typically involves measuring the reflected power from individual antenna elements and summing them to determine the total reflected power. By minimizing the TARC parameter, MIMO antenna systems can optimize signal transmission and reception, thereby enhancing overall efficiency and performance.

In a two-element MIMO antenna system, both elements operate simultaneously, necessitating consideration of the influence of each port on the other to effectively manage interference and maximize system performance. The TARC parameter measures this mutual influence and is given by

$$TARC = \frac{\sqrt{(s_{11} + s_{22})^2 + (s_{21} + s_{12})^2}}{\sqrt{2}} \tag{6}$$

For any MIMO system, the acceptable TARC is below −5 dB. For the proposed antenna, the simulated TARC is estimated as 0.874.

Moreover, the computation of channel capacity loss in a MIMO antenna system, based on S-parameters and radiation patterns, entails the evaluation of both the electrical attributes of the antennas (illustrated by S-parameters) and their spatial characteristics (illustrated by radiation patterns). By amalgamating information derived from S-parameters and radiation patterns, the optimization of the MIMO antenna is achievable. Nonetheless, the Channel Capacity Loss (CCL) represents the utmost channel capacity without any communication loss. The permissible threshold stands at less than 0.4 bits/s/Hz. Calculations are conducted employing the following mathematical equations:

$$CCL = -\log|\alpha| \tag{7}$$

where

$$\alpha = \begin{bmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{bmatrix}$$

$$\alpha_{ij} = 1 - \left(\sum_{j=1}^{2} \left| S_{ij} \right|^2 \right) \tag{8}$$

$$\alpha_{ij} = -\left| S_{ii}^{*} S_{ij} + S_{ji}^{*} S_{jj} \right| \tag{9}$$

where σ_{ii}, and σ_{ij} represent the correlation between the antenna elements of a MIMO system. For the proposed antenna, the estimated CCL appeared as below 0.32 bit/s/Hz.

3.4 Diversity and Isolation

In MIMO systems, it is vital to achieve a high degree of diversity and isolation between the individual antennas to minimize mutual interference and maximize the system's capacity. This requires careful consideration of the spacing and orientation of the antennas to ensure that they operate independently and effectively in tandem. Quantifying the impact of polarization on data rates and other relevant metrics of wearable MIMO antennas involves assessing signal strength, interference levels, and multipath effects. Polarization alignment enhances signal strength and data rates, mitigates interference, and improves overall communication performance. Table 1 provides a comparative analysis between the present work and existing literature. Upon reviewing Table 1, it becomes evident that the proposed antenna exhibits superior performance compared to the published literature.

Table 1. Comparison with Published Literature

Ref	F_0 (GHz)	Size ($\lambda_0{}^3$)	No. of Elements	ECC	DG	TARC (dB)	CCL (bits/s/Hz)	Substrate
[15]	2.4	0.24 × 0.24 × 0.004	2	<0.1	NA	NA	NA	FR-4
[16]	2.52	0.04 × 0.03 × 0.001	2	<0.11	>9.9	NA	NA	RT 6010
[17]	2.4	0.19 × 0.59 × 0.05	2	<0.01	>9.8	NA	NA	Jeans
Proposed	**2.4**	**0.596 × 0.29 × 0.02**	**2**	**<0.169**	**>9.46**	**<−5**	**0.32**	**Jeans**

4 Conclusions

An efficient circularly polarized MIMO antenna is successfully built and simulated for high-data wearable devices. The MIMO system has achieved an impedance bandwidth of 440 MHz, and the MIMO wearable antenna displays a diversity performance in terms of MIMO parameters. The predicted antenna was a promising contender for the high data wearable biomedical device at ISM band applications because to its high gain and good MIMO features.

References

1. Hariprasad, S., Anusree, S., Sreedevi, R., Anoop, A., Kishor, K.K., Balamurugan, V.: A compact flexible two-port textile antenna. In: 2022 IEEE 19th India Council International Conference, INDICON 2022, pp. 8–11 (2022)

2. Mallavarapu, S., Lokam, A.: A critical survey on fractal wearable antennas with enhanced gain and bandwidth for wban. Lect. Notes Netw. Syst. **145**, 737–745 (2021)
3. Te Liao, C., Yang, Z.K., Chen, H.M.: Multiple integrated antennas for wearable fifth-generation communication and internet of things applications. IEEE Access **9**, 120328–120346 (2021)
4. Shankar Singh, H.: Investigations of MIMO antenna for smart mobile handsets and their user proximity. Med. Internet Things Enabling Technol. Emerg. Appl. (2019)
5. Govindan, T., Palaniswamy, S.K., Kanagasabai, M., Kumar, S.: Design and analysis of UWB MIMO antenna for smart fabric communications, vol. 2022 (2022)
6. Kumar, S., et al.: Wideband circularly polarized textile MIMO antenna for wearable applications. IEEE Access **9**, 108601–108613 (2021)
7. Mallavarapu, S., Lokam, A., Farooq, U.: A small, flexible, circularly polarized wearable antenna for wireless applications. In: Proceedings of 2022 IEEE International Symposium on Smart Electronic Systems, iSES 2022, pp. 175–179 (2022)
8. Babu, B.A., Pokkunuri, P.S., Boddapati, M., Srigakolapu, S.S., Chintha, M., Donepudi, T.S.C.: Design and analysis of a compact textile MIMO antenna for ISM band wearable applications. In: IEEE Delhi Section Conference, DELCON 2022, pp. 6–10 (2022)
9. Noghanian, S.: A dual-band wearable MIMO WiFi antenna. In: Proceedings of 2022 International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, pp. 1170–1171 (2022)
10. Mallavarapu, S., Lokam, A.: Circuit modeling and analysis of wearable antennas on the effect of bending for various feeds. Eng. Technol. Appl. Sci. Res. **12**(1), 8180–8187 (2022)
11. Balanis, C.A.: Antenna Theory: Analysis and Design (1996)
12. Mahfuz, M.M.H., Islam, M.R., Sakib, N., Habaebi, M.H., Raad, R., Tayab Sakib, M.A.: Design of wearable textile patch antenna using C-shape etching slot for Wi-MAX and 5G lower band applications, pp. 168–172 (2021)
13. Sran, S.S., Sivia, J.S.: Design of C shape modified Sierpinski carpet fractal antenna for wireless applications. In: International Conference on Electrical, Electronics, and Optimization Techniques, ICEEOT 2016, pp. 821–824 (2016)
14. Patil, S., Singh, A.K., Kanaujia, B.K., Yadava, R.L.: Design of dual band dual sense circularly polarized wide slot antenna with c-shaped radiator for wireless applications. Frequenz **72**(7–8), 343–351 (2018)
15. Qu, L., Piao, H., Qu, Y., Kim, H.H., Kim, H.: Circularly polarised MIMO ground radiation antennas for wearable devices. Electron. Lett. **54**(4), 189–190 (2018)
16. Alazemi, A.J., Iqbal, A.: A compact and wideband MIMO antenna for high-data-rate biomedical ingestible capsules. Sci. Rep. **12**(1), 14290 (2022)
17. Pathan, T.U., Kakde, B.: A compact circular polarized MIMO fabric antenna with AMC backing for WBAN applications. Adv. Electromagn. **11**(3), 26–33 (2022)