Wideband Circularly Polarized MIMO Antenna for High Data Wearable Biotelemetric Devices

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ABSTRACT This paper presents a miniaturized circularly polarized multiple-input multiple-output (MIMO) antenna for wearable biotelemetric devices. The proposed MIMO antenna consists of four elements, which are placed orthogonally to the adjacent elements. The proposed antenna has a wideband response [10-dB bandwidth of 2210 MHz (fractional bandwidth (FBW) = 92.08%) in free space and 10-dB bandwidth of 2200 MHz (FBW = 91.66%) when worn on human-body], this frequency range covers the important and unlicensed industrial, scientific and medical (ISM) band (2.40–2.48 GHz). The antenna exhibits a wideband 3-dB circularly polarized bandwidth of 1300 MHz (FBW = 54.16%) and 1040 MHz (FBW = 43.33%) in free space and when worn on the body, respectively. The optimized antenna in free space (on-body) has an envelop correlation coefficient (ECC) less than 0.21 (0.23), a diversity gain (DG) greater than 9.77 dB (9.71 dB), a multiplexing efficiency (ME) greater than −0.85 dB (−0.63 dB), and a channel capacity loss (CCL) less than 0.13 bps/Hz (0.13 bps/Hz). The stable radiation, high gain, high efficiency, and good MIMO properties in free space and on human-body make the proposed antenna a suitable choice for use in high data wearable biotelemetric devices.

INDEX TERMS Circularly polarized antenna, MIMO antenna, wearable antenna, wearable biotelemetric devices, wireless body-area networks (WBAN).

I. INTRODUCTION

The design of on-body wearable antennas attracted the attention of researchers worldwide due to their use in interesting applications such as: monitoring health issues, sports activities, military applications and more [1]–[4]. Such antennas are required to be of a low profile, compact size, perform well on a moving body, and most importantly emit low backward radiation. Moreover, it has been well-established that the tissues of the human body have severe impact on the antenna’s performance which makes the design of on-body wearable antennas a challenging task. To improve the antenna’s performance under such an impact, the use of special structures in the antenna design such as electromagnetic bandgap structures (EBG) [5] and high impedance structures (HIS) [6] was proposed. However, these structures increase the complexity of the antenna and the number of its layers. Another issue to consider is the data rate as biomedical devices nowadays are required to receive and transmit data at a high rate. For instance, modern image sensors can transfer high quality images at a rate of 78 Mbps [7]. In that regard, the selection of the operating band becomes critical, and the ISM band (2.4 GHz) presents a suitable choice for high data rate devices [8]. To reach such high...
data rates, many MIMO antennas have recently been proposed for Wireless Body Area Networks (WBAN) [9]–[11]. To achieve compactness, the antennas are densely packed in MIMO systems. The nearby placed MIMO elements induce an effect on each other (mutual coupling [MC]) which is undesirable and therefore impairs the system’s performance. The MC can be reduced by either placing the elements far away from each other or by introducing a decoupling structure to the existing system [12]. However, these techniques either enlarge the system size or increase its complexity which is undesirable in a compact system. Another convenient way to keep the elements isolated from each other is to arrange them optimally. The orthogonally arranged MIMO antennas have an almost non-existent MC between them and there is no need to add additional decoupling structures [13]. The MIMO antennas reported for WBANs are mostly linearly polarized and are easily affected by polarization mismatches especially when the wearer changes his/her position.

Circularly polarized (CP) antennas are known to be less impacted by polarization mismatches besides their ability to reduce multi-path distortions. Due to these capabilities, a wideband CP filtering antennas have been developed for biomedical wearable devices in [14]–[15]. In [16], a flexible CP antenna is reported using polydimethylsiloxane (PDMS) and silver nanowires (AgNWs). However, these CP antennas cannot provide high data rates due to their single-input single-output (SISO) topology. Therefore, it is desirable to develop CP MIMO antennas for WBANs to combat polarization mismatches while providing high data rates. Despite their obvious importance, only a few works tackled the design of such antennas [17]–[19]. The designs reported in [17]–[19] demonstrated less performance deterioration due to polarization mismatches compared to their linearly polarized counterparts, however, they all suffered from narrow 3-dB axial ratio bandwidth.

In this paper, we propose a CP MIMO antenna with a wider operational bandwidth and better circular polarization bandwidth for wearable biotelemetric devices. The key advantages of the proposed work are summarized as follows:

- To the best of the authors’ knowledge, the presented work performs better than any comparable work in the literature in terms of the 3-dB axial ratio bandwidth. Also, a wide 3-dB axial ratio bandwidth is demonstrated in on-body worn scenario which confirms the suitability of the designed antenna for use in wearable biotelemetric devices and proves its ability to alleviate the severity of the associated polarization mismatch issues. Moreover, the antenna supports high data rates and can resist multi-path fading because of the MIMO architecture.

II. DESIGN METHODOLOGY

The schematic of the proposed wideband four element circularly polarized MIMO antenna is shown in Fig. 1a. The antenna is printed on a 1.6 mm FR-4 substrate ($\varepsilon_r = 4.4$). The design model consists of four identical elements where each element is fed by a 50 $\Omega$ microstrip transmission line from one edge. The transmission line width is calculated using equations (1)-(2) [20]. The radiating structure is a modified square patch (SP). The modifications are done to attain miniaturization and to generate circular polarization (CP). The common methods to attain CP include truncating the corners of the patch, cutting the diagonal slots in the patch, and by using additional stubs and slits [17]. In this design, the CP is obtained by the truncated corner technique and the CP bandwidth is further enhanced by using an additional open circuited stub on the ground plane. The truncated corner patch and hook-shaped open circuited stub assisted in the production of two orthogonal modes of the same amplitude. The final results of the optimized antenna in terms of reflection coefficient ($S_{11}$), elements isolation, axial ratio are shown in Fig. 2. The antenna has an absolute bandwidth of 2.23 GHz (1.71–3.94 GHz), as shown in Fig. 2a. The antenna also retains the 3-dB CP bandwidth of 1.3 GHz (1.8–3.1 GHz), as illustrated in Fig. 2b. The MIMO system elements are fairly isolated from each other (transmission coefficient $<-24$ dB) within the operating band, as given in Fig. 2c. The surface current distribution of the proposed antenna is portrayed in Fig. 2d. It is concluded from the directions of the $J_{\text{surf}}$ fields that the proposed antenna exhibits a left-hand
FIGURE 2. Simulated results (a) reflection coefficient, (b) axial ratio, (c) mutual coupling and (d) fields distribution at 2.4 GHz.

FIGURE 3. Design evolution of the wideband CP MIMO antenna.

FIGURE 4. Antenna parameters in design evolution (a) reflection coefficient, (b) axial ratio, (c) mutual coupling, and (d) gain.

In this iteration, the antenna resonated at 3.75 GHz with linear polarization. A 10-dB bandwidth (fractional bandwidth) of 3.81 GHz (102% at the center frequency of 3.75 GHz) is achieved in the first iteration. The isolation of $-23.6$ dB is observed at 2.4 GHz in the first iteration. The peak gain is 1.98 dBi at 3.34 GHz. In the second stage, the SP is truncated at the edges. The linear polarization of the antenna is changed to circular polarization due to the truncated corners. In this step, the antenna resonated at 4.18 GHz with circular polarization (as shown in Fig. 4a and 4b). A 10-dB bandwidth (fractional bandwidth) of 4.78 GHz (114% at the center frequency of 4.18 GHz) is achieved. The isolation of $-24$ dB is observed at 2.4 GHz in the second iteration. The peak gain is 1.99 dBi at 4.72 GHz. In the third stage, two rectangular sections are etched from the edge truncated SP. The rectangular slots produce an additional capacitance effect which shifted the resonant frequency to the lower frequency edge. In this iteration, the antenna resonated at 2.4 GHz with a circular polarization. A 10-dB bandwidth (fractional bandwidth) of 1.69 GHz (70% at the center frequency of 2.4 GHz) is achieved in the third iteration. The isolation of $-24.12$ dB is observed at 2.4 GHz in third iteration. A 3-dB circular polarization bandwidth of 20% at the center frequency of 2 GHz is observed, as illustrated in Fig. 4b. The peak gain is 2.22 dBi at 1.66 GHz. In the last iteration, a hook-shaped open-ended stub is connected to the ground plane to increase the antenna operational bandwidth and circular polarization bandwidth. In this stage, the proposed antenna has two resonances located at 2.5 and 3.47 GHz with a circular polarization. A 10-dB bandwidth (fractional bandwidth) of 1.69 GHz (70% at the center frequency of 2.4 GHz) is achieved in the final iteration. The isolation of $-30.1$ dB is observed at 2.4 GHz in the final iteration. A 3-dB circular polarization bandwidth of 54.16% (1.8–3.1 GHz) at the center frequency of 2.4 GHz is observed, as illustrated in Fig. 4b. The peak gain is 2.36 dBi at 2.1 GHz.

\[
\epsilon_{\text{eff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + \frac{12}{W} \frac{h}{W}\right)^{-0.5}
\]

\[
Z = \frac{120\pi}{\sqrt{\epsilon_{\text{eff}}}} \left[1 + 1.393 + 0.677 \times \ln \left(\frac{W}{h} + 1.444\right)\right]^{-1}
\]

where $\epsilon_{\text{eff}}$ is the effective permittivity of the material, $\epsilon_r$ is the relative permittivity of the substrate, $h$ is the substrate thickness and $W$ is width of the transmission line.

A. DESIGN EVOLUTION
An iterative process for obtaining the desired results is consist of four steps as shown in Fig. 3. In the first iteration (step 1), SP is excited by a microstrip transmission line from one edge.

\begin{align*}
\epsilon_{\text{eff}} &= \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + \frac{12}{W} \frac{h}{W}\right)^{-0.5} \quad (1) \\
Z &= \frac{120\pi}{\sqrt{\epsilon_{\text{eff}}}} \left[1 + 1.393 + 0.677 \times \ln \left(\frac{W}{h} + 1.444\right)\right]^{-1} \quad (2)
\end{align*}
B. EQUIVALENT CIRCUIT MODEL

Fig. 5a portrays the equivalent resonance circuit model for the four elements MIMO system where each element is represented by the RLC lumped component [21]. Each element is excited by a separate 50 Ω terminal. We know that there is always some coupling associated with the nearby Antennas. The coupling between the nearby antennas is modeled by LC series lumped elements [22]. The value of each component of the system is shown in Fig. 5a. The equivalent circuit model is simulated using ADS software. A comparison between S-parameter results of the full-wave electromagnetic model and the equivalent circuit model is shown in Fig. 5b-5c. The results of both models are well-matched within the desired band.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

The proposed antenna model is fabricated on a standard FR-4 substrate (εr = 4.4, thickness = 1.6 mm). A photograph of the final antenna is shown in Fig. 1b. The antenna reflection coefficient, gain, axial ratio, radiation pattern, and MIMO parameters are measured. The impact of human body on performance of the antenna is also studied in terms of the aforementioned parameters. The antenna is placed on the right arm of a full-scale model of the human body (Fig. 6a). The antenna resonates at slightly shifted lower frequencies due to high permittivity of the human body. It is noticed that the antenna bandwidth remains the same and maintains the wideband response at the targeted ISM band.

A. REFLECTION AND TRANSMISSION COEFFICIENT

The simulated and measured antenna reflection coefficient (|S11|, |S21|, |S33|, and |S44|) in free space are shown in Fig. 6a (|S22|, |S33|, and |S44| are identical to |S11| and not shown for brevity). The simulated |S11| has two resonances at 2.56 and 3.47 GHz while the measured |S11| has one resonance at 2.6 GHz. The simulated and measured 10-dB bandwidths are 2210 MHz (1.73–3.94 GHz) and 2200 MHz (1.6–3.8 GHz), respectively. The simulated and measured 10-dB fractional bandwidths (FBW) are equal to 92.08 % and 91.66 % at the center frequency of 2.4 GHz, respectively.

The simulated and measured antenna transmission coefficient (|S21|) in free space is shown in Fig. 6b. The simulated (measured) |S21| in on-body worn case is < −26 dB (< −26.5 dB) within the same operating frequency band, as shown in Fig. 6b.

B. AXIAL RATIO AND PEAK GAIN

The simulated and measured axial ratio (AR) of the antenna in free space is illustrated in Fig. 6c. The simulated AR is 1.79 dBi. The simulated and measured AR of the antenna in on-body worn case is 1.81 dBi (< 1.9 dBi) within the same operating frequency band, as shown in Fig. 6c.
less than 3 dB from 1.9 GHz to 3.2 GHz, covering a 3-dB AR bandwidth of 1300 MHz (FBW of 54.16 % at the center frequency of 2.4 GHz). The measured AR is less than 3 dB from 1.81 GHz to 3 GHz, covering a 3-dB AR bandwidth of 1190 MHz (FBW of 49.58 % at the center frequency of 2.4 GHz). The AR measurements agree well with simulations. The simulated and measured results of AR of the antenna as worn on the model are shown in Fig. 6c. The AR bandwidth of the antenna is reduced when worn on the human body. The simulated 3-dB AR bandwidth of the antenna is equal to 1040 MHz (1.8–2.8 GHz) with a 3-dB FBW of 49.58 %, while the measured AR bandwidth is equal to 940 MHz (1.86–2.8 GHz) with a 3-dB FBW of 39.16 %.

Fig. 6d portrays the simulated and measured peak gain of the antenna in free space versus frequency. The simulated peak gain has a maximum value of 2.36 dBi at 2.1 GHz. The simulated peak gain of the antenna lies between 1.96 and 2.36 dBi in the operational frequency band (1.71–3.94 GHz). The measured peak gain has a maximum value of 2.39 dBi at 3.75 GHz. The measured peak gain of the antenna lies between 1.89 and 2.39 dBi in the operational frequency band. Also, peak gain of the antenna is simulated and measured on human body. The simulated (measured) peak gain is greater than 1.88 dBi (> 1.75 dBi) in the operational band on-body worn case.

C. RADIATION PATTERN

The radiation patterns [2-D left-hand circular polarization (LHCP) and right-hand circular polarization (RHCP)] of the antenna are measured in free space in two principal planes ($\phi = 0^\circ$ and $\phi = 90^\circ$) at 2.4 GHz. Fig. 7 shows that the simulated (measured) LHCP is greater than the RHCP by 19.1 dB (20.8 dB). Additionally, the radiation patterns are evaluated on on-body worn case. The simulated and measured antenna radiation patterns in both principle planes ($\phi = 0^\circ$ and $\phi = 90^\circ$) in on-body worn case at 2.4 GHz are compared in Fig. 7c–7d. The LHCP is predominated over the RHCP in both planes. The simulated (measured) LHCP is predominated over the RHCP by 18.06 dB (16.34 dB), as shown in Fig. 7. The results show that the antenna exhibits LHCP in free space as well as when worn on the human-body model.

D. ENVELOP CORRELATION COEFFICIENT (ECC)

The envelop correlation coefficient (ECC) is one of the important factors in determining the suitability of the MIMO antenna systems. The ECC determines the independency of elements in their individual performance. It is desirable for the ECC of the MIMO antenna system to have a zero value, but MIMO antenna systems with an ECC less than 0.5 are considered acceptable. The ECC can be evaluated from the S-parameter using Equation. (3) [23] or from the far-field radiation patterns using Equation. (4) [24]. In this paper, far-field radiation patterns are used to determine ECC of the system. The ECC between antenna 1 and rest of the antennas is calculated in free-space as well as on the human-body model, as shown in Fig. 8a. The ECC of the antenna in free space is less than 0.21 within the operating frequency band. Furthermore, the ECC of the antenna as worn on the human-body model is less than 0.23 within the operating frequency band. The low values of the ECC make this system suitable for wearing on human-body and in devices where high data rate is required.

$$ECC = \frac{|S_{11}^0|^2 + |S_{22}^0|^2}{|1 - (|S_{11}|^2 + |S_{22}|^2)||1 - (|S_{22}|^2 + |S_{21}|^2)|}$$

$$ECC = \frac{\int d\Omega |\vec{B}_i(\theta, \phi)|^2 \Omega d\Omega}{\int d\Omega |\vec{B}_j(\theta, \phi)|^2 \Omega d\Omega}$$

where $S_{11}$ and $S_{22}$ are the reflection and transmission coefficients of the antenna. $B_i(\theta, \phi)$ is the three dimensional radiation pattern upon excitation of the $i^{th}$ antenna and $B_j(\theta, \phi)$ is the three dimensional radiation pattern upon excitation of the $j^{th}$ antenna. $\Omega$ is the solid angle.

E. DIVERSITY GAIN (DG)

Another parameter related to the MIMO antenna system is the diversity gain (DG), which portrays impact of the diversity scheme on the transmitted power. The DG of the system can be evaluated using Equation. (5) [12].

$$DG = 10\sqrt{1 - (ECC)^2}$$
TABLE 1. Performance comparison with the on-body antennas.

| Ref. | MIMO (Yes/No) | Polarization | Size ($\lambda_x$) | Bandwidth (MHz/FBW) | Bandwidth (MHz/FBW) | CP Bandwidth (MHz/FBW) | CP Bandwidth (MHz/FBW) | Gain (dBi) | Gain (dBi) |
|------|---------------|--------------|-------------------|---------------------|---------------------|------------------------|------------------------|------------|------------|
|      |               |              |                   | (Free Space)         | (On-body)           | (Free Space)           | (On-body)           |            |            |
| [5]  | No            | Linear       | $0.80 \times 0.45$| 120/4.88%           | 140/5.83%           | –                      | –                      | 6.88       | 7.43       |
| [9]  | Yes           | Linear       | $0.34 \times 0.34$| $\sim$48/20%        | $\sim$456/19%       | –                      | –                      | 2.79       | 1.67       |
| [10] | Yes           | Linear       | $0.64 \times 0.40$| 959/0.127%          | –                    | –                      | 5.1                    |            |            |
| [11] | Yes           | Linear       | $\pi \times 0.05$ | 90/3.68%            | Not Given            | –                      | –                      | 4.2        | 3          |
| [14] | No            | Circular     | $0.44 \times 0.44$| 100/4.5%            | $\sim$100/4.5%      | Not Given              | 60/2.4%               | 4.7        | 4.68       |
| [15] | No            | Circular     | $0.53 \times 0.53$| 490/12.2%           | $\sim$490/12.2%     | 490/12.2%              | $\sim$490/12.2%       | 5.3        | 6.7        |
| [16] | No            | Circular     | $0.41 \times 0.41$| 270/10.77%          | Not Given            | 69/2.72%               | Not Given              | 5.2        | $\sim$3.4  |
| [17] | Yes           | Circular     | $0.50 \times 0.50$| 140/5.7%            | Not Given            | 100/4.08%              | Not Given              | Not Given  | Not Given  |
| [18] | No            | Dual         | $\pi \times 0.065$| Not Given           | 320/10%             | Not Given              | 2000/83.3%             | -5.1       | Not Given  |
| [19] | No            | Dual         | $0.68 \times 0.68$| 31/1.84%            | Not Given            | 120/6.9%               | Not Given              | 5.1        | 5.1        |
|      | Yes           | Circular     | $0.67 \times 0.67$| 2210/92.08%         | 2200/91.66%         | 1300/54.16%            | 1040/43.33%            | 1.96–2.36  | 1.88–2.18  |

FIGURE 8. Diversity results (a) ECC, (b) diversity gain, (c) multiplexing efficiency, and (d) CCL.

F. MULTIPLEXING EFFICIENCY (ME)

The multiplexing efficiency (ME) of the antenna is calculated using Equation. (6) [25].

$$\eta_{\text{Max}} = \sqrt{1 - |\rho|^2}\eta_1\eta_2$$  (6)

where $\eta_{\text{Max}}$ represents ME, and $\eta_1$ represents the efficiency of antenna 1, $\eta_2$ shows the efficiency of antenna 2 and $\rho$ shows the complex ECC. Fig. 8c portrays the simulated ME of the antenna in free space and as worn on the human-body model. The ME of the antenna in free space is between $-0.85$ dB and $-1.01$ dB within the operating frequency band. Also, the ME of the antenna on-body worn case is between $-0.63$ dB and $-1.04$ dB within the operating frequency band.

G. CHANNEL CAPACITY LOSS (CCL)

The channel capacity loss (CCL) of the MIMO antenna system is calculated using Equation. (7) [26]. The simulated and measured antenna CCL in free space and in on-body worn scenario is illustrated in Fig. 8d. The simulated and measured CCL results in free space are $0.07–0.1$ bps/Hz and $0.08–0.13$ bps/Hz within the operating frequency band. Also, the simulated and measured CCL results of the MIMO system in on-body worn case are $0.09–0.13$ bps/Hz and $0.103–0.13$ bps/Hz within whole operating frequency band. It is found that the CCL values of the system are within the limit ($<0.5$ bps/Hz [21]) in free space as well as in on-body worn case, which confirms its suitability for use in MIMO system.

$$CCL = -\log_2 \det(\Psi_{\text{ant}})$$  (7)

where $\Psi_{\text{ant}}$ is the correlation matrix of the antenna and it is given by

$$\Psi_{\text{ant}} = \begin{bmatrix} \rho_{11} & \rho_{12} & \rho_{13} & \rho_{14} \\ \rho_{21} & \rho_{22} & \rho_{23} & \rho_{24} \\ \rho_{31} & \rho_{32} & \rho_{33} & \rho_{34} \\ \rho_{41} & \rho_{42} & \rho_{43} & \rho_{44} \end{bmatrix}$$  (8)

where

$$\rho_{ii} = 1 - \frac{\sum_{n=1}^{4} S_{in}^* S_{in}}{n}$$, for $i, j = 1, 2, 3, or 4$.

and

$$\rho_{ij} = -\frac{\sum_{n=1}^{4} S_{in}^* S_{nj}}{n}$$, for $i, j = 1, 2, 3, or 4$. 

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IV. SPECIFIC ABSORPTION RATE (SAR) ANALYSIS

In order to evaluate the specific absorption rate (SAR), the antenna is placed on the right arm of a full-scale model of the human body. A 4 mm airgap is kept between the antenna arm and the model while simulating the antenna. The human body absorbs the backward electromagnetic radiations [at what is called the specific absorption rate (SAR)] of the antenna when it is operated in the environs. The temperature of the tissues can rise due to excessive absorption (beyond healthy limits) of these electromagnetic radiations. Keeping in mind the concern for wearer safety, the regulatory authorities (FCC, IEEE and ICNIRP) standardized the SAR limits. With the same concern in mind, SAR values are set according to IEEE C95.1-2005 standards. The SAR levels are evaluated on the chest, right arm, and right thigh of the human model. For all three positions, the 10-g peak SAR values are evaluated on the chest, right arm, and right thigh of the body. A 4 mm airgap is kept between the antenna arm and the model while simulating the antenna. The human body absorbs the backward electromagnetic radiations [at what is called the specific absorption rate (SAR)] of the antenna when it is operated in the environs.

A. LINK BUDGET ANALYSIS

To analyze effectiveness of the designed antenna, it is analyzed based on two different cases. In the first case, we analyzed the power transmitting ability of the antenna when it is worn on the human body. In this case the receiving antenna is located away in free space. In the second case, we considered the communication between an implantable device and our designed wearable antenna.

1) CASE 1

In this case our proposed antenna acted as a transmitting antenna while it is placed above the human body and an ideal λ/2 dipole antenna acted as an antenna to receive the transmitted power. We keep the distance \( a \) between our antenna arm and the λ/2 dipole antenna. Equation. (9) is used to calculate the power at the receiving end [14].

\[
P_{\text{ra}}(\text{dBm}) = P_{t}(\text{dBm}) + G_{ta}(\text{dB}) + G_{ra}(\text{dB}) - PL(\text{dB}) \quad (9)
\]

where \( P_{\text{ra}}(\text{dBm}) \) is the receiving power for ideal dipole antenna in dBm, \( P_{t}(\text{dBm}) \) is the transmitted power by our CP MIMO antenna in dBm, \( G_{ta}(\text{dB}) \) is the gain of our CP MIMO antenna in \( dB \), \( G_{ra}(\text{dB}) \) is the gain of an ideal λ/2 dipole antenna in \( dB \), and \( PL(\text{dB}) \) is the distance dependent path loss in \( dB \). We used Equation. (10) to compute the \( PL(\text{dB}) \) [14].

\[
PL(\text{dB}) = 10\gamma\log_{10}\left(\frac{a}{\lambda_{\sigma}}\right) + 20\log_{10}\left(\frac{4\pi a}{\lambda_{\sigma}}\right) + X_{\sigma} \quad (10)
\]

where \( \gamma \) is the path loss exponent. The value of \( \gamma \) depends on the nature of communication. The value of \( \gamma \) is 1.5 and 3 for line of sight (LOS) and non-line of sight communication (N-LOS), respectively. The distance between the proposed antenna (transmitting antenna) and the ideal λ/2 dipole antenna (receiving antenna) is represented as \( a \), \( \lambda_{\sigma} \) is the free space wavelength calculated at 2.4 GHz and \( X_{\sigma} \) is the shadowing factor for Gaussian distribution with a standard deviation of \( \sigma \). We keep the transmitting power \( (P_{t}) \) value of 10 dBm and 27 dBm under the assumption that the antenna is mounted on the human body. The gain of the receiving antenna \( (G_{ra}) \) is chosen as 2 dBi.

It is found that receiving power of the antenna in the LOS scenario is better than N-LOS. It is also found that the receiving power \( (P_{\text{ra}}) \) is increasing with the transmitting power \( (P_{t}) \), as illustrated in Fig. 10a. In LOS communication, the power received by the receiving antenna is better than \(-37 \text{ dBm}\).
The power received by the antenna is better than $-5 \text{ dBm}$ when the transmitted power is $10 \text{ dBm}$. In N-LOS communication, the power received by the antenna, when the transmitted power is $27 \text{ dBm}$ and $10 \text{ dBm}$, respectively. In the on-body worn situation, the power received by the antenna is better than $-65 \text{ dBm}$ at a separation of $15 \text{ m}$ from the body worn antenna, when the transmitted power is $10 \text{ dBm}$. With the increase in the transmitted power ($P_t = 27 \text{ dBm}$), the power received by the antenna is better than $-65 \text{ dBm}$ at a distance of $40 \text{ m}$. As a conclusion from this analysis, the proposed antenna satisfies the minimum sensitivity of ISM receivers [29].

### TABLE 3. Parameters of link budget.

| Transmission (Implantable device) |  |
|-----------------------------------|-----------------|
| Polarization                      | LHCP            |
| Transmitting power ($P_t$)        | $-5 \text{ dBm}$ |
| Transmitting antenna gain ($G_{t1}$) | $-27 \text{ dBi}$ |

| Propagation |  |
|-------------|-----------------|
| Distance    | 1-20 m          |
| Free-space loss ($L_f$) | Distance dependent |

| Receiver (wearable antenna) |  |
|-----------------------------|-----------------|
| Polarization                | LHCP            |
| Receiver antenna gain ($G_{r0}$) | 2.1 dBi |
| Temperature                 | 273 K           |
| Boltzmann constant          | $1.38 \times 10^{-23}$ |
| Noise power density ($N_o$)  | $-203.9 \text{ dB/Hz}$ |

| Signal Quality |  |
|----------------|-----------------|
| Bit rate ($B_r$) | 50, 78, 100, 200 Mbps |
| Bit error rate   | $1 \times 10^{-5}$ |
| $E_b/N_0$ (ideal PSK) | 9.6 dB |

| Margin (dB) | $A_p - B_p$ |

and $-54 \text{ dBm}$ even at a separation of $40 \text{ m}$ for the transmitting power of $27 \text{ dBm}$ and $10 \text{ dBm}$, respectively. In the N-LOS communication, the power received by the antenna is better than $-65 \text{ dBm}$ at a separation of $15 \text{ m}$ from the body worn antenna, when the transmitted power is $10 \text{ dBm}$. With the increase in the transmitted power ($P_t = 27 \text{ dBm}$), the power received by the antenna is better than $-65 \text{ dBm}$ at a distance of $40 \text{ m}$. As a conclusion from this analysis, the proposed antenna satisfies the minimum sensitivity of ISM receivers [29].

2) **CASE 2**

In this case, down-link communication is assumed, where implantable antenna of the biomedical device is a transmitting antenna and the proposed wearable antenna is a receiving antenna. The link budget parameters are listed in Table. 3. The required receive power of the wearable antenna can be found using Equation. (11) [30]. The available antenna power from the implantable device can be derived from Equation. (12) [30].

$$B_p(dB) = \frac{E_b}{N_0} + kT_o + B_r$$

$$A_p = P_{t1}(dBm) + G_{t1}(dBi) + G_{r1}(dBi) - PL(dB) - L_f(dB)$$

where

$$L_f = 20 \log_{10} \left( \frac{4\pi a}{\lambda} \right)$$

The authors of [30]–[32] proposed that the margin between the $B_p$ and $A_p$ should be at least $20-25 \text{ dB}$ for quality communication. The link margin against several distances and data rates is plotted in Fig. 10b. It is noticed that the margin is decreasing with the distance and data rates. It is also noticed that reliable communication is possible up to a distance of $10 \text{ m}$ for the highest data rate of $200 \text{ Mbps}$. The reliable communication of our antenna with the implantable devices even at the highest data rate of $200 \text{ Mbps}$ confirms the suitability of our antenna for high data rates biotelemetric devices.

The performance of the proposed antenna is compared with published wearable antennas in Table. 1. The proposed antenna exhibits a greater $10$-dB bandwidth in free space and in on-body worn situation. Additionally, it has a wider $3$-dB CP bandwidth in both conditions.

**V. CONCLUSION**

In this paper, a wideband circularly polarized MIMO antenna for high data wearable biotelemetric devices is designed and measured. The MIMO system includes four microstrip antennas with the same shape and size and they are placed orthogonally to adjacent elements. A wider $10$-dB bandwidth is obtained for antenna in free space and in on-body worn case. Also, the $3$-dB CP bandwidth is $1300 \text{ MHz}$ in free space and $1040 \text{ MHz}$ in on-body worn scenario. Additionally, the antenna peak gain, efficiency, ECC, DG, CCL and ME are satisfied on the human-body and in free space. The SAR value is in limit (for the input power of $<575.87 \text{ mW}$) which confirms safety of the antenna for use in on-body communication. The link budget shows suitability of the antenna for high date rates over a reasonable area.

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