Mutual Coupling Suppression in Wearable MIMO Antenna for On/Off-Body WBAN Applications

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Abstract. A 2x1 wearable multiple-input-multiple-output (MIMO) antenna with line patch as mutual coupling suppression is presented. The proposed MIMO antenna is based on a simple rectangular structure that works at 2.45 GHz frequency. The patches are designed using ShieldIt textiles and are placed to a very closed (0.1λ) gap. The results show that the suppression in the mutual coupling of 5 dB (from -20 dB to -25dB), reduced by 25% after the line patch is inserted in between patches. On a positive note, an improvement in the antenna gain, from 4.4 dB to 4.7 dB is achieved. On top of that, the performance of the reflection coefficient (S11) and the antenna impedance bandwidth is preserved. Important diversity performance parameter for MIMO antenna such as ECC, diversity gain and MEG results are found to be in an acceptable limit

1. Introduction
In the era of the Internet of Things (IoT), wearable devices are predicted to be part of technologies in high demand. One important part it is a wearable antenna. Wearable antennas offer a small size, lightweight, the comfort offered to users, and the robustness in reducing the on-body detuning [1]–[4] which suitable for wearable on/off-body wireless communication [5] and sensing devices. One of the consideration in designing a wearable antenna, the power transfer is limited. Hence, to achieve high data rate without increasing transmitted power, MIMO is the best solution. Due to space limitation, a small size MIMO is preferable. This will contribute to a closely spaced between radiator elements, which increasing the mutual coupling between elements.

Numerous techniques were proposed in order to suppress the mutual coupling, due to high mutual coupling degrades the antenna performance. Among the proposed techniques are feeding allocation [6], [7], introducing parasitic elements [8] and slot [9], DGS structure [10] and hybrid techniques [11], [12] and [13].

The patches in the MIMO are placed orthogonally to each other to obtain high inter-element isolation in [6], while in [7], the authors proposed differential feeding with interlaced subarray to reduce the mutual coupling. High isolation is achieved in [11] by employed a combination of three ground stubs and DGS. Alternatively, a hybrid of a parasitic patch and diagonal position of radiating elements helps in reducing the mutual coupling [12]. Design for 5.6 GHz, the authors proposed a modified Minkowski
fractal with EBG structure for a spacing of λ/3. In the structure, a reduction of 20dB mutual coupling is achieved.

In this paper, a parasitic line patch isolator is proposed in between patch elements as a simple mutual coupling suppression method for wearable MIMO. The line patch helps to break the current distribution from one port to other port [8]. The simple structure assist in maintaining the antenna performance since for a wearable application, the curvature is not static [8]. The antenna is designed in Industrial, Scientific, and Medical (ISM) frequency band, at 2.45GHz to cater for the Wireless Fidelity (Wi-Fi) integrated to the IoT applications and energy harvesting applications [14].

2. Antenna Design
The geometry of the antenna MIMO proposed is shown in Fig. 1. The antenna is a rectangular patch with surface of each patch is $56 \times 47$ mm$^2$ and the 2x1 MIMO is $140 \times 70$ mm$^2$. Edge to Edge the separation between the antennas is taken as $d = 12.5$ mm ($0.1 \lambda_0$). The antennas are fed with a microstrip transmission line of 4 mm width.

![Figure 1](image)

**Figure 1.** The proposed MIMO antenna.

A flexible substrate, felt was used, with a relative permittivity of 1.44 a loss tangent of 0.0044, and a thickness of 3 mm. *ShieldIt* Super electrotextile, was used to form the conducting parts of the antenna with a thickness, $ht$, of 0.17 mm. The estimated conductivity of *ShieldIt* Super is $\sigma = 1.18 \times 10^5$ Sm$^{-1}$. A line patch of 4 mm is introduced in between the patches for mutual coupling reduction. The parameters of the antenna are shown in the Table 1.

| Parameter | Value (mm) |
|-----------|------------|
| Wp        | 56.5867    |
| Lp        | 47         |
| Ws        | 140        |
| Ls        | 70         |
| Lf        | 16.5       |
| Wf        | 4          |
| gap       | 12.5       |
| Pw        | 4          |

**2.1. Gap Analysis**
In MIMO antenna, mutual coupling is highly dependent on the gap between the radiator elements. Analysis on how close the radiator elements can be placed is carried out, with edge to edge distance between patches are varied from $0.5 \lambda_0$ to $0.1 \lambda_0$. The defined gap is illustrated in Fig. 2.
Figure 2. The edge to edge of the proposed MIMO antenna.

The relationship between reflection coefficient ($S_{11}$) and mutual coupling ($S_{21}$) are shown in Fig. 3. From Fig. 3, it can be observed that the resonant frequency remained constant; however, impedance matching is reduced when the gap is reduced. Fig. 3 demonstrates that the depth of $S_{11}$ was lessen from -36 dB to -29 dB. Meanwhile, the impedance bandwidth of the antenna is remained of 180 MHz. On the other hand, $S_{21}$ line in Fig. 3 depicted the higher coupling between patches as the patch gap closer. The $S_{21}$ increased to -38 dB from -20 dB when the gap is reduced from 0.5λ to 0.1λ. In the proposed antenna, the patches in the antenna are closely placed, thus leading to higher mutual coupling due to near field effect from the other port. In addition, the antenna patches are sharing the same common full ground plane.

![Figure 3. S parameter results with varies distance in λ.](image-url)

2.2. Mutual Coupling Suppression Method

A simple technique to suppress mutual coupling of the MIMO antenna is by introducing a parasitic line or slot in between patch elements [8], [9]. A line patch is inserted in between the patches to isolates the current distribution between the patches. In the analysis, the width of the line patch is varied between 1 to 5 mm, $P_w = \{1,2,3,4,5\}$ in mm.

The effect of decoupling can be observed by visualizing the surface current distribution on the MIMO antenna with and without the line patch structure. Fig. 4 illustrated the difference in current distribution when port 1 is excited. There are some surface current propagates from port 1 towards adjacent patch as shown in Fig. 4(a). While, the surface current is suppressed by introducing line patch in the middle of antenna structure as shown in Fig. 4(b).
Figure 4. The surface current distribution in the proposed MIMO antenna.

Table 2 tabulates the results on the mutual coupling suppression using line patch method. Adding the line patch in the middle of MIMO antenna reduces the coupling between the patches. From Table 2, it can be seen that a maximum of 5 dB decreased was observed in the $S_{21}$ when the line patch is inserted. There is no significant difference on resonant frequency and antenna’s bandwidth, but there is a slight improvement with the attained antenna gain, from 4.49 dBi to 4.7 dBi, up to 0.21 dBi.

Table 2. MIMO antenna performance with varying line patch width.

| Parameter | $S_{11}$ | $S_{21}$ (dB) | BW (MHz) | Gain (dBi) |
|-----------|----------|---------------|-----------|------------|
| PW (mm)   | fc (GHz) |              |           |            |
| none      | 2.41     | -31           | -20.2     | 180        | 4.49       |
| 1         | 2.42     | -31           | -23.2     | 170        | 4.7        |
| 3         | 2.42     | -31           | -24.8     | 170        | 4.7        |
| 4         | 2.42     | -31           | -25.0     | 172        | 4.72       |
| 5         | 2.42     | -31           | -25.2     | 173        | 4.67       |

3. Result and Discussion

The result on the proposed MIMO antenna reflection coefficient ($S_{11}$) and mutual coupling ($S_{21}$) is given by Fig. 5(a). The antenna resonates at 2.42 GHz with lower frequency of 2.33 GHz and upper frequency of 2.51 GHz, with impedance bandwidth of 7.4%. The mutual coupling is suppressed at -25 dB. The antenna radiation pattern is directional with a gain of 4.72 dBi, as shown in Fig. 5(b). The antenna is suitable for wearable devices as where the radiation pattern towards off-body direction.

Figure 5. Simulated $S_{11}$ and $S_{21}$ Result for the proposed MIMO antenna with edge to edge gap = 0.1λ.
The diversity of the MIMO antenna can be evaluated by Envelope correlation coefficient (ECC), diversity gain and mean effective gain (MEG). ECC is used to described the correlation between antenna elements and the diversity characteristic of the array antenna is evaluated by diversity gain. The equation to calculate both values is given by (1) and (2), where the values is calculated based on scattering parameter.

\[
ECC = \frac{|S'_{11}S_{12} + S'_{22}S_{21}|^2}{(1-|S_{11}|^2)(1-|S_{22}|^2-|S_{12}|^2)} \quad (1)
\]

\[
DG = 10\sqrt{1 - (ECC)^2} \quad (2)
\]

Fig. 6 shows the comparison of ECC and diversity gain with and without line patch in the proposed antenna. A good performance in terms of diversity of the antenna where ECC less than 0.03 and diversity gain value is close to 10 dB. Both result give a stable reading between 2.4 GHz to 2.5 GHz, however the values of diversity gain and ECC for antenna without line patch have fluctuation in points.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{Figure 6. ECC and Diversity gain of the proposed MIMO antenna.}
\end{figure}

Meanwhile, MEG is defined as the mean received power by considering environment effect [15] and is calculated using Equation (3). Given \( k \) is the number of antennas and \( i \) represents antenna under observation.

\[
MEG_i = 0.5 \left( 1 - \sum_{j=1}^{k} |S_{ij}| \right) \quad (3)
\]

The practical standard for good diversity performance is the MEG should be in range of -3 to -12 dB. Fig. 7 illustrated the obtained MEG result for the proposed MIMO antenna. The MEG is below -6 dB from 1.5 to 3.5 GHz, and lowest at 2.4 GHz which is 6.52 dB.

On the basis of spacing, isolation technique, number of elements, \( S_{21} \), ECC and gain, the Table 3 compares the proposed antenna with some previous works studied in the literature. It can be observed that the proposed design could achieve the high isolation for small element separation distance with a modest isolation technique.
Figure 7. Mean effective gain for the proposed MIMO antenna.

Table 3. Performance comparison of MIMO antenna

| Reference | Frequency (GHz) | Number of elements | Isolation Technique | Edge-edge spacing | S21 (dB) | ECC | Maximum Gain |
|-----------|----------------|--------------------|---------------------|-------------------|---------|-----|--------------|
| 7         | 15.6 – 16.4    | 4                  | differential feeding | 0.18 \(\lambda_0\) | -30     | < 0.01 | 8.8 dBi      |
| 8         | 1.8 - 2.6      | 2                  | parasitic element   | 0.3 \(\lambda_0\)  | -25     | < 0.01 | 4 dBi        |
| 9         | 2.8 & 3.5      | 2                  | folded slot + partial ground plane | - | -20 | <0.001 | 3.36 dBi |
| 10        | 4.8            | 2                  | H-Shape DGS         | 0.05 \(\lambda_0\) | -21     | -     | 5.5 dBi      |
| 11        | 2.5 - 2.55     | 2                  | grounded stubs +DGS | 0.06 \(\lambda_0\) | -20     | 0.003 | 6.1 dBi      |
| 12        | 3.5 – 4.95     | 2                  | DRA positioning + parasitic element | 0.5 \(\lambda_0\) | -28 | <0.04 | 6.5 dBi      |
| Proposed  | 2.33-2.51      | 2                  | parasitic element   | 0.1 \(\lambda_0\)  | -25     | <0.001 | 4.7 dBi      |

4. Conclusion
A simple wearable MIMO antenna for on/off WBAN applications has been studied in this article. The presence of parasitic element of 3mm Pw enhanced the isolation between radiator. The results show an improvement of 25% in \(S_{21}\) with 0.3 dB gain increment. An important diversity performance parameter for MIMO antenna like ECC, diversity gain and MEG results are found to be in an acceptable limit.

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