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Slot-Enabled to Reduce a Mutual Coupling Effect in MIMO Textile Antenna for Wearable System

Penggunaan Slot untuk Mengurangi Efek Mutual Coupling pada Antena Tekstil MIMO untuk Sistem Wearable

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Abstrak

Mutual coupling merupakan tantangan utama dalam perancangan antena tekstil Multiple-Input Multiple-Output (MIMO), dikarenakan interferensi gelombang elektromagnetik antar antena dapat menurunkan kapasitas kanal serta kualitas sinyal. Penelitian ini mengusulkan struktur slot ortogonal yang diintegrasikan pada bagian tengah patch untuk menekan interaksi gelombang. Antena tekstil dirancang dan difabrikasi menggunakan substrat berbahan denim jeans dengan konstanta dielektrik, ε_r sebesar 1.38 dan ketebalan 1 mm. Hasil simulasi dan pengukuran antena menunjukkan kinerja S21 sebesar –32.08 dB untuk antena tanpa slot dan –58.32 dB dengan slot pada frekuensi kerja 2.45 GHz. Antena ini menghasilkan pola radiasi unidirectional dengan distribusi energi yang merata, sehingga sesuai untuk aplikasi antena *wearable.*

Kata kunci: Antena Wearable, MIMO, Mutual Coupling, Tekstil.

Abstract

Mutual coupling is a main challenge in designing textile Multiple Input Multiple Output (MIMO) antennas, as electromagnetic wave interference between antennas can degrade channel capacity and signal quality. This study proposes an orthogonal slot structure integrated in the center of the patch to suppress wave interaction. The textile antenna was designed and fabricated using a denim jeans substrate with a dielectric constant, ε_r of 1.38 and a thickness of 1 mm. Both simulation and measurement results of the antenna show an S21 performance of –32.08 dB for the antenna without slot and –58.32 dB for antenna with slot at a working frequency of 2.45 GHz. This antenna shows an unidirectional radiation pattern with a uniform energy distribution, making it suitable for wearable antenna applications.

Keywords: MIMO, Mutual Coupling, Textile, Wearable Antenna.

I. INTRODUCTION

Alongside the growth of mobile communication technologies, wearable technology has developed rapidly. For body centric applications, antennas are required to be lightweight, flexible, and comfortable to wear [1–6]. Unlike conventional antennas, wearable antennas operate very close to the human body, where signal absorption and detuning can affect their performance. In addition, the compact size of wearable devices provides only limited space for antenna integration [4]. To improve communication reliability and data capacity within this limited space, Multiple Input Multiple Output (MIMO) technology has been widely adopted in wearable systems [7-11]. By employing multiple antenna elements, MIMO can enhance link robustness and overall system performance. Nevertheless, antenna elements need to be placed close to one another due to limited space. As a result, electromagnetic interaction between elements becomes unavoidable, leading to mutual coupling. This coupling can degrade signal quality, reduce radiation efficiency, and weaken the diversity performance of the antenna system [6]. Therefore, designing wearable MIMO antennas that achieve high isolation while maintaining compact dimensions has become an important research focus.

Several techniques have been developed to overcome this issue. One commonly used approach involves the integration of electromagnetic band gap (EBG) [11-14], which can reduce electromagnetic interaction between antenna elements. Another widely adopted method is defected ground structures (DGS), which modifies the current distribution on the ground plane to minimize coupling effects [15,16]. DGS is appropriate for compact systems since prior research has demonstrated that it may efficiently increase isolation without significantly increasing antenna size. Another method, the use of parasitic elements has also been explored [17]. The additional structures are placed to redirect electromagnetic fields and reduce interference between antenna elements. Despite these advancements, many of the existing techniques often introduce increased design complexity and fabrication challenges, particularly in textile-based implementations. Therefore, a simpler and more compact approach is still required to achieve high isolation while preserving the flexibility and practicality of wearable antennas. In this work, a slot-enabled technique [18,19] is proposed to enhance mutual coupling in a MIMO textile antenna. This method offers a compromize between performance improvement and structural simplicity for wearable applications.

This paper aims design and fabrication of a MIMO textile antenna operating at 2.45 GHz. The proposed antenna employs a hybrid slot configuration, consisting of one vertical and three horizontal slots arranged orthogonally within the radiating patch to enhance isolation performance. In addition to the decoupling strategy, substrate selection plays a main role in textile antenna design. While textile materials such as felt, cotton, and polyester have been widely explored [21-24], their electromagnetic performance varies depending on their dielectric properties and mechanical flexibility. In this study, denim jeans is chosen as substrate due to its favourable balance between robustness, flexibility, and suitability for practical wearable applications [22-24].

II. LITERATURE REVIEW

Recent studies on wearable wireless systems have shown that Multiple-Input Multiple-Output (MIMO) technique can improve channel capacity and communication reliability by enabling multiple antenna elements to work together [7-9]. In wearable applications, these advantages are particularly useful because signal fading is often caused by body movement or changes in the surrounding environment [1-4]. However, when MIMO antennas are implemented, the close spacing between antenna elements causes their electromagnetic fields to interfere with one another, resulting in mutual coupling. This interaction can decrease antenna performance [7-11]. In wearable systems, the problem becomes even more critical because the human body itself can absorb energy and shift the resonant behaviour of the antenna [1], [4]. As a result, reducing mutual coupling is one of the main design concerns in wearable MIMO antennas.

Several studies have investigated different approaches to suppress mutual coupling in textile-based MIMO antennas. One of the earlier studies by Kumar [7], proposed a compact wearable UWB MIMO antenna with improved port isolation, reporting isolation better than 17 dB. A related study in [8] further improved decoupling performance by optimizing the element configuration, achieving isolation above 20 dB while also reducing envelope correlation. These results indicate that the relative placement of antenna elements and inter-element spacing strongly influence coupling behavior even before additional decoupling structures are introduced. Singh et al. [9] developed a wideband textile MIMO antenna using felt as the substrate and ShieldIt™ as the conductive layer, achieving a maximum mutual coupling reduction of –29.26 dB over the 2.00–6.23 GHz band. Although the reported isolation was relatively good, the study also showed that coupling performance remains closely related to the radiator arrangement and the electromagnetic characteristics of the textile material.

Slot based decoupling techniques have attracted attention because they offer a relatively simple way to modify current paths without adding external structures. Revati [10] demonstrated that introducing slots at suitable positions in the ground plane could reduce |S21| to below –20 dB across the operating band. In another study, [11] combined split-ring resonators (SRR) with bar slot structures in a dual band textile MIMO antenna for WBAN and 5G applications. Their design achieved isolation better than 18 dB in both operating bands and maintained stable performance under bending conditions. These studies suggest that slot geometry and its position relative to the radiating elements play an important role in controlling surface current coupling.

Other coupling reduction methods have also been widely reported. In [12] introduced a parasitic electromagnetic band gap (EBG) structure for a 2.45 GHz MIMO antenna and reported an isolation improvement of approximately 8 dB compared with the reference design. In wearable applications, Pei et al. [13] showed that an EBG-backed belt antenna improved radiation stability and reduced body absorption during on-body operation. Likewise, in [14] demonstrated that a miniaturized EBG structure could improve radiation pattern of textile antennas. Although EBG methods are effective, they often require additional periodic layers, which may increase fabrication complexity. Defected ground structure (DGS) techniques have also been reported as an effective way to suppress coupling by altering current paths on the ground plane. In example, [15] demonstrated that introducing a DGS significantly improved isolation in a two-element MIMO antenna without increasing the antenna footprint. A more recent study , [16] combined a slotted-ring EBG with an H-shaped DGS and achieved further coupling suppression in a compact MIMO configuration. Similarly, [17] reported approximately 20 dB isolation improvement by combining parasitic elements and DGS. Despite their effectiveness, these approaches generally rely on additional structures that may reduce flexibility in textile-based wearable systems.

In addition to decoupling structures, substrate material has also been identified as an important factor affecting wearable antenna performance. Textile substrates determine not only mechanical flexibility but also resonant stability, impedance matching, and radiation efficiency [1], [4]. Among the available textile materials, denim jeans has received increasing attention because of its mechanical durability and relatively stable dielectric properties. Author in [2] reported that denim-based wearable antennas could maintain reliable operation for WBAN applications while preserving flexibility. In another study, Kavitha et al. [13] showed that denim improved return loss and radiation efficiency in broadband antenna applications. Similarly, [14] demonstrated the suitability of jeans fabric for wearable patch antennas, although their work was limited to single-element configurations without mutual coupling analysis.

Overall, previous studies have shown that mutual coupling performance in wearable MIMO antennas is influenced not only by the decoupling technique itself, but also by element placement, inter-element spacing, and substrate properties. Most reported wearable textile MIMO antennas achieve isolation in the range of approximately 17–30 dB [7]–[12], whereas higher isolation is often obtained at the expense of additional structural complexity [13]–[17]. Comparatively few studies have investigated direct modification of the radiating patch using hybrid slot configurations on denim-based textile MIMO antennas [18], [19]. This indicates that a simpler slot-based approach integrated directly into the radiator remains relevant for further investigation in wearable MIMO antenna design.

III. RESEARCH METHOD

The proposed textile MIMO antenna is designed at 2.45 GHz frequency. Denim jeans were selected as the substrate due to the durability, ease of fabrication, and dielectric stability [11-15]. The antenna elements are designed as rectangular microstrip patches with a modified radiating surface. To reduce mutual coupling between elements, a hybrid slot configuration was incorporated directly into the radiating patch. The slot arrangement consists of one vertical slot positioned along the center axis of the patch and three horizontal slots placed symmetrically across the radiating surface (see Figure 1 and 2). This configuration modifies the surface current distribution and weakens the electromagnetic interaction between elements, thereby improving isolation while preserving the radiation characteristics of the antenna. For compact wearable operation, the two antenna elements are arranged with an edge-to-edge spacing of $d = 0.1\lambda$.

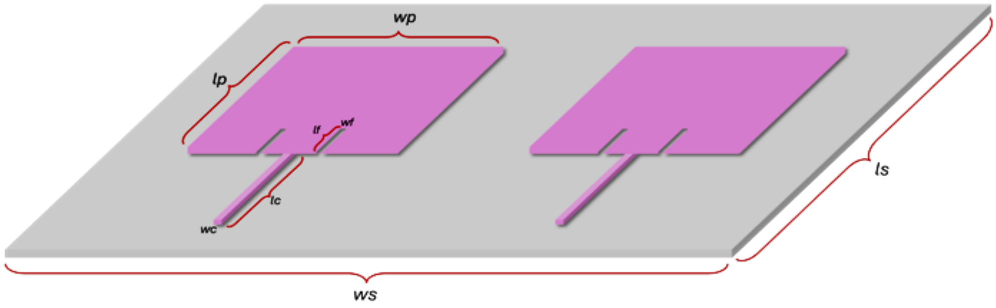

Figure 1. Design of textile MIMO antenna without slot

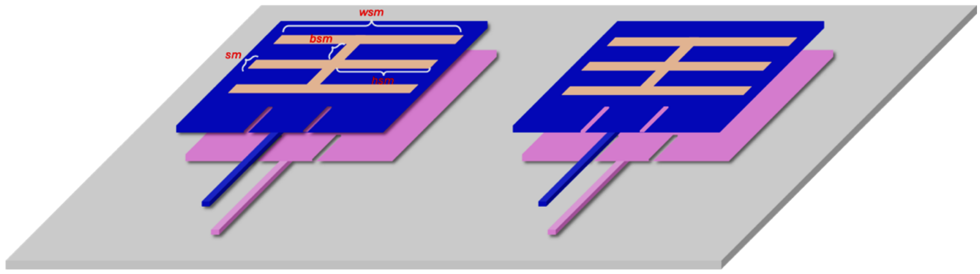

Figure 2. Design of textile MIMO antenna with slot

In this study, denim jeans were also characterized to determine their dielectric properties before being used as the antenna substrate. The dielectric constant is measured using ring resonator method [20], with the resonator geometry that depicted in Figure 2. The proposed ring resonator in this research had an inner diameter, d_{inner}, of 11 mm and an outer diameter, d_{outer}, of 17 mm. The result of transmission coefficient (S_{21}) was measured, yielding resonance frequencies at 3.54 GHz and 5.81 GHz. Based on these resonances, the effective dielectric constant (ε_{re}ff) was calculated to be approximately 1.38.

Using this dielectric constant and a substrate thickness, h, of 1 mm, the initial antenna design was developed as a two elements rectangular patch MIMO structure. The calculated dimensions each patch is width, W, ≈ 38.72 mm, patch length, L, ≈ 46.72 mm, ground plane dimensions, $Wg \approx 44.72$ mm, $Lg \approx 52.72$ mm. Then, the two patches were positioned edge-to-edge with a spacing of approximately 0.1λ.

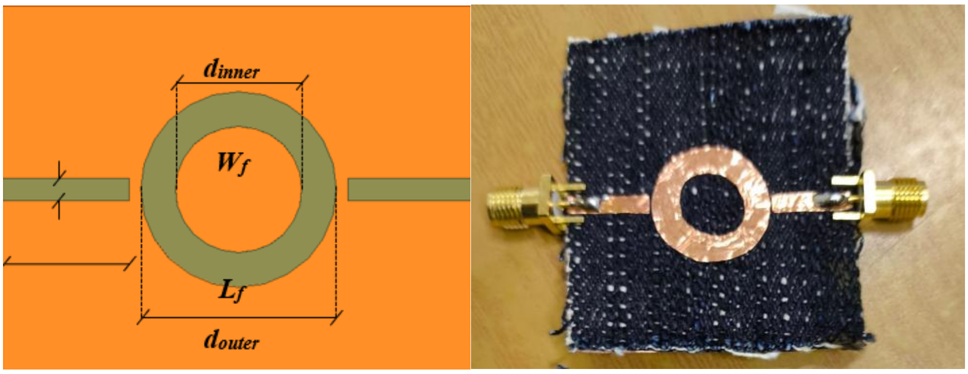

Figure 2. Ring resonator method is implemented on denim jeans material.

Table 1. The ring resonator size parameter

Parameter	Size
Inner diameter of resonator ring (d*inner*)	11 mm
Outer diameter of resonator ring (douter)	17 mm
Feedline width (Wf)	2 mm
Feedline length (Lf)	11 mm

The initial antenna was simulated using HFSS. At this preliminary stage, the return losses (S_{11} and S_{22}) of the antenna without slot were not yet fully optimized, with values of approximately –10.07 dB and -11.23 dB, while the mutual coupling (S_{21}) was approximately –42.66 dB.

To enhance the decoupling performance, the patch geometry was then modified by introducing the proposed hybrid slot configuration. One vertical slot and three horizontal slots were embedded at the center of each patch in order to suppress coupling. The final slot dimensions were optimized through parametric studies in HFSS, and the resulting antenna parameters are summarized in Table 2.

Table 2. The optimized size of denim jeans-based textile MIMO antenna

Parameter	Size after optimization
a	51 mm
b	50 mm
W_f	27 mm
L_f	3 mm
L_{in}	5 mm
W_{in}	0.5 mm
c	42 mm
d	27 mm
e	2 mm

IV. RESULTS AND DISCUSSION

The proposed textile MIMO antenna was fabricated using denim jeans substrate and copper foil tape (CFT) as the conductive material for patches and the ground plane. CFT was selected because it combines good electrical conductivity with mechanical flexibility and strong adhesion to textile surfaces. As depicted in Figure 3, the fabricated prototype preserves the compact two element MIMO arrangement, where the hybrid slot configuration is clearly integrated into each radiating patch. During fabrication, particular care was taken to maintain dimensional accuracy of the slot features and to avoid wrinkles or air gaps between the copper layer and the denim substrate, since even minor irregularities can affect current distribution and shift the resonant response.

For experimental validation, the antenna was measured using a Vector Network Analyzer (VNA). The measurement setup is presented in Figure 4. Due to the two-port limitation of the available VNA, one antenna element was excited while the second element was terminated during measurement. Coaxial connectors were attached directly to the feed lines of the textile antenna. In practice, connector attachment and cable positioning are critical in textile antennas because the flexible substrate can slightly deform under mechanical loading, while the relatively rigid SMA connectors may introduce local perturbations around the feeding region. These effects contribute to deviations between measurement results, particularly in the return loss characteristics.

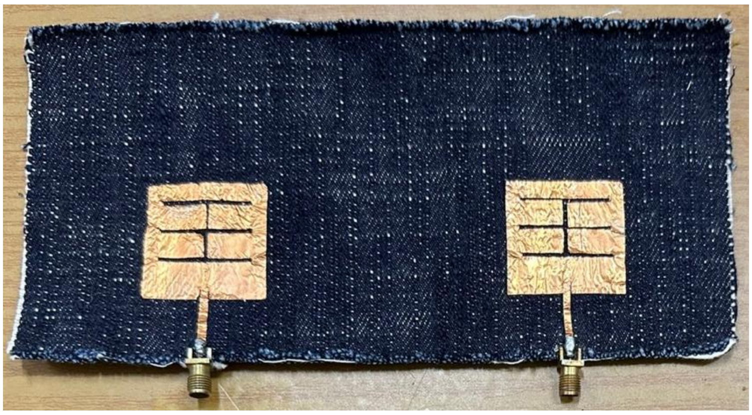

Figure 3. The fabricated of denim jeans-based textile MIMO antenna with slot.

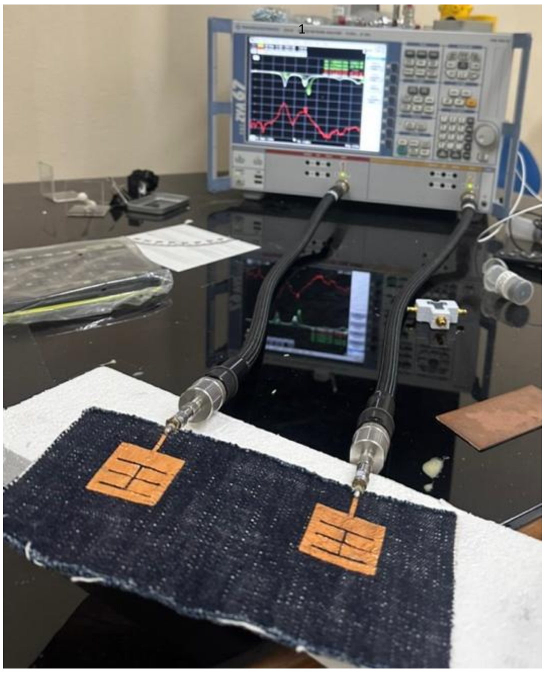

Figure 4. Measurement setup for denim-based textile MIMO antenna with slot.

Figure 5 presents results of reflection coefficients the proposed denim-based textile MIMO antenna from both simulation and measurement. The reflection coefficient comparison shows the effect of the hybrid slot configuration into the radiating patch. From the conventional design, the reflection coefficient, $S_{11}$is observed at approximately 2.46 GHz with a value of around –19.8 dB, while S_{22}reaches approximately –18.5 dB at nearly the same frequency. For the simulation with slots (red curves), both $S_{11}$and S_{22}remain centered close to 2.45 GHz, matching reaches approximately $-16$to -22dB.

The measurement results (blue curves), however, shows a slight frequency shift and asymmetry between the two ports. The measured S_{11} results is in 2.58 GHz frequency, while the measured S_{22} minimum appears around 1.93 GHz. This discrepancy between simulation and measurement is typical for textile antennas and is most likely caused by fabrication tolerances.

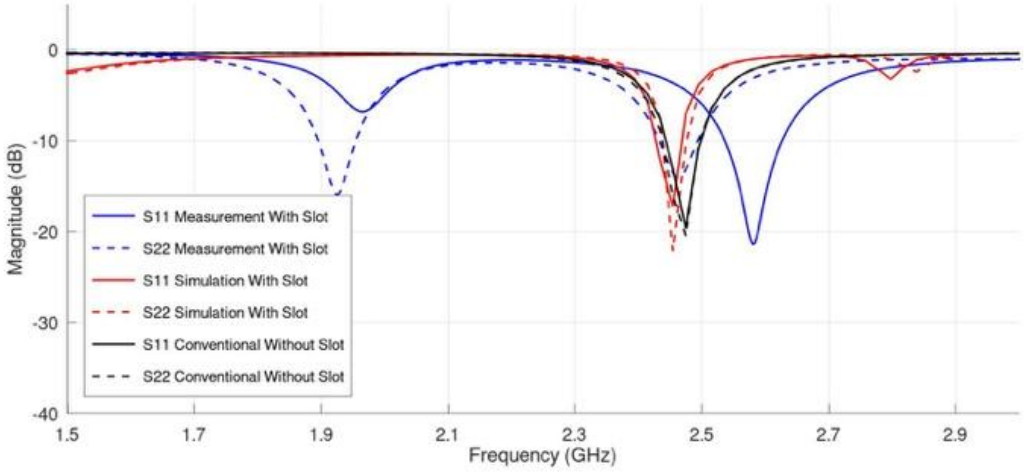

Figure 5. Comparison of both simulation and measurement of the proposed textile antenna.

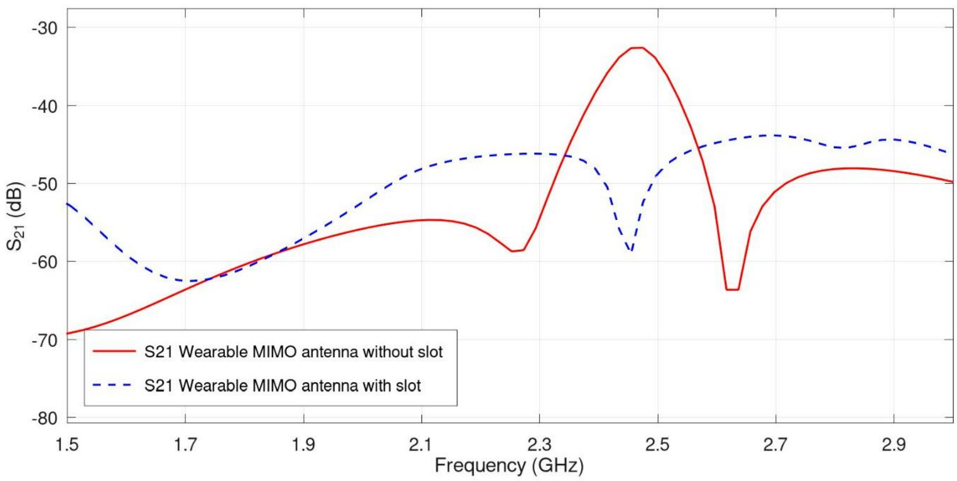

Figure 6. The mutual coupling response of the MIMO textile antenna.

Figure 6 further illustrates the effect of the slot configuration on the coupling response of the proposed MIMO textile antenna. For the conventional antenna without slots, the coupling level varies significantly across the operating band. Around the frequency of 2.45 GHz, the isolation reaches approximately –35 dB, indicating that electromagnetic interaction between the two elements is still relatively noticeable. A deeper coupling minimum appears near 2.64 GHz, where S_{21}drops to approximately –63 dB.

After introducing the hybrid slot structure, the coupling behavior becomes more favorable around the operating frequency. The slot-loaded antenna exhibits a mutual coupling approximately –58.32 dB. Compared with the conventional design, this corresponds to an isolation improvement of roughly 23 dB at the target operating frequency.

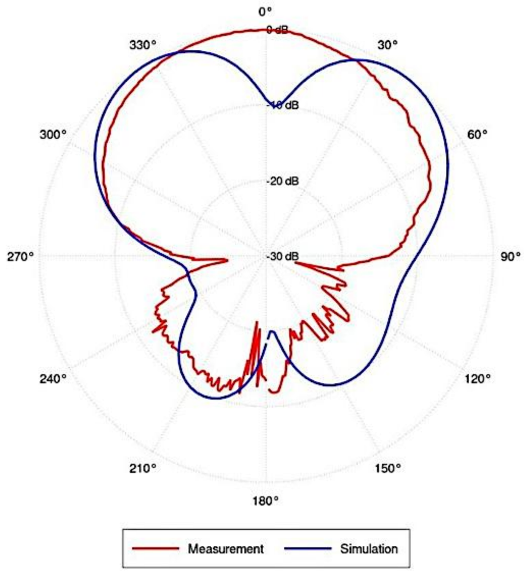

Figure 7. The radiation diagram of the proposed MIMO textile antenna

Radiation pattern measurements were carried out using a horn antenna as the transmitting reference. Figure 7 shows radiation pattern of the MIMO textile antenna. The antenna exhibited a unidirectional pattern**,** with relatively uniform radiation across most angles. The results confirm that the hybrid slot configuration is highly effective in reducing mutual coupling, achieving isolation levels significantly better than conventional textile MIMO antennas.

V. CONCLUSION

The study has presented the design and experimental validation of a MIMO textile antenna using denim jeans as the substrate for 2.45 GHz frequency. A hybrid slot that consisting of one vertical and three horizontal slots configuration was introduced into each patch to mitigate a mutual coupling. The dielectric characteristic of the material were characterized using the ring resonator method, yielding an effective permittivity of 1.38. The proposed MIMO textile antenna achieved S_{21} of –58.32 dB in simulation and experimental measurements further confirmed the improved isolation performance, with a $S_{21}$of –78.19 dB. The findings confirm that slot modification on MIMO textile antenna provides an effective and structurally simple solution for mutual coupling reduction, while maintaining flexibility and wearability.

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