

Design and Implementation of Wearable Antenna Textile for ISM Band

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Abstract—Wearable antenna is one component needed for mid-range communication. It can be integrated into clothing, bags, or any other item worn. This paper presents the structure and performance of a wearable antenna used in place of the ESP8266 Wi-Fi module antenna in dresses. With a higher gain than 2 dBi, this replacement will provide greater signal coverage than the existing Wi-Fi antenna module. The proposed geometry utilizes rectangular patches with the inset feed method in the feedline segment, constructed using copper foil tape, 2.85 mm thick polyester as a substrate with a permittivity (ϵ_r) of 1.44 Defected Ground Structure (DGS) technique. The operating frequency of the proposed antenna is at 2.4 GHz in the ISM (Industrial, Scientific, and Medical) band. The whole process was used to optimize the structure, fabricated, and measured. The result of the simulation and measurement of the proposed antenna's VSWR is less than 2. The measurements scenario for the substitute and existing antenna are divided into two categories: line-of-sight (LOS) and non-line-of-sight (NLOS). Each of them experiences the vertical and horizontal positions of the antenna. In LOS conditions, the vertical position has an average coverage of 9.84 meters more than the antenna module, and the horizontal position is 13.84 meters. In NLOS conditions, the horizontal position has an average coverage of 9.22 meters more than the EP8266 antenna module, which in the vertical condition is about 17.06 meters. The obtained data successfully demonstrated that the proposed antenna could significantly increase the coverage of the ESP8266 module.

1. INTRODUCTION

Telemedicine is one of the advances in health administration. Recently, remote correspondence technology has enabled compact electronic gadgets to become adaptable [1]. The most progressive development is that people can utilize electronic devices for correspondence proposes in zones of the body, individual, etc. or typically referred to as Body Area Network (BAN) and Personal Area Network (PAN).

Wearable devices are used for effective wireless communication networks, and they are typically embedded into textile materials for transmitting electromagnetic waves. A wearable antenna has an essential role in supporting the correspondence concepts, which provide flexibility, wearable processing, and open security [2]. They are frequently difficult to build; inventory availability at different body sites, host organism impact, and efficiency decrease due to structural bending are all issues that must be addressed throughout the design process [3, 4].

This type of antenna is a significant area of research for body-centric communication, particularly with the continued advancement of The Internet of Things (IoT) innovation and the improvements of

Received 25 February 2022, Accepted 3 April 2022, Scheduled 30 April 2022

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wearable electronic devices [5]. The antenna plays a vital role in communication by transmitting and receiving electromagnetic waves in free space [6].

Microstrip antenna is frequently used for low profile, simple fabrication, and omnidirectional radiation pattern [7]. Microstrip patch antennas are constructed as three-section circuit loads: patch, substrate, and ground plane. They influence each other to form the antenna characteristic.

This paper describes a 2.4 GHz microstrip wearable rectangular antenna with inset feed technique in feedline and defected on the ground plane. This antenna is intended to be used in medical applications to substitute the ESP8266 Wi-Fi antenna module. Sensors are used to monitor a patient's condition in the hospital. Data from these sensors will be transmitted to the cloud via Wi-Fi for remote monitoring and forwarded to healthcare services. This concept will occur when an antenna has a higher gain. A wearable antenna can be embedded into a patient's clothing and replace the existing antenna on the Wi-Fi module.

Polyester was chosen as the substrate for this design because it is frequently used in hospitals for patient clothing. This material's dielectric constant (r) is 1.44 [8]. Typically, wearable textile antennas are composed of conductive patches [9]. The antenna is designed to fulfill these parameters: return loss ≤ -10 dB, VSWR ≤ 2.00 , gain ≥ 2 dBi, and SAR value of 1.6 watts per kilogram.

2. ANTENNA DESIGN

The proposed antenna design is resonant with a 2.4 GHz frequency. A polyester with relative permittivity (ϵ_r) of 1.44, thickness of substrate 3 mm (m), loss tangent ($\tan \delta$) of 0.01, and input impedance of 50Ω is used. The antenna's geometry is adjusted based on its width, patch length, and ground plane to meet the required characteristic [10].

The proposed antenna is designed by varying the length (h) and width (g) of inset feed to improve input impedance (Z_0), resonant frequency, and return loss or VSWR. The inset width (g) should be an essential part of the feed width (e). Defected Ground Plane (DGS) concept is also used to increase the antenna's performance.

There are many designs for antenna patches: circular, rectangular, and square shapes [11]. A rectangular shape was chosen for the design due to its simplicity and ease of fabrication. The patch material is identical to the copper tape on the ground plane.

Numerous textiles such as flannel, polyester, fleece, cotton, and felt are utilized as antenna substrates [12]. The picked fabric material will decide the antenna performance, particularly efficiency and bandwidth. According to previous works, the substrate with low permittivity and thickness will affect the antenna performance [12, 13].

The suggested antenna's geometry is depicted in Figure 1 and consists of two parts, (a) the design's front side and (b) the ground plane view. The ground plane structure is based on the M-shape DGS structure described in [14], which gives a relatively wide bandwidth, low VSWR, and efficiency. The dimension is changed from [14] to attain the needed performance. Each parameter's value was determined using standard microstrip antenna equations and then optimized using the simulation method. The values for the calculated and optimized design parameters are listed in Table 1.

The design depicted is the one that produces the best results in previous simulations. The simulated results have not revealed the effects when starting with a rectangular patch with a feedline on the front and a full ground plane on the back. Then, afterward, the inset feed technique was used to enhance the impedance match between the transmission line and the patch. It allows the antenna to absorb more power due to the ideal impedance match, thus having a low VSWR [15]. The simulation results are acceptable, but the efficiency value is still low enough to affect the value of gain and directivity. Table 3 and [16] explain how the problem is solved using the defected ground plane method.

Due to the human body's heterogeneous and lossy nature, an antenna's performance degrades when being positioned near it [17]. The metamaterial surface is applied as a high impedance that protects the body from electromagnetic radiation risks by lowering the Specific Absorption Rate (SAR) [17]. This study uses a flat phantom to simulate the human body replica; however, based on [18], the bent measurement of the antenna is not significantly affected by the required characteristics.

SAR has been defined as the rate at which radiofrequency electromagnetic energy is absorbed by a biological body's unit mass [19]. IEEE specifies a limit of 1.6 watts per kilogram. The antenna is

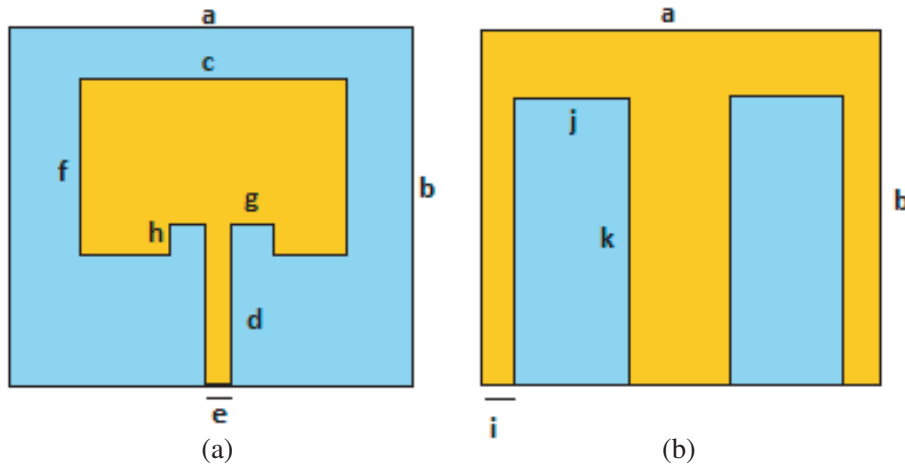


Figure 1. Geometry and configuration of the proposed rectangular patch design. (a) Front view. (b) Back view M-Shape DGS.

Table 1. Dimension of proposed rectangular antenna.

Parameters	Dimensions (mm)	
	Calculated	Optimized
Width of the substrate (a)	90	90
Length of the substrate (b)	90	90
Length of patch (c)	48.46	41.82
Feed length (d)	24	24
Feed width (e)	3.3	3.3
Width of patch (f)	55.43	47.83
Inset gap (g)	2	2
Inset distance (h)	10	10
Edge of slot in ground plane (i)	5	5
Width of slot in ground plane (j)	25	25
Height of slot in ground plane (k)	75	75
The thickness of patch (l)	0.06	0.06
The thickness of the substrate (m)	2.85	2.85

attached to a replica of a flat human phantom [20]. As illustrated in Figure 2, a three-layered body segment comprises muscle, fat, and skin. These strata have the following average permittivity and conductivity: muscle ($\epsilon_r = 52.79$; $\sigma = 1.705 \text{ S/m}$), fat ($\epsilon_r = 5.28$; $\sigma = 0.1 \text{ S/m}$) and skin ($\epsilon_r = 31.29$; $\sigma = 5.0138 \text{ S/m}$) [17]. The thicknesses of muscle, fat, and skin layers are 40 mm, 2 mm, and 1 mm, respectively.

3. RESULT AND DISCUSSION

The 2.4 GHz wearable microstrip inset feed single patch antenna using polyester as a substrate is analyzed using the CST Studio Suite software (with and without the DGS method). This software adds substrate as new material with relative permittivity (ϵ_r) of 1.44 and loss tangent ($\tan \delta$) of 0.01. The bandwidth was between 1.903 GHz and 2.897 GHz. The required parameter is determined by observing the graph and then comparing it.

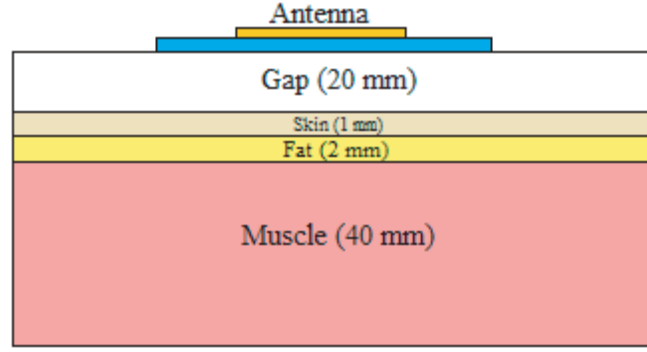


Figure 2. Fix reception apparatus mounted on body phantom.

3.1. Full and Defected Ground Structure

The optimization procedure used two different ground plane structures: full ground plane and defected ground plane. They had compared themselves to determine which was the best. The VSWRs with and without DGS are illustrated in Figures 3 and 4. It takes three attempts of re-scaling the overall geometry size to achieve the required frequency. The gain of the full ground plane is -2.098 dBi; the directivity is 8.112 dBi; the efficiency is -10.21 dB; and the bandwidth is 2.1–2.16 GHz. Meanwhile, the DGS method design has gain about -0.2892 dBi, with 6.839 dBi of directivity, -7.128 dB of efficiency, and 1.93–2.1 GHz of operating frequency band.

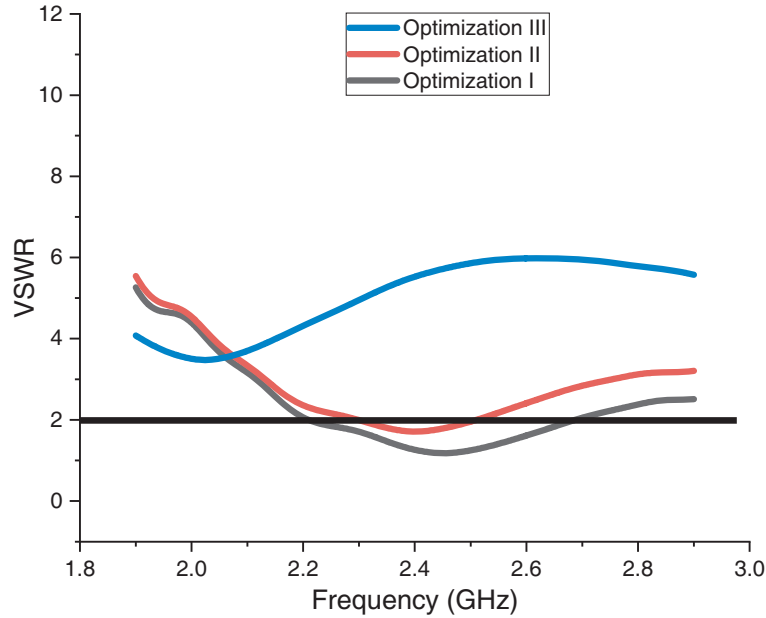


Figure 3. VSWR of the proposed design.

Figure 5 and Table 2 compare the third simulation and optimization results for these two-ground plane configurations. The Full Ground Structure (FGS) approach results indicate that the required parameters for VSWR and directivity were passed. Nevertheless, the efficiency value was about 50% lower, affecting the decreased value of gain. This behavior does not occur with the DGS approach. As a result, the suggested antenna applies the DGS technique as the ground plane structure.

Table 3 indicates the defected process in the proposed antenna's ground plane. Starting with the whole ground plane, reducing parts of the width produces a smaller gain than before — however, radiation and overall efficiency rise around 0.6622 dB and 1.5943 dB, respectively. We add specific

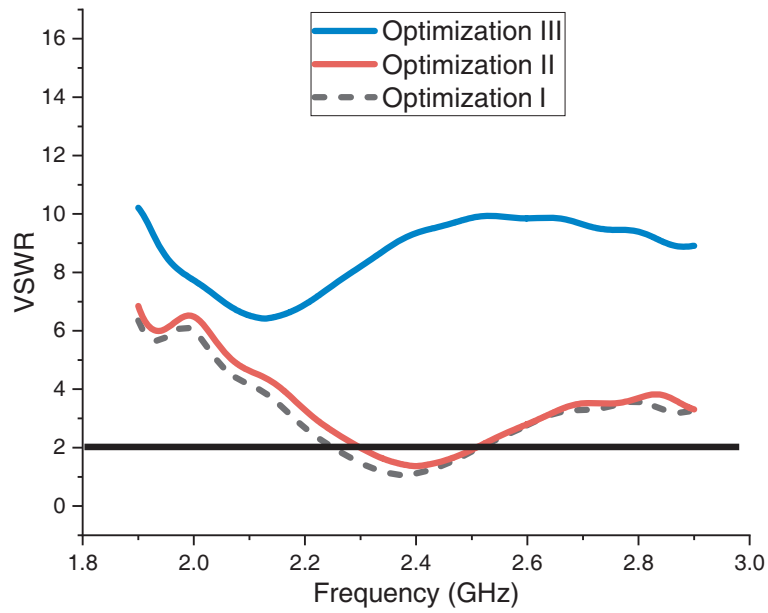


Figure 4. VSWR of Textile Antenna without DGS.

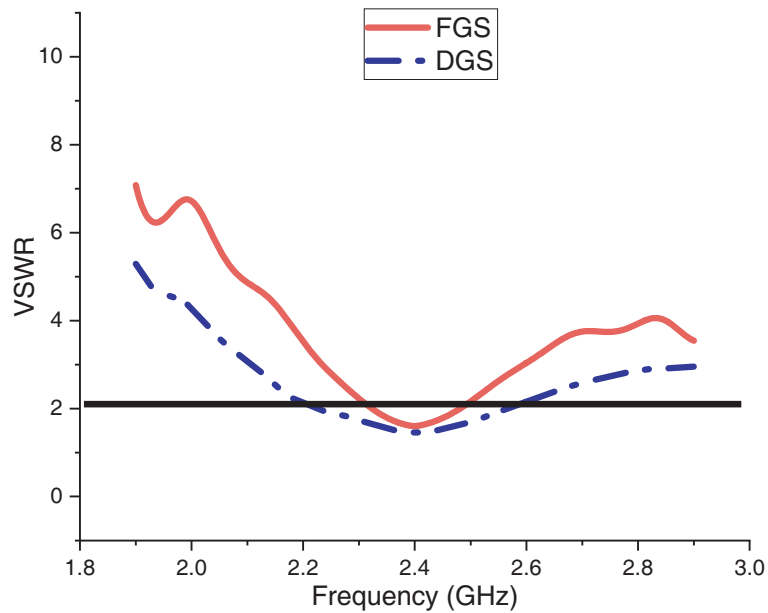


Figure 5. Comparison of VSWR from the defected ground structure and full ground structure.

Table 2. Parameters comparison of antenna with and without DGS.

Parameters	With DGS	Without DGS
Directivity	7.931 dBi	8.508 dBi
Gain	6.953 dBi	6.438 dBi
Rad. Efficiency	83.3470%	71.680%
Tot. Efficiency	79.8509%	62.087%

Table 3. The ground plane shapes of the proposed simulated antenna.

Shape	Rad. Effic. (%)	Tot. Effic. (%)	Gain (dBi)
Square	77.144	58.762	6.438
1/6 of width	89.8504	84.8262	5.803
<i>T</i>	89.2750	84.5649	4.456
<i>E</i>	89.8607	87.4078	6.953

components to the previous section to produce T-shape [21], the same result condition as before. Finally, we create a shape with a more significant result than the previous one, the E-shape [22].

3.2. SAR Value Comparison

A metamaterial surface shields the human body from electromagnetic radiation, lowering the body's Specific Absorption Rate, or SAR [17]. SAR describes the absorption of power per unit mass in a body form. In the software environment, the body form is a phantom with three levels, depending on the location of the antenna on the body, and each of these three layers is defined as a new material. Table 4 demonstrates the effect of DGS on the SAR value in the simulation process. The results are relatively good, including gain, VSWR, and return loss. The excellent result slowly appears at a particular gap.

Table 4. Simulated result antenna with phantom.

Gap (mm)	VSWR	Gain (dBi)	SAR (W/kg)
0	2.641	2.847	6.42
1	2.205	4.171	4.17
5	1.590	6.009	2.73
7	1.483	6.506	1.9
10	1.409	6.829	1.16
20	1.361	7.242	0.302

The on-body condition information in Table 5 is obtained with 10 mm gap between the antenna and the phantom, integrated with the optimization DGS design from simulation. This is the optimized result after varying the gap, from 0 to 20 mm separation. This simulation then indicates little difference between off- and on-body circumstances. It is important to note that the technique is only simulated using software, which provides ideal conditions as a standard. This ideal situation suggests no impedance present inside or outside, and yet it is not identical to the absolute measurement.

Table 5. The simulated result with and without phantom.

Parameters	Off-Body	On-Body
VSWR	1.506	1.409
Gain	6.953 dBi	6.829 dBi
SAR	-	1.16 W/kg

The data were analyzed at the Indonesia Institute of Science's Research Center for Electronics and Telecommunication. It can be done in two ways: on or off-body. The antenna is placed close the top of the chest. The Network Analyzer equipment in Figure 7 measures near-field antenna parameters such as return loss, VSWR, and antenna bandwidth.

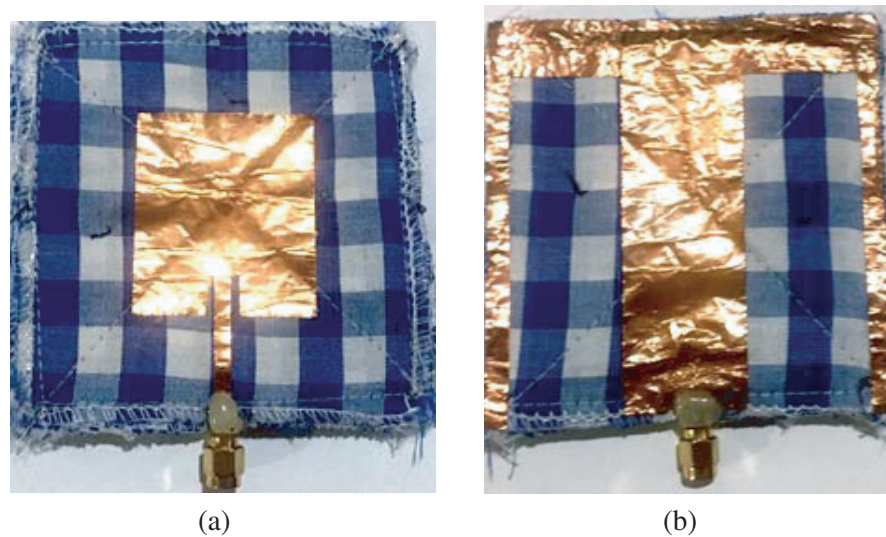


Figure 6. The developed antenna. (a) Front-view. (b) Back-view.



Figure 7. The measurement of the proposed antenna wearable.

Figure 6 depicts the fabrication results from the front and back. This antenna was constructed manually with a few polyester layers to fill the required thickness of the substrate. The patch's dimension has already been adjusted to simulate the process same as the ground plane design.

Layers of substrate material must be completely sealed off from one another. It is accomplished by compressing the substrate's layer. The port is installed by soldering copper to the antenna's feed line. The results of the antenna shown in Figure 8 exhibit a slight difference between simulation and measurement.

Figure 9 shows the graph of the measurement result using a network analyzer. Body tissue heterogeneity influences the performance of a transceiver operating near the body, and RF waves have various biological effects on the human body [23, 24]. The following literature lists the parameters that affect the design of in-body and on-body antennas [23, 25]. At off-body, the VSWR parameter has 1.556 in the center frequency of 2.36–2.475 GHz; however, on- and off-body designs have nearly the same result. The measurement procedure is carried out in an anechoic chamber provided by the Indonesia Institute of Science's Research Center for Electronics and Telecommunication.

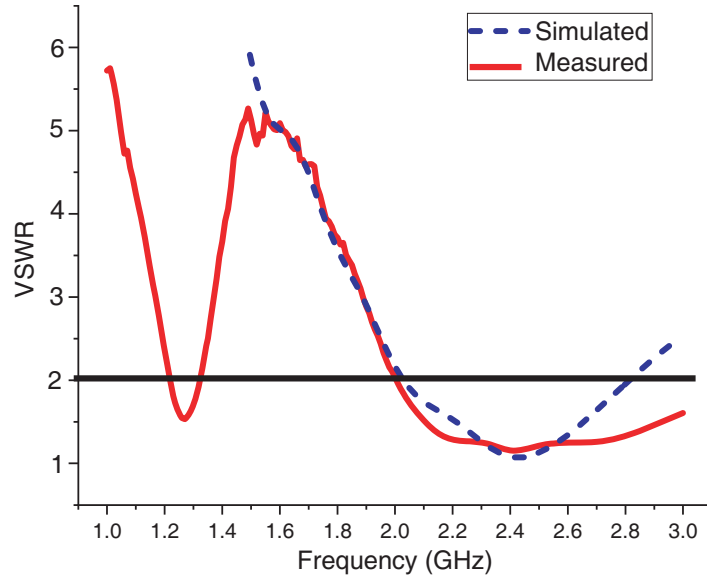


Figure 8. The measurement result of VSWR.

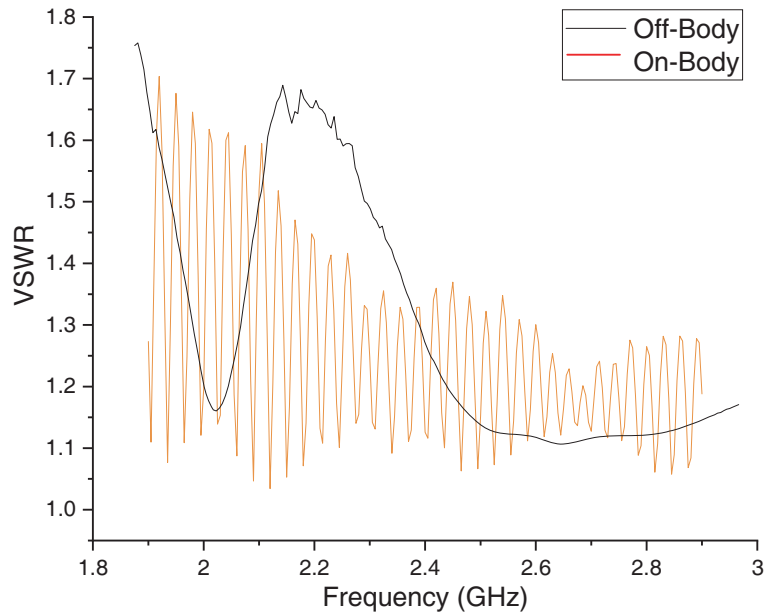


Figure 9. The measurement On-Off Body result of VSWR.

Figure 10 shows the comparison of the proposed antenna radiation pattern, between the utilization of Full Ground Structure (FGS) and Defected Ground Structure (DGS). The pattern shows a consistent unidirectional characteristic. However, radiation pattern with DGS inherits a higher back lobe level. The body's primary influence on the antenna's performance has signaled interference, distorted radiation pattern, shifting in the resonant frequency, also a reduced gain and radiation efficiency [23, 26–28]. Spatial, temporal, and polarization patterns are crucial parts of the electromagnetic environment because they influence the extent of biological effect when the antenna is operated near the body [23]. Also, the DGS method plays an essential role in this proposed antenna parameter, as explained in [29].

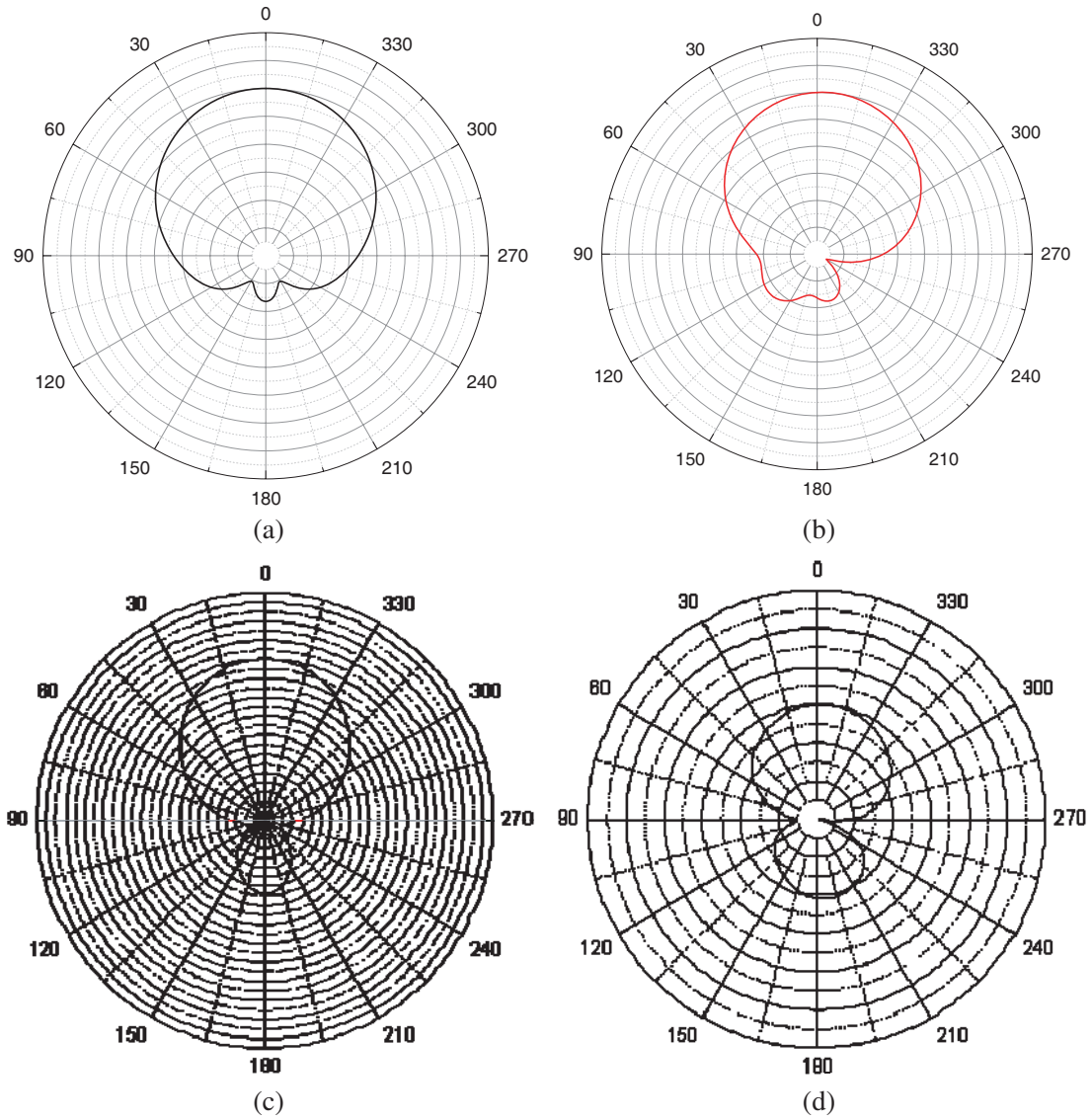


Figure 10. The radiation pattern of a proposed antenna. (a) FGS *H*-plane. (b) FGS-*H*-Plane. (c) DGS *H*-Plane (d) DGS *E*-Plane.

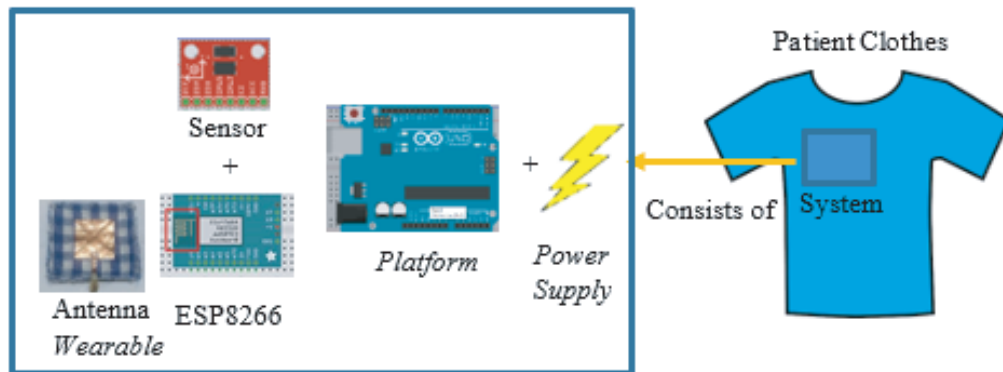


Figure 11. Antenna placement on the patient’s clothes.

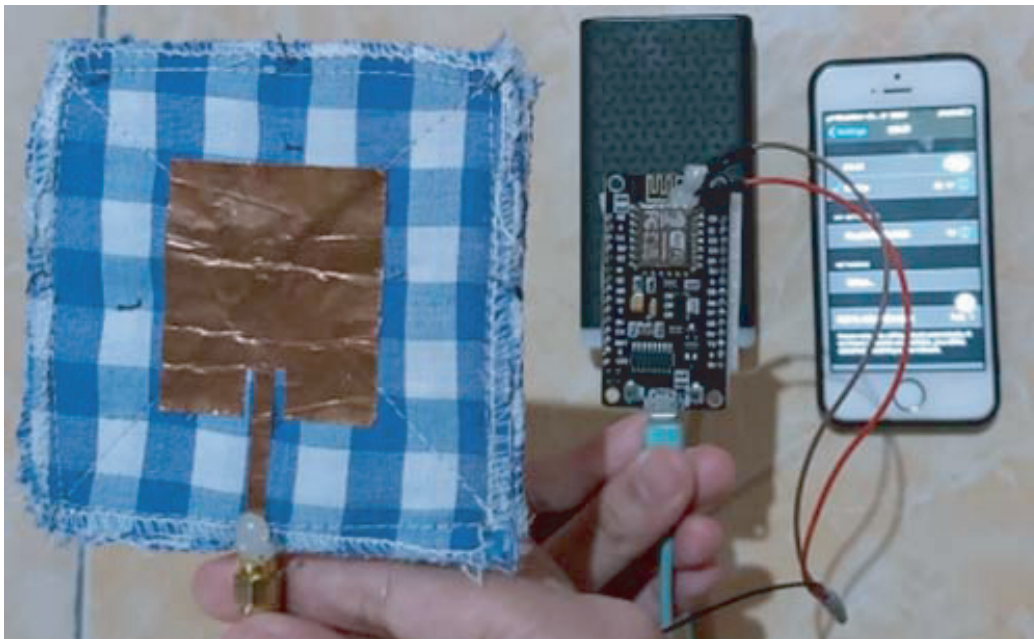


Figure 12. Propose antenna integrated with ESP8266.

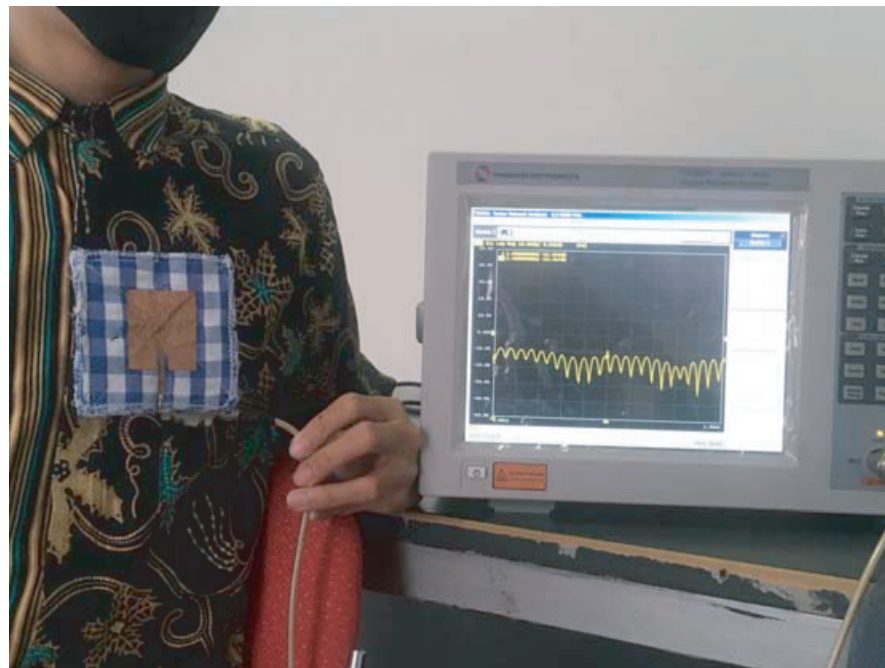


Figure 13. Indoor test of the proposed antenna as a transmitter.

3.3. Integrated of ESP8266 Wi-Fi Module

The antenna is attached to the patient's garments on the top of his chest, as shown in Figure 11. With a higher gain than 2 dBi, the proposed antenna can be used as a replacement antenna in the ESP8266 Wi-Fi module. We discovered that the existing antenna previously had an identical input impedance of



Figure 14. Outdoor test of the proposed antenna as a transmitter.

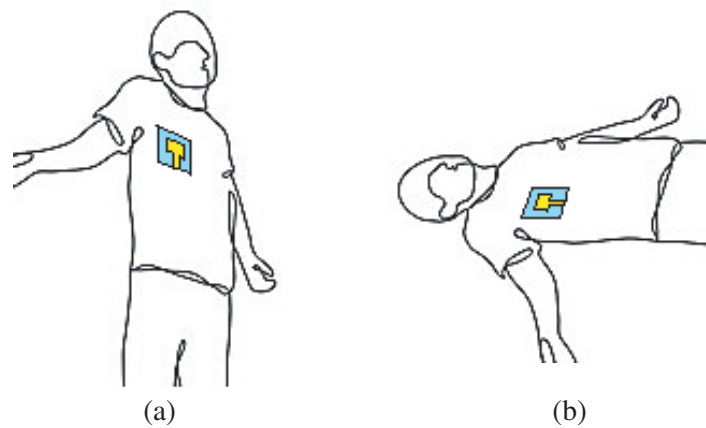


Figure 15. Antenna measurement position. (a) Vertical. (b) Horizontal.

50 to this integrated approach [30]. As indicated in Figure 12, the antenna communicates information to the specialist’s smartphone.

Figures 13 and 14 show the proposed antenna’s measurement process for line-of-sight indoor and outdoor conditions. The process is calculated by measuring the proposed antenna until it reaches the end of the connection with the ESP8266 Wi-Fi module.

Figures 15(a) and (b) illustrate how vertical and horizontal antenna locations are measured while the patient is standing, sitting, or sleeping. The received signal is represented by three bars, indicating that the gadget’s antenna can receive it. This condition is split into two categories: Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS), along with their respective horizontal and vertical positions.

Three different measurements were taken during the day throughout the morning, afternoon, and evening. The data were collected for three days. Estimates were made during daytime and nighttime due to different air conditions.

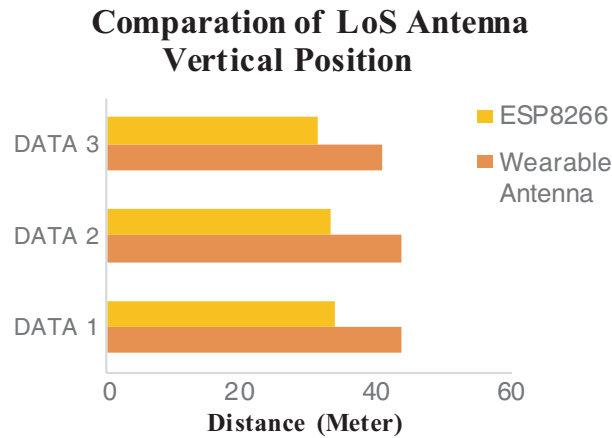


Figure 16. Examination graph in the Line-of-Sight condition of vertical antenna position.

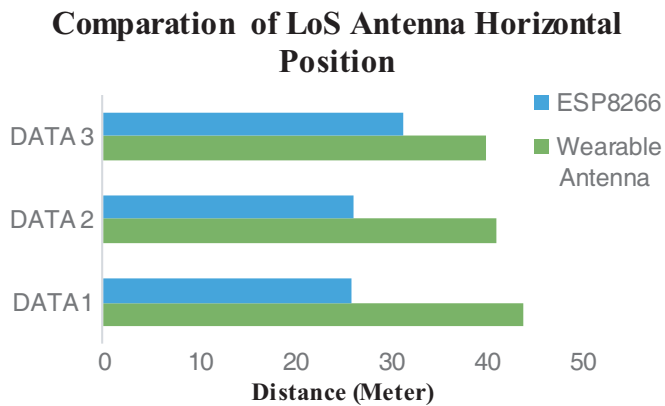


Figure 17. Examination graph in the Light of Sight condition of horizontal antenna position.

Figures 16 and 17 indicate the distance parameter between the receiver phone and both transmitter antennas, the wearable antenna and the ESP8266 Wi-Fi Module antenna, respectively, in a Line-of-Sight scenario. The measurement procedure is used to estimate the Wi-Fi signal strength on the device. The first process is taken in the morning, the second in the afternoon, and the third in the evening.

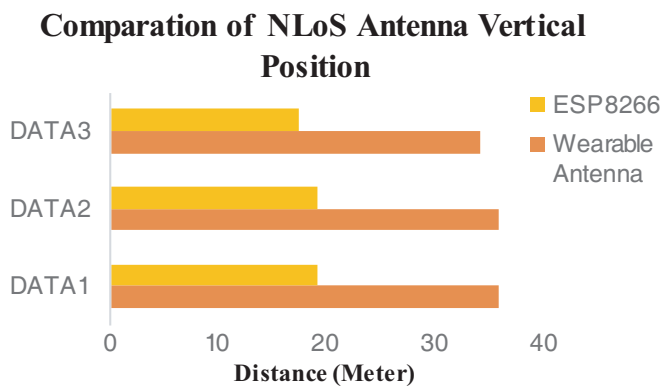


Figure 18. Examination graph in Non-Line-of-Sight condition of vertical antenna position.

The antenna’s vertical position measurement results include the first measurement of 9.839 meters higher than the antenna module; second, over 10.333 meters; and third, surpassing 9.337 meters. The conditions are identical to those in the vertical position in the horizontal position. The first measurement exceeds the present antenna by 18 meters, followed by the second and third measurements, which exceed 14.837 and 8.67 meters, respectively.

The graphs show a decrease in the vertical and horizontal distance of the last measurement. The first and second estimations have relevant results. Figures 18 and 19 represent the measuring process under the Non-Line-of-Sight condition. These two graphs demonstrate a constant decrease in the distance in the third measurement. For the first measurement, the antenna in a horizontal position achieved a range of 9.333 meters, more significant than the ESP8266 Wi-Fi Module; second, over 8.8333 meters;

Table 6. Journal from the previous study.

Journal	Description	VSWR	Gain (dBi)
[31]	This paper explains that a low-profile wearable planar antenna is designed and proposed to observe vital human signs using WBAN technology constantly. Operates in 2.45 with polyester as substrate.	1.848	7.81
[32]	This previous study is about a microstrip antenna with a simple rectangular patch that operates at 2.4 GHz. They do experiments with different types of material as their subtract. One of them is polyester. They also provide two conditions on and off the body.	1.292 (On-Body) & 1.166 (Off-Body)	4.871 (On body) and 4.783 (Off body)
[33]	The journal is considering designing a wearable textile antenna for medical and health applications and is calling it an intelligent apron. The proposed antenna is using conductive stainless-steel thread, sewn on polyester as substrate. It operates at 2.4 GHz (ISM band) used for the industrial and medical fields. This garment can be used in hospitals to exchange data between medical services.	1.433 (at 1.5 GHz–2.0 GHz)	–11
[34]	The proposed antenna uses a polyester substrate with permittivity of 1.44 and thickness of 3 mm. The structure is low profile and suitable for medical application	1.162	6.0
[35]	This paper discussed a monopole-based antenna with two triangles cut at the bottom corners and a few parallel slots cut at the top edge of the radiation patch, respectively, to obtain small form factor and ultrawide bandwidth. The proposed antenna is made of conductive copper taffeta and polyester textiles. These materials can be obtained easily the market. As a result, the prototypes are well suited to wearable applications, where flexible components must adhere to the curved human bodies. It operates between 1.198 to 4.055 GHz.	1.671	2.9

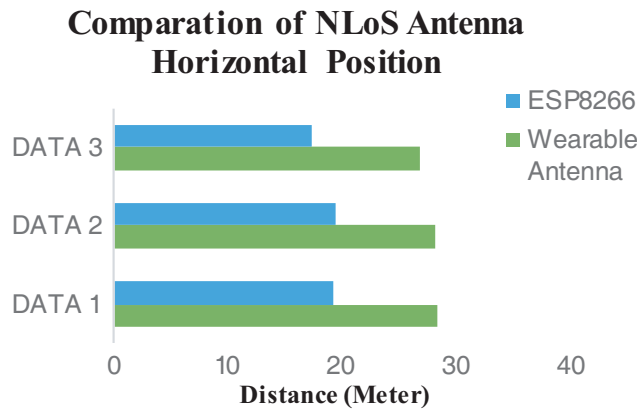


Figure 19. Examination graph in Non-Line-of-Sight condition of horizontal antenna position.

and third, surpassing 9.4997 meters.

The vertical position is similar to a horizontal position. The substitute antenna's first measurement is 17.167 meters greater than the original antenna, followed by the second and third measurements, which are over 17 and 17.003 meters, respectively. To provide additional perspective, in Table 6, we provide references to other articles with similar functional and substrate, health monitoring, and polyester. These references illustrate a range of VSWR and gain values. The proposed antenna performance for the VSWR parameter is the same as theirs, which is less than 2. The gain parameter includes a high level in comparison between them.

4. CONCLUSION

A wearable textile rectangular patch antenna is introduced in this paper, with all the adjustments of transmitter antenna dimension alongside inset feed and DGS method utilized. The antenna is operated in the ISM band of 2.4 GHz. The gain values of simulated and measurement are higher than 2 dBi, 6.953 dBi, and 6.829 dBi, respectively, with or without flat phantom. Furthermore, make the antenna suitable for replacing the ESP8266 antenna module for medium-range communication. However, for future works, the characteristic of the bent proposed antenna will be measured and analyzed.

ACKNOWLEDGMENT

This research has been supported by the Research Center of Electronics and Telecommunication Indonesia Institute of Sciences to provide measurement facilities.

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