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Development of wearable textile patch antenna 2.43 GHz for biomedical applications

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Abstract

A body area network (BAN) is classified within the Personal Area Networks (PANs) spectrum and enables communication between devices positioned on the human body. BANs play a pivotal role in medical applications, notably in the continuous monitoring of a patient's health and the documentation of their medical history. Consequently, medical wearable products, such as textile antennas, have emerged as a leading area of research, posing significant challenges for researchers in this field. In this article, the design and implementation of a microstrip wearable patch antenna (WPA) with a rectangular configuration for use in medical applications were presented. The WPA was engineered to function at 2.43 GHz, and its capabilities for monitoring, issuing alerts, and facilitating requests for assistance during medical emergencies were demonstrated. The testing and modeling outcomes affirmed that the antenna met the criteria for compact size and extensive bandwidth capabilities. The design's practicality was enhanced by the incorporation of washable fabrics and the integration of conductive threads into the conductive elements. The innovation of the proposed WPA was found in its flexibility, lightweight design, ease of manufacturing, cost efficiency, and seamless integration into medical practices. The design process of the WPA included the utilization of the computer simulation technology (CST) software package for simulating the antenna, which was based on theoretically calculated dimensions. Subsequently, prototype samples were fabricated. The performance evaluation, particularly the measured results of the reflection coefficient (S_{11}), confirmed the antenna's effective operation, with a radiated gain of 7.8224 dB being achieved at the operating frequency of 2.43 GHz. Moreover, these findings revealed that the performance of the wearable antenna was influenced when it was positioned on the human body, yet it remained suitable for a variety of medical diagnostic and monitoring applications.

Keywords

Wearable antenna, Biomedical, Micro-strip antenna, CST, Reflection coefficient.

1.Introduction

Wearable technology combines electronic and computer technologies into clothing or devices for daily wear. Wearable devices include spectacles, watches, jewellery, caps, and textiles. These gadgets can do functions like smartphones and computers, as well as offer sensory, tracking, and scanning capabilities. This is a significant advancement in pervasive computing, allowing access to information from any location [1, 2]. Textile architectures feature inbuilt antennas have proven to be a vital feature of wearable device, allowing garment-based wireless communication [3]. Wearable devices can serve as monitoring systems for assisted living and life care (among other applications). When these monitoring systems are combined with textile clothes, they form wearable textile systems [4, 5].

Antennas have long been utilized in a variety of medical applications, including microwave imaging, medical implants, hyperthermia therapies, and remote wellness monitoring. In general, an antenna is a device capable of receiving and transmitting electromagnetic waves [5, 6]. In communication systems and search engines, micro-strip patch antennas are commonly used to create required communication links for biomedical equipment.

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Attractive qualities of micro-strip antennas are low profile, easy to use, lightweight, and cheap of production. The benefits of a compact low-cost feed network are achieved. At the last decade is widespread using micro-strip antenna in books and publications [7, 8].

Medical antennas serve two primary applications: therapeutics and diagnostics. In therapeutic scenarios, the antenna is either embedded inside the human body or in direct contact with the skin [9]. On the other hand, in diagnostic applications, the antenna is positioned entirely outside the body, either in direct contact or worn as a wearable device [10, 11]. *Figure 1* shows scenarios of wearable antenna for biomedical applications.

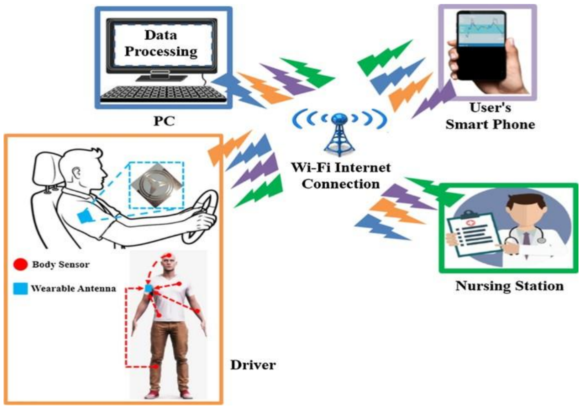


Figure 1 Wearable antenna for biomedical applications [11]

Among a variety of antenna topologies, textile patch antennas are the most common for wearable applications. These antennas are ideal for wearable applications due to their flat configuration, uncomplicated design, adaptability, lightweight, and effortless incorporation into any attire [3, 12]. The design of a wearable patch antenna (WPA) incorporates an insulating fabric substrate positioned in the gap between the conductive patch and the conductive ground plane. Additionally, the inclusion of a conductive ground plane layer mitigates potential adverse effects on the skin arising from the back radiation of the antenna [12, 13]. The development and optimization of WPA present researchers with various challenges, including issues related to flexibility, compact size, and integration with textiles, frequency band coverage, and power consumption. Overcoming these challenges necessitates collaborative efforts across different research disciplines to produce WPA that are not only efficient and reliable but also user-friendly [14]. These antennas are made up of a textile conductive element and a substrate made of another textile material [15]. They're light, flexible, simple to make, fairly priced, and simple to incorporate into a garment. Textile antennas are being developed and are capable of many jobs such as monitoring, alerting, and asking for help at any time of hospital emergency is required, thus reducing labor and resource requirements [16].

The wearable device becomes more popular especially nowadays, in the medical field where the doctor can track their patients' conditions and monitor their activities remotely. Those devices contain an antenna to exchange the data with the monitoring system [16]. Therefore, the design antenna is very important to guarantee the wearer is comfortable without affecting the antenna's performance [17]. Reports suggest that textile materials can be utilized as substrates for antennas designed specifically for medical purposes. These antennas are expected to meet the criteria of a broad operating bandwidth, compact size, wash-ability, and flexibility, aligning with the applications outlined in the pursuit of their utilization [18, 19]. This paper showcases the design and fabrication of a rectangular-shaped microstrip WPA for medical applications, implemented through fiber casting. The WPA is characterized by its small size, lightweight, ease of manufacturing, and high reliability. It is specifically engineered to operate at 2.43 GHz, providing noteworthy capabilities in monitoring, issuing alerts, and seeking assistance during emergencies within a hospital setting.

The remainder of this work is organized into six sections. Section 2 explores into existing work in the same field, offering insights into previous research. Section 3 provides a comprehensive overview of the methods applied. In Section 4, the results are discussed. Section 5 synthesizes all the findings, including a discussion of the key outcomes and insights gained from the research. The paper concludes in Section 6.

2.Literature review

Numerous researchers are currently focused on addressing the intricate challenges associated with installation. Specifically, in the design of textile antennas, careful consideration is given to meeting the electromagnetic requirements of textile materials, particularly permittivity and loss tangent [19, 20]. Today, wearable antennas are considered one of the hot topics in medical applications that attracts the attention of researchers. In [18], advocacy was made for textile patch antennas featuring various shapes such as rectangular, triangular, and circular, operating within the frequency band of 2.4–2.5 GHz. Simulation results demonstrated robust performance even under bending conditions. The design and implementation of a double-band, small-shape wearable antenna is presented in [21, 22]. Tailored for the industrial, scientific, and medical (ISM) band spanning frequencies between (2.45 to 5.8) GHz, this design utilized denim as the base material and employed a radiating element crafted from copper tape. The effect of bending on the use of a rectangular textile antenna is explained in [23]. Within the 2.4 GHz range, this antenna finds use in the industrial and medical domains. Denim fabric serves as the antenna's base, while layers of polyester fabric coated in copper and nickel make up the layers above it. The bending characteristics of the antenna were evaluated by the authors at the wrist, arm, and chest, among other places. They illustrated the bending impact based on the radius are 39, 45 and 55 mm. Where the antenna is connected to a human arm [24]. The investigation into a monitoring system employing a vest integrated with a flexible ultra-wideband (UWB) antenna is introduced by [25], this design for the identification of potential breast malignant tumors. The concept relies on discerning variations in the radio signals received from multiple UWB antennas strategically positioned around the breast. In [26, 27], four wearable UWB antennas are scrutinized for their ability to detect tumor cells placed in diverse locations within a heterogeneous phantom. These antennas operate within the bandwidth range of 4.90 GHz to 15.97 GHz. The presented results include a comparison between the measured and simulated outcomes, illustrating the effectiveness of the concept based on the penetration and propagation of electromagnetic waves within the breast phantom. Most previous works discussed the WPA concerning the ISM bands, this paper proposes a developed antenna micro-strip WPA of rectangular shape operates in the 2.43 GHz for biomedical applications and provides a high capability of monitoring, alerting, and demanding help and interest, whenever hospital emergency is needed. Recent improvements in bio-embed antennas with various shapes are discussed in [28]. They introduced the summaries of design needs, the dimensions, antenna configurations, and features for the ISM and medical implanted communication system (MICS) bands. A configurable fractal antenna tailored for wearable applications and capable of supporting frequencies at 2.4 GHz and 5.2 GHz was introduced by [29]. A circular polarization antenna is proposed by [18, 30, 31]. This antenna is implanted and designed to operate in the 2.45 GHz ISM band with an appropriate feeding scheme. It has been utilized in the medical industry, particularly about cardiac pacemakers. A description of the development of a biological sensor with an implanted antenna can be found in [32]. Incorporating a compact embedded antenna that operates within the 2.4 to 2.48 GHz ISM band. The testing involved subjecting the antenna to a human tissue model, employing magnetic negative characteristics (MNG) in Rogers 6010 as demonstrated in [33]. In [34], four distinct models of a 2.4 GHz flexible micro-strip patch wearable antenna are formulated and assessed. The antenna designs incorporate a substrate material of 3-mm-thick wash cotton textile, which is also utilized for the electromagnetic band gap (EBG) surfaces. For conductivity in the proposed antennas, an electro-textile material known as Zelt is employed. The three-dimensions (3D) description of antenna radiating architectures, as proposed by [35], is acknowledged to be more difficult, the theoretical requirement often leads to extended measurement times, especially for antennas situated on electrically massive objects. Precisely aligning the antenna with the measuring device has potential to enhance the low frequency section of the antenna. In [36, 37], the metasurface technique is presented, aiming to enhance return loss, gain, and radiation patterns. The design is intended for operation within the 6 to 14 GHz range, comprising three layers: a copper patch for radiation, a felt substrate, and a ground copper layer. The overall structure thickness is 4.68 mm, and it has successfully achieved a gain ranging from 7.33 to 7.4 dBi. Suggested building a textile patch antenna with (49×51) mm dimensions that is intended to function at 2.45 GHz [3]. The selection of textiles with excellent conductivity, air permeability, and a multitude of minuscule perforations to increase antenna flexibility was carefully considered [38]. Featuring radiation gains of (4.2 and 5.4) dBi in the E-plane and H-plane respectively. Described a dual-band patch antenna intended for wearables [39]. The antenna is 44mm×41mm and can dynamically modify its frequency, making it ideal for wireless body area network (WBAN) applications. It emits a bidirectional radiation pattern at 2.4 GHz and a directed pattern at 5.8 GHz. At these frequencies, the antenna achieves gains of 4.84 and 5.87 dBi, respectively. The antenna's performance was assessed using a human tissue model [39]. Unveiled a new concept: a hexagonal ring wearable antenna designed and manufactured exclusively for WBAN applications [40, 41]. The prototype design achieved a 2.5 dB gain at 3.5 GHz, which was in great agreement with the simulated findings. The author also proposed a unique method for monitoring and detecting bone health. In [42], a textile wearable antenna for the 2.45 GHz ISM band is introduced. This antenna uses a monopole radiator and is designed primarily for medical applications. The 35.4×82.4 mm² design was tested on the human body and showed a significant 7.46 dBi gain. Furthermore, the research presents a specific absorption rate (SAR) analysis, with the results confirming the embedded design's viability for integration into wearable devices.

Researchers have primarily concentrated on traditional designs utilizing textile materials and inkjet/screen printing methods. While demonstrating certain positive results [36, 43], these efforts have not effectively tackled all the mentioned challenges. Therefore, given the recent progress in wearable antennas and their utilization in WBAN systems, it is essential to reevaluate and enhance current approaches to discover solutions for these challenges. Designing wearable antennas poses several challenges that researchers and engineers need to address. Some of the key challenges in wearable antenna design include: limited size, Integration with clothing and materials, flexibility, and frequency band considerations therefore addressing these challenges requires a multidisciplinary approach, involving expertise in antenna design, materials science, electronics, and human factors engineering. Ongoing research and technological advancements continue to contribute to overcome these challenges in the field of wearable antenna design [42].

3.Materials and methods

This paper introduces the steps for designing and building the micro-strip WPA, along with the final measurements. The progress of this work could be illustrated as follows; first, mathematical numerical design depending on the existing equations based on the literature. Second, simulation and optimization using computer simulation technology (CST) software package modeling. Third, building micro-strip WPA as a prototype. Finally, the comparisons between the implemented and simulation antenna are implemented based on measuring their characteristics.

3.1Design and modeling of micro-strip WPA

Numerical design of a micro-strip antenna is a straightforward process, since its design procedure available in antenna textbooks and handbooks. Interestingly, the effect of the surroundings must be taken into consideration, it has an effects on the total performance of the antenna [42, 44]. Hence, simulation model must be run to study these effects, and adjust the design to counter these changes. Hence, the procedures outlined for the creation of this antenna in this study involve numerical design, simulation, and optimization [45].

In this section, the design of micro-strip antenna is presented. The stage of designing this antenna depends on the sequence of equations that are presented in this work. The materials used in this design are conductive cloth made of copper, nickel and polyester threads. The substrate is made of a clothes adhesive material with relative permittivity of ε_r = 1.175 and thickness h = 1.4 mm. The suggested antenna operating frequency is 2.43 GHz. This frequency is suggested due to its popularity since it is used in many wireless communications techniques such as WiFi, Bluetooth, and Zigbee. Hence, the design procedure is mainly to obtain the important dimensions of micro-strip antenna such as W and L.

- The width that leads to good radiation efficiencies is determined by applying Equation 1 [18, 46].

$$W=\frac{1}{2fr\sqrt{\mu_\circ \varepsilon_\circ}}\sqrt{\frac{2}{\varepsilon r+1}}=\frac{\upsilon_\circ}{2fr}\sqrt{\frac{2}{\varepsilon r+1}}=\frac{30}{2*2.4}\sqrt{\frac{2}{1.175+1}} \quad (1)$$

v_0 is the speed of light and it is around 3×10^8 m/sec. Thus, W=5.99 cm.

- To determine L, the constant of effective dielectric of the micro-strip antenna must be determined by using Equation 2:

$$\mathcal{E}_{eff}=\frac{\mathcal{E}r+1}{2}+\frac{\mathcal{E}r-1}{2}\left[1+12\,\frac{h}{w}\right]^{-12} \qquad (2)$$

$$\mathcal{E}_{eff}=\frac{1.175+1}{2}+\frac{1.175-1}{2}\left[1+12\,\frac{1.4\ x\ 0.1}{5.9932912686}\right]^{-12}$$

$$\mathcal{E}_{eff=}\ 1.65$$

- Inserting W, h, and ε_{eff} determined previously, the extension of the length ΔL can be determined as Equation 3:

$$\frac{\Delta L}{h}=0.421\frac{(\mathcal{E}eff+0.3)\left(\frac{W}{h}+0.264\right)}{(\mathcal{E}eff-0.258)\left(\frac{W}{h}+0.8\right)} \qquad (3)$$

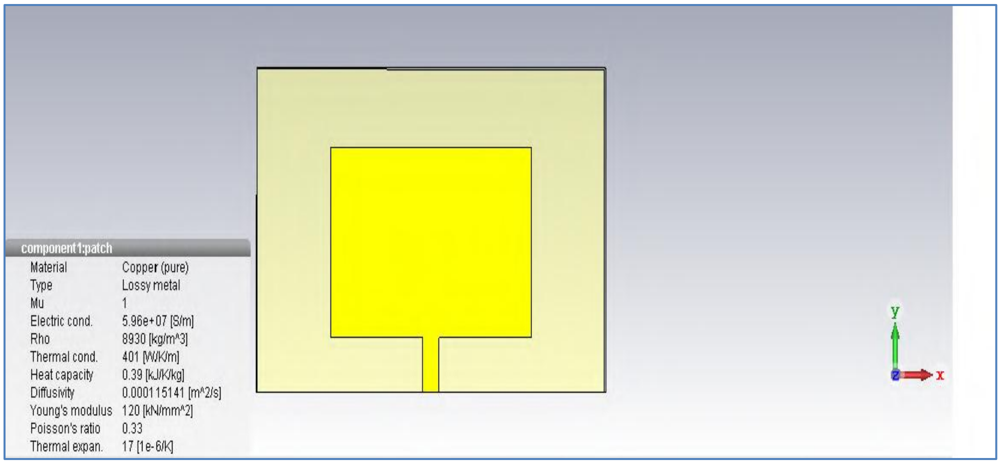
Hence, ΔL = 0.83 cm

- Finally, the length L of the patch can be established through the process of solving Equation 4:

$$L=\frac{1}{2fr\sqrt{\mathcal{E}eff\sqrt{\mu_\circ \mathcal{E}_\circ}}}-2\Delta L \qquad (4)$$

L= 4.12 cm

The first step is building the initial prototype mode using the CST software package, with the parameters (L=4.12, *W*=5.99 cm). CST studio suite provides an extensive array of tools dedicated to the design, analysis, and optimization of antennas and it is based on the finite integration technique (FIT) [44]. As the antenna is crafted to function in close proximity to the human skin. The prototype antenna mode is shown in *Figure 2*, which consists of a patch pattern of rectangular shape. To simplify the model, copper material is used to model the fabric, since it is expected to show the ignorable effect on the overall results.


component1:patch

Material	Copper (pure)
Type	Lossy metal
Mu	1
Electric cond.	5.96e+07 [S/m]
Rho	8930 [kg/m^3]
Thermal cond.	401 [W/K/m]
Heat capacity	0.39 [kJ/K/kg]
Diffusivity	0.000115141 [m^2/s]
Young's modulus	120 [kN/mm^2]
Poisson's ratio	0.33
Thermal expan.	17 [1e-6/K]

Figure 2 Micro-strip patch antenna CST model

Secondly, three layers of human body (skin, fat and muscle layers) model are added to the design model to investigate the changes due its presence on the antenna performance. Because of the various and loss characteristics of the body, the operation of an antenna is affected when positioned nearby. As a result, the antenna's performance is initially assessed in free space before undergoing testing in an on-body flat section. To achieve this objective, a tri-layered body model is created using CST, comprising muscle, fat, and skin [39, 47] as illustrated in *Figure 3*. The permittivity and conductivity values at 2.4 GHz are as follows: muscle (ε_r =52.79; σ=1.705), fat (ε_r=5.28; σ=0.1), and skin (ε_r=31.29; σ=5.0138). The respective thickness of the fat, skin and muscle layers is 8 mm, 2 mm and 23 mm as shown in *Figure 3*.

Finally, it is important to investigate the effect of antenna bending due to its flexibility on its performance. When antennas are positioned on the body, the bending leads to a decrease in the impedance of the antenna. This, in turn, induces a slight changing of the resonance frequency and a decrease in return loss. It is noteworthy that, when bent, the metamaterial-moved antenna exhibits a relatively favorable return loss compared to conventional antennas [48]. Two bending scenarios have been studied by θ =10, bending alongside W, and L. The bending models are shown in *Figure 4*.

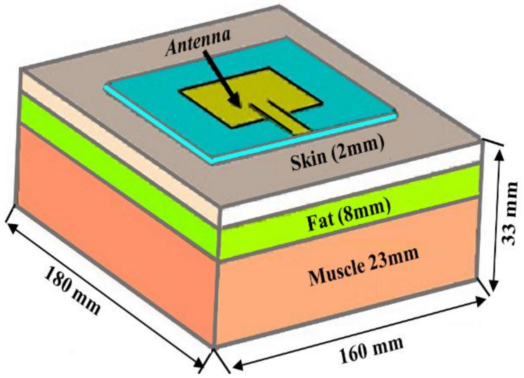
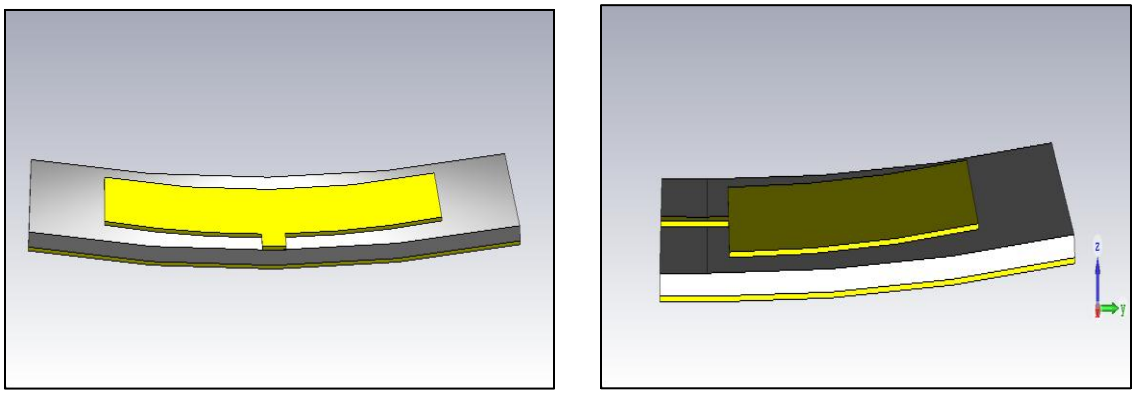


Figure 3 An antenna is affixed to the flat-body phantom resembling the human body [47]

4.Results

4.1Experimental and simulation for micro-strip WPA in free space

In this stage, the obtained parameters in the previous sub-section are used to build a micro-strip patch antenna using CST software package free space conditions to evaluate the performance of WPA and its dependence on the proposed materials. However, wearable antennas are susceptible to other materials effects, mainly the human body, which would affect the total impedance characteristics of the antenna environments, causes shift in operating frequency as well as radiation pattern. In addition, the antenna is made of flexible materials, which are subjected to bending and shape distortion, which results into additional characteristics changes. Therefore, the simulation procedure can investigate the antenna in free space environments, attached to a portion of human body model, and under bending conditions. Finally, an adjusted design can be extracted from all these simulations which is used to build the final practical prototype that would be used in the experimental measurements.



(a) (b)

Figure 4 Antenna bending (a) alongside W, (b) alongside L

Figure 5 shows simulated reflection coefficient (S_{11}), which is a parameter that depicts the reflection of electromagnetic wave by an impudence discontinuity in transmission medium. It shows that the operating frequency is f_r =2.43GHz, with improving in bandwidth BW =3.509% and the target was to get maximum power in 2.43 GHz frequency. These results are in good agreement with the intended design parameters.

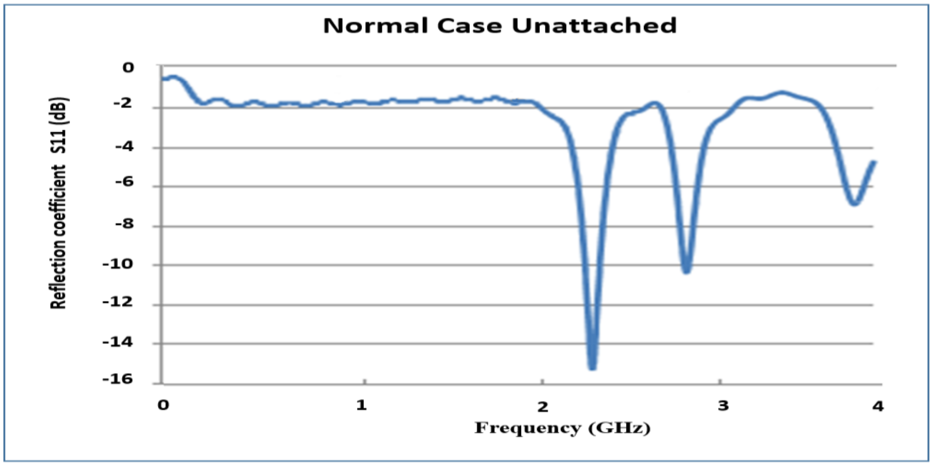
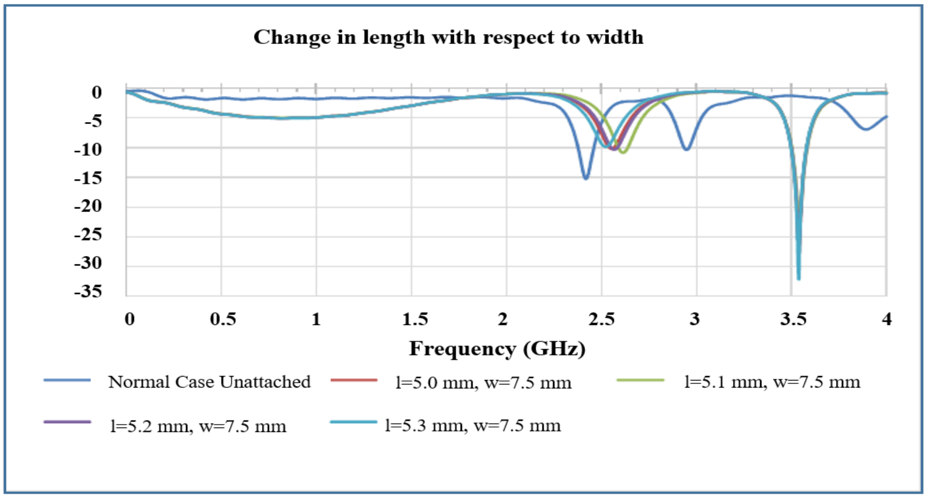


Figure 5 S_{11} of Micro-strip patch antenna model using CST in free space conditions

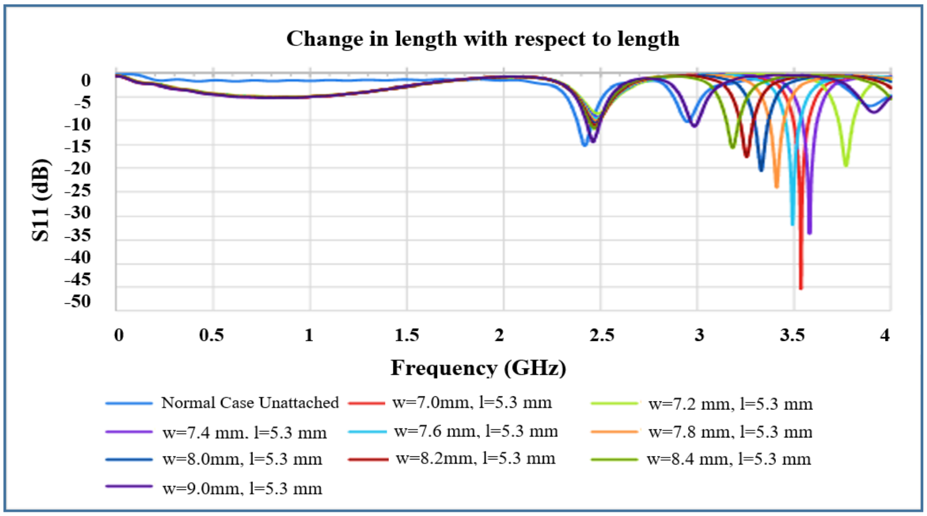
As expected, the operating frequency has shifted due to the added layers effect. Hence, an optimization process is conducted to adjust both *L* and *W of* micro-strip antenna to achieve model that have targeted parameters. This can be achieved by using parameters sweeping in CST software package, which changes a parameter and perform simulation for each case to compare the results. Therefore, the designers can choose the best-case scenario, in which the length *L* was optimized at first with the original *W*, and a parameter sweeping was performed for *W* in which *L* from the first process was used. The results of these simulation are illustrated in *Figure 6*, which shows that the new parameters are *L* = 5.3 cm and *W* = 9 cm. *Figure 6* demonstrates the effect of changing the antenna dimensions for the S_{11} when the antenna near the body compared with original design in free space. The following step is to investigate the effect of different body sizes, since it is expected that this antenna would be worn by different people with different body sizes. Hence, a simulation is run for changing body fat thickness. The results are illustrated in *Figure 7*, it shows that the change in body fat thickness has a negligible effect on the S_{11}. This result is expected due to the impedance of the human skin that has high impedance value at 2.45 GHz.

4.2Simulation results for micro-strip WPA under bending

Figure 7 explains the response of the antenna due to the bending for x- and y-axes over the WPA both cases, two bending scenarios are studied by θ =10 degree, bending alongside W, and alongside L mentioned by *Figure 4*. The bending models are shown *Figure 8* caused shifting in operating frequency by 7 MHz for the prototype design under the not - bending, therefore, WPA exhibits a better performance in comparison with [18]. The total radiated gain of simulated micro-strip WPA is 7.8224 dB as illustrated in *Figure 9*. The total gain represents an agreement value compared with standard result of rectangular patch antenna.



(a)The effect of changing the length



(b) The effect of changing the width

Figure 6 Parameters optimization for the antenna dimensions for countering human body effects on operating frequency

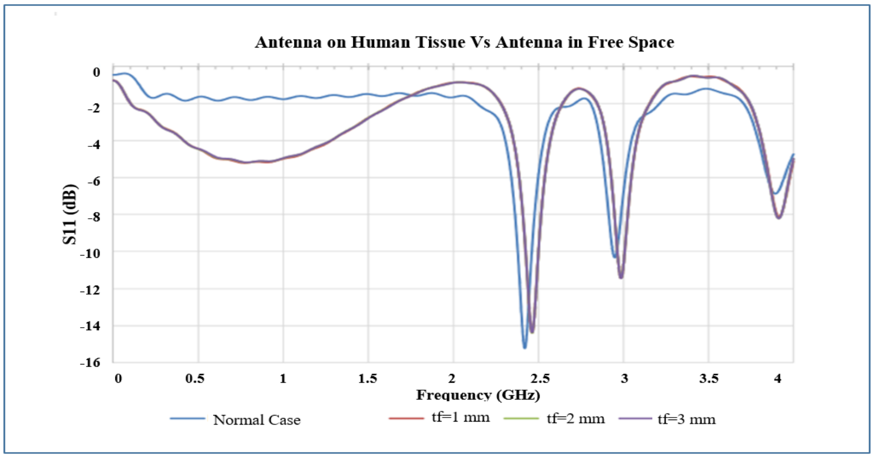
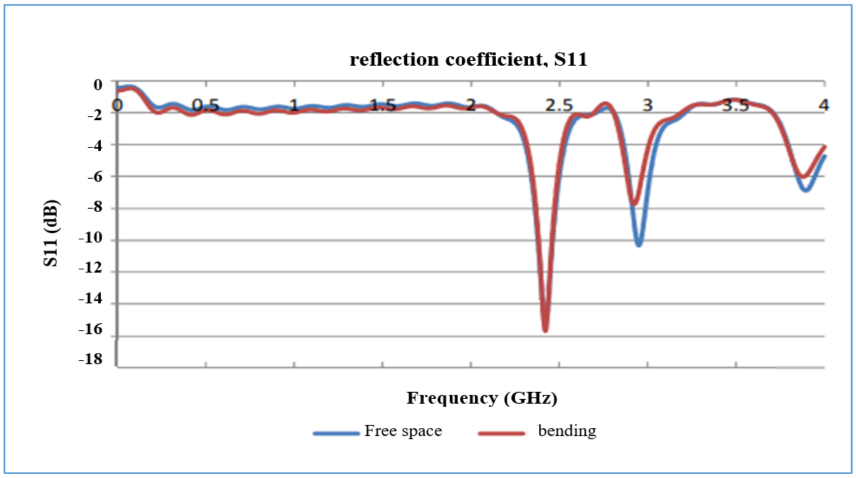
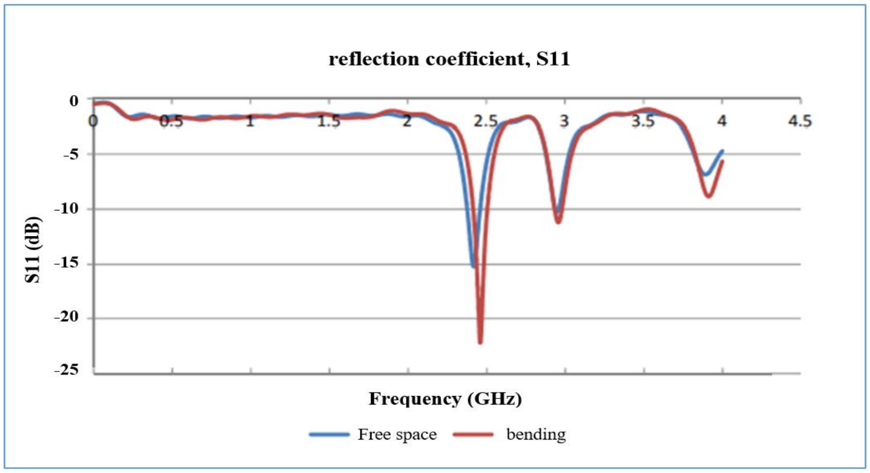


Figure 7 Changes fat thickness of the antenna performance compared to antenna in the free space



(a)W Bending



(b)L Bending

Figure 8 Bending effect on S_{11}

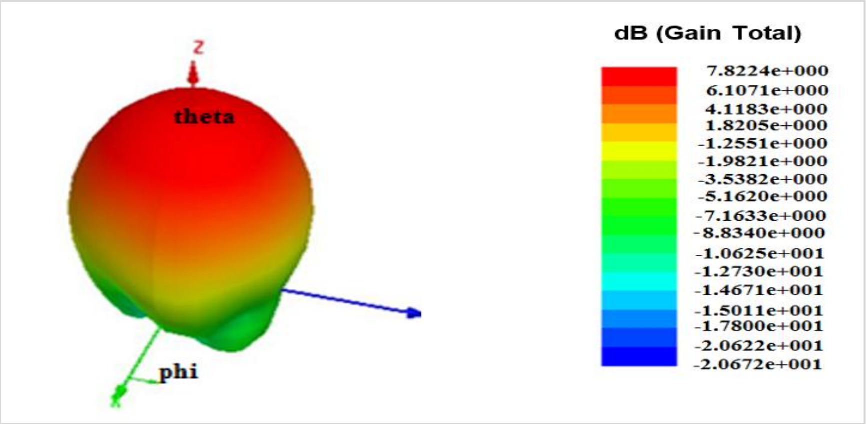


Figure 9 3D radiation pattern of micro-strip WPA

4.3Experimental and practical mode of micro-strip WPA

On the bases of using data obtained in the previous section of simulation results of micro-strip antenna designed, a prototype antenna is assembled as shown in *Figure 10*. The micro-strip antenna is made of flexible conductive materials such as conductive cloth is threaded on substrate which is an isolated material between the micro-strip and the ground which consists of the same connective material of the micro-strip antenna. The conductive material consists of 23% copper, 20% nickel and 57% polyester. In addition, a sub-miniature a connector (SMA) connecter is soldered to the micro-strip feed line to feed the antenna.

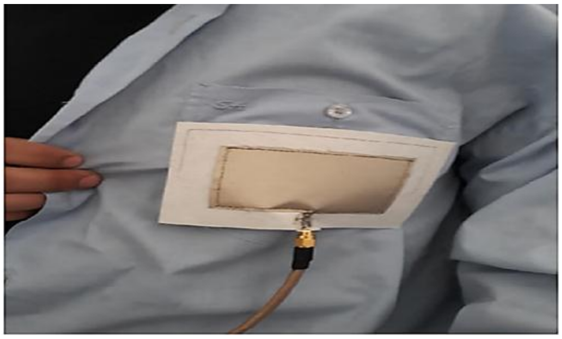


Figure 10 Micro-strip antenna prototype sewn on a shirt with SMA connecter

To validate the simulation results of the WPA prototype, measurements were performed on the fabricated antenna. Subsequently, the antenna's performance and the magnitude of the S_{11}, were tasted using the vector network analyzer (VNA) with the model ZVA 67, where the return loss of the WPA directly measured by the VNA [49, 50]. Calibration becomes necessary as the antenna needs to be connected to the VNA through a cable, which possesses its electrical network parameters and introduces additional impedance characteristics to the antenna. Therefore, the calibration process computes the cable's impedance characteristics, enabling the VNA to consider it in the antenna response calculations. After the calibration, a volunteer wore the shirt with the sewn antenna, and the antenna was subsequently connected to the VNA. The resulting center frequency of the prototype antenna is fr = 2.43 GHz, and impedance matching bandwidth is BW = 3.5094650206%. These results are in a compatible with the theoretical results of the micro-strip antenna (*Figure 11*). The practical test of manufactured WPA to measure the S_{11} at 2.43GHz. This value coincides to some extent with the theoretical design and simulation measurements, indicating that the prototype has achieved results worth noting, as illustrated in *Figure 11*.

Figure 11 S_{11} results for the worn antenna

5.Discussion

Clothing has revolutionized the field of wearable intelligent textile technology, which is easy to use like vital sign for monitoring systems and provides favourable conditions for a short-range wireless communication. Wearable antennas are substantial element of wearable designs due to their light weight, low cost, and adaptable manufacturing. So, in place of the wireless sensors, they serve as substitutes. From the previous figure, one can suggest that the results indicate that S_{11} for the micro-strip wearable antenna achieved satisfied analysis in term of S_{11} at the operating frequency is fr =2.43GHz, with impedance bandwidth BW =3.509% and the target was to get maximum power in 2.43 GHz frequency. Some of results show that the operating frequency has shifted due to the added layers effect; however, the improvement has been achieved by adjusting both L and W of micro-strip antenna. After seeing the results, the design can easily be improved through the adjustment both L and W of microstrip antenna to create a model that is able to achieve the desired goals as mentioned in the results section. On the other hand, the thickness of body fat was considered when examining the antenna based on the anatomical voxel model, (see *Figure 3*), where it can be worn of different people by body fat to guarantee high accuracy results.

The results suggest a correlation between the simulations and the practical outcomes of the proposed WPA model. Minor discrepancies occurred due to the need for calibration processes in some devices, and the consideration of cable impedance characteristics in calculations. These discrepancies could potentially be addressed in future experiments. Numerous studies are conducted previously to improve parameters like gain, size, and efficiency. *Table 1* shows works related to the suggested research based on their proximity in frequency. Typically, the frequency depends on the design and application used, here we have adopted the ISM frequency used for medical purposes. Developing WPA tailored for a particular frequency introduces distinct obstacles, including restrictions related to dimensions and the highest achievable gain to address the challenge of signal absorption by the human body. The suggested antenna demonstrates superiority concerning both size and gain, aiming to overcome these hurdles. Finally, it is necessary to consider the change in environmental conditions for textile wearable and corrosion that affects the data transmission of the electronic fabric, as it could change the resistance of the textile's surface and the radiation features of the patch antenna. A complete list of abbreviations is summarised in *Appendix I.*

Table 1 Comparison results for similar previous works

References No.	Size (mm^2)	Frequency (GHz)	Gain dBi	Year
[42]	49×51	2.45	5.4	2021
[18]	45.5×62.3	2.4 to 2.5	5.45	2021
[21]	98×109.4	2.4	7.39	2022
[23]	51×46	2.4	4	2017
[34]	49.48×55.79	2.4	6.54	2019
[37]	4.68×4.68	6 and 14	7.33	2024
[38]	35.4×82.4	2.45	7.46	2023
[39]	41.25×43.75	2.4	4.84	2023
[40]	100×100	1.5 to 4.5	2.5	2024
[42]	35.4× 82.4	2.45	7.46	2023
Proposed WPA	41.2×59.9	2.43	7.8	2024

6.Conclusion and future work

In the present study, the initial phase involved the theoretical design of the micro-strip wearable antenna. Subsequently, the obtained parameters were applied to a CST software package. A simplified model of human body layers was then incorporated into the antenna model to study its effects and to adjust the antenna parameters for the final design. The prototype antenna was fabricated considering these parameters, and the measurements demonstrated good agreement between the theoretical and practical results.

The operating frequency obtained is 2.43 GHz, as determined from the measured S_{11}. Additionally, simulation results indicated that the wearable antenna is affected by its environment, such as the human body. However, altering the thickness of the fat layer has almost no effect on the antenna's performance. Therefore, it would be suitable for anyone without significant differences in a practical environment;

this is attributed to the chosen operating frequency encountering high impedance in human skin.

The primary challenge encountered in this study was related to the soldering of the SMA connector to the prototype, which led to frequent breakages upon even minor movements during experimental testing. This issue was due to the delicate nature of the clothing material, requiring special care during soldering to prevent burning or overheating. To address this issue, a solution was implemented by attaching a small section of a thin copper layer to the microstrip line feed. The SMA connector was then soldered to this copper plate, effectively mitigating the problem.

The proposed antenna shows promise for applications in wearable electronics, emergency response, communications, and smart clothing. Its potential usage extends to the ISM band. Future research may focus more on micro-strip WPAs for various medical applications, particularly in terms of small size and bending properties.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Data availability

Not applicable.

Author's contribution statement

Each author has contributed equally to the conceptualization, methodology, design, validation, allocation of resources, preparation of the original draft, and the subsequent review and editing processes.

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Appendix I

S. No.	Abbreviation	Description
1	3D	Three-Dimensions
2	BAN	Body Area Network
3	CST	Computer Simulation Technology
4	EBG	Electromagnetic Band Gap
5	FIT	Finite Integration Technique
6	ISM	Industrial, Scientific, and Medical
7	MICS	Medical Implanted Communication System
8	MNG	Magnetic Negative Characteristics
9	PANs	Personal Area Networks
10	S_{11}	Reflection Coefficient
11	SAR	Specific Absorption Rate
12	SMA	Sub-Miniature A Connector
13	UWB	Ultra-Wideband
14	VNA	Vector Network Analyzer
15	WBAN	Wireless Body Area Network
16	WPA	Wearable Patch Antenna