Wearable Textile Substrate Patch Antennas

Eng Gee Lim, Zhao Wang, Jing Chen Wang, Mark Leach, Rong Zhou, Chi-Un Lei and Ka Lok Man

***Abstract*—The development and utilization of wearable antennas has grown rapidly in recent years for application in the miniaturization of wireless communication devices. The main advantage of wearable antennas is that they are designed as elements of clothing able to transmit or receive wireless signals. The wearable antenna system plays an important role in many fields, including tracking and navigation. This paper reviews the current state of the art in wearable antenna development, focusing on design and analysis issues. Extensive investigation is carried out into the development of wearable antennas from the past to the present. Following the review a case study is undertaken, examining the performance of a rectangular microstrip antenna fabricated on various textile substrates. In addition, to significantly reduce the size of the antenna, the short circuit pins method is proposed as an integral design component of the antenna. Using the method proposed, the antenna size has been reduced by approximately 68% (from 47.4 mm x 54.06 mm to 20 mm x 41 mm).**

***Index Terms*—wearable, textile antenna, wireless communication.**

I. INTRODUCTION

WITH the rapid development of wireless communication technology, many researchers are now paying increasing attention to the study of wireless body area networks (WBANs). WBAN links various electronic devices in and on the human body. The application of WBANs has been expanding in medical services, national defense, wearable computing, and so on. Several frequency bands have been assigned for WBAN systems, such as the Medical Implant Communication System (MICS: 400 MHz) band, the Industrial Scientific Medical (ISM: 2.4 GHz and 5.8 GHz) band, and the Ultra-wideband (UWB: 3~10 GHz) [1-3].

The wide ranging applications of WBAN's including, military, ubiquitous health care, sport, entertainment and many others have been categorized into two main areas by the IEEE 802.15.6 standard. These two areas are medical and non-medical (Consumer Electronics); shown in Table I [4].

Table I: WBAN Applications

<table>
<tr><td rowspan="13">Medical</td><td rowspan="5">Wearable WBAN</td><td>Soldier Fatigue Assessment and Battle Management (Military and defense)</td></tr>
<tr><td>Professional and Amateur Sport Training</td></tr>
<tr><td>Sleep staging</td></tr>
<tr><td>Asthma</td></tr>
<tr><td>Wearable Health Monitoring</td></tr>
<tr><td rowspan="3">Implant WBAN</td><td>Diabetes Control</td></tr>
<tr><td>Cardiovascular Detection</td></tr>
<tr><td>Cancer Detection</td></tr>
<tr><td rowspan="3">Remote control of Medical Devices</td><td>Ambient Assisted Living (AAL)</td></tr>
<tr><td>Patient Monitoring</td></tr>
<tr><td>Tele-medicine Systems</td></tr>
<tr><td rowspan="6" colspan="2">Non-Medical</td><td>Real Time Streaming</td></tr>
<tr><td>Entertainment Applications</td></tr>
<tr><td>Emergency (non-medical)</td></tr>
<tr><td>Emotion Detection</td></tr>
<tr><td>Secure Authentication</td></tr>
<tr><td>Personal information sharing</td></tr>
</table>

One of the key attributes affecting the performance of textile based antennas is related to multipath fading. This arises from a number aspects particular to the physical characteristics of a flexible antenna. In particular the relatively large movement of the human body, can produce shadowing, polarization mismatch, and undesired scattering by the body and the surrounding environment. To improve the performance and overcome multipath fading, the antenna diversity technique can be adopted for off-body to on-body communications. The diversity technique can lead to improvements in signal strength, Signal to Noise Ratio (SNR), and Bit Error Rate (BER) of a single antenna with no diversity, for a particular level of outage probability [5-6].

In addition, the effect that the human body has on the antennas performance needs to be considered, due to its close proximity to radio frequency sources in a WBAN system. The human body has a high dielectric constant and low conductivity at microwave frequencies. These material properties will have a direct, most likely detrimental effect on the gain and radiation efficiency of an antenna located on or within the human body [7]. The Specific Absorption Rate (SAR) is an essential factor for evaluation when an antenna operates on or near the human body. To protect the human

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body from radio wave exposure, antennas used in WBAN's must have a low specific absorption rate [8].

This paper reviews the state-of-the-art in wearable antennas, focusing on design and analysis issues. Extensive investigations are carried out into the development of wearable antennas from the past to the present, in two parts. Firstly, wearable antenna designs are introduced and reviewed. Secondly, using a case study, this paper also examines the performance of a rectangular microstrip antenna fabricated on various textile substrates. In addition, this work shows that a reduction in miscrostrip antenna size, of around 68%, can be accomplished using the short circuit pins method. The proposed method, reduces antenna size from 47.4 mm x 54.06 mm to 20 mm x 41 mm without significant loss of performance.

II. THE STATE-OF-THE-ART WEARABLE ANTENNAS

Wearable communication systems require that the transmitter be compact, minimize power consumption, and be optimized for signal transmission on the human body. Designing an antenna to meet these criteria is a challenging task. The design must satisfy a number of requirements including: miniaturization, as to be invisible on the body; produce an omnidirectional radiation pattern to provide transmission regardless of antenna orientation and receiver location; tuning adjustment to compensate for body effects. To meet the above requirements, some recently proposed designs of wearable antennas are described in this section.

A. Electrically Coupled LC resonator Antenna

A WBAN patch antenna operating at 2.45 GHz (ISM band), and using an electrically coupled LC (ELC) resonator was proposed by Lee *et. al.* [9]. The overall dimensions of the antenna are given as 54 mm × 45 mm × 2.4 mm, it is shown to provide a gain of over 1 dBi for the entire 2.45 GHz ISM band. The proposed antenna has an enhanced Front-to-Back ratio (F/B ratio), compared with those of a conventional patch antenna.

The proposed antenna has a two-layered substrate and consists of a rectangular patch antenna with four ELC's, as shown in figure 1. Two FR4 substrates with relative permittivity (ε_r) = 4.4 are used, with thicknesses of 1.6 mm and 0.8 mm, respectively. The size of the patch is 27.8 mm × 27.8 mm, which has a resonant frequency of 2.45 GHz. Figure 2 shows the reported return loss (S_{11}) characteristics on a body model with size 200 mm × 200 mm × 50mm and electrical properties: $\varepsilon_r = 52.7$ conductivity (σ) = 1.95 S/m and loss tangent($tan\delta$)=0.27. The simulated and measured radiation characteristics for the proposed antenna are summarized in Table II. When the proposed antenna is placed on the flat body model, the SAR value of the proposed antenna is 0.005 W/kg (1 g tissue) [9].

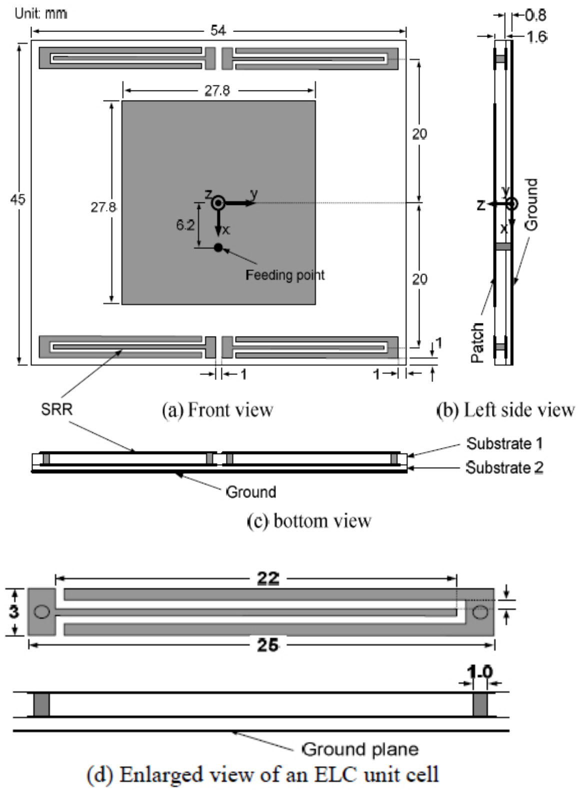


Figure 1: Configuration of antenna proposed by Lee *et. al.* [9]

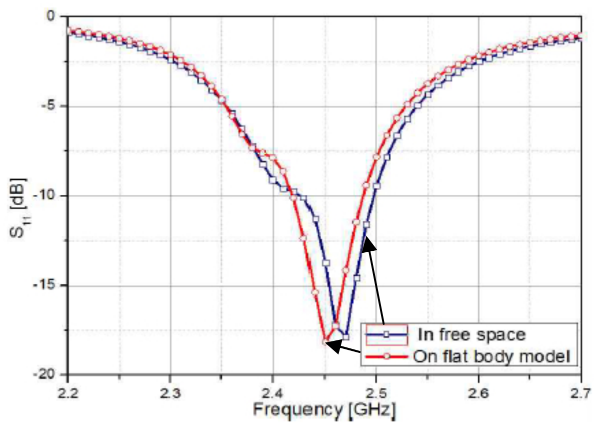


Figure 2: Simulated S_{11} characteristics of antenna on flat body model.

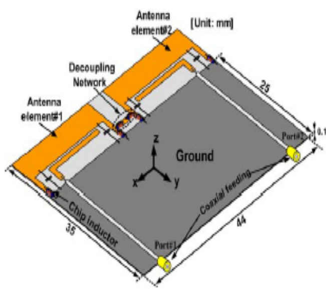
Table II: Simulated and measured results

	In free space			On flat body model		
	BW (MHz)	Peak gain (dBi)	F/B (dB)	BW (MHz)	Peak gain (dBi)	F/B (dB)
Simulated	170	2.6	34.8	160	2	21.7
Measured	50	2.0	34.6	60	1.7	19.2

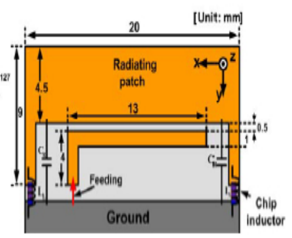
B. Flexible diversity zeroth-order resonance antenna

A flexible diversity Zeroth-order Resonance (ZOR) antenna for WBAN applications in the ISM band (2.45-2.485 GHz) has been proposed by Lee *et. al.* [11]. To antenna achieve flexibility and a compact size, a flexible substrate with a thickness of 0.127 mm and the ZOR technique are used. A pair of antenna elements is placed on the substrate with a small ground and is shown to improve the performance in regards to multipath fading affects.

Figure 3(a) and (b) show the proposed configuration of a flexible diversity ZOR antenna for on-body WBAN applications. The antenna element has a size of 20 mm × 9 mm and is located on the top side of a flexible substrate with ε_r=2.2 and a thickness of 0.127 mm. The overall dimensions of the antenna, including the system ground, are 44 mm × 35 mm × 0.127 mm. To measure the S-parameter characteristics and 3-D radiation patterns of the antenna, a semi-solid flat phantom with dimensions of 200 mm × 270 mm × 60 mm is used. Figure 4 shows the simulated and measured S-parameter characteristics of the proposed diversity antenna. When the antenna is located 5 mm above the semi-solid phantom surface, the S_{11} and values at 2.45 GHz are -22.8 dB and -25.4 dB, respectively. The -10 dB impedance bandwidth of both antenna elements #1 and #2 are over 680 MHz (from 2.32 GHz) and over 700 MHz (from 2.3 GHz), respectively. Additionally, the measured 3D radiation patterns of the each antenna element (#1 and #2), when located on the semi-solid flat phantom have peak gains of -0.49 dBi and -0.25 dBi at 2.45 GHz, respectively[11].



a) perspective view of the antenna



b) radiating element

Figure 3: Flexible diversity ZOR resonance antenna design [11].

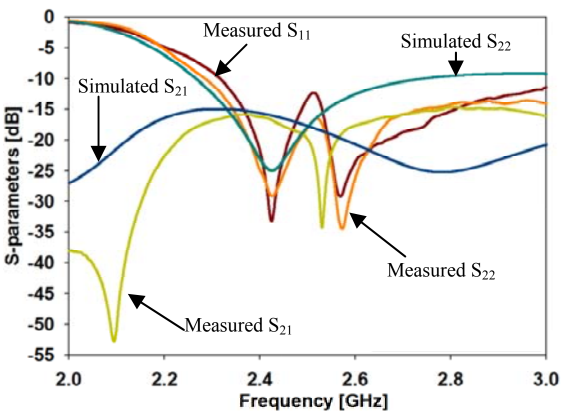


Figure 4: Simulated element of the diversity antenna [11]

C. A planar UWB loop antenna

A UWB loop antenna targeted for use in an on-body WBAN communication system has been proposed by Tuovinen *et. al.* [12]. The antenna can be used in a free space system (i.e. off-body link) or located at an optimal distance from the human body (on-body link), where the optimization reduces the effects of the human body on radiating characteristics. In the simulations presented, the human body is modelled using multiple layers of tissues with varying dielectric properties. In the measurements, the impedance bandwidth (S_{11}) of the antenna has been measured in contact with the author's body. The modelled human body tissue layers for the simulation models are chosen such that the antenna is meant to be located on the chest wall of the human body.

Figure 5 shows the antenna design layout with the UWB loop antenna and detailed dimensions. The antenna was printed on one side of FR4 substrate, with the ground plane on the same side. In simulations using CST, the FR4 substrate was assigned dielectric properties of: $\varepsilon_r = 4.3$ and $\tan\delta = 0.025$ as described in the CST material library. The FR4 substrate thickness was 1.6 mm. The antenna is simulated in 3 situations, free space, direct contact with the modelled human body tissues and with a 16 mm gap between the antenna and layered human body tissues (the tissues replicated layers of skin, fat, breast, muscle and bone).

Good agreement was seen between the simulation and measurement results. However, the antenna was unable to fulfill the design requirements of -10 dB return loss over the UWB bandwidth when it was placed in direct contact with the human body, as shown in Figure 6. The antenna efficiency was also significantly degraded when in direct contact with the body; however, performance similar to that achieved in free space was obtained for the antenna with 16 mm body gap as shown in Figure 7. This antenna design is considered to provide a valid solution for on-body WBAN communication systems when the antenna-body spacing is at least 16 mm [12].

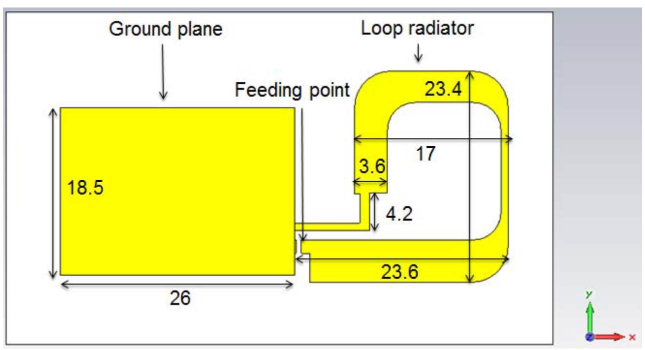


Figure 5: Simulation model

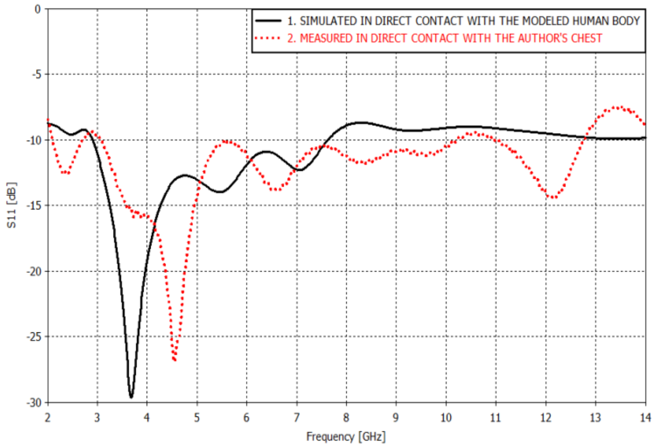


Figure 6: Simulated and measured impedance bandwidth of antenna in direct contact with the body

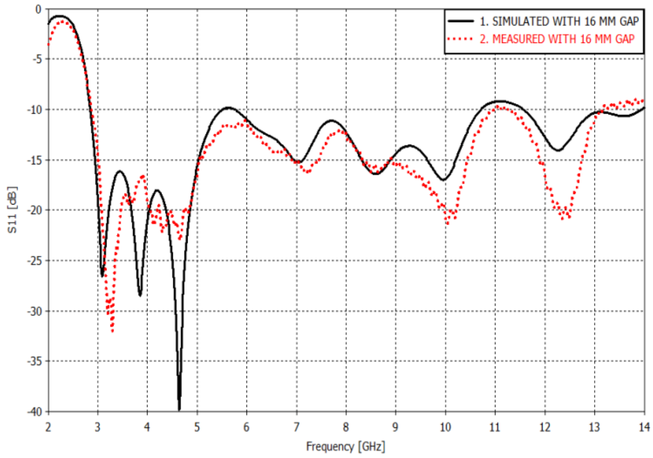


Figure 7: Simulated and measured impedance bandwidth of antenna with the 16 mm gap

D. *Dual-band wearable Antenna*

A dual-band on-body antenna for a WBAN repeater system has been presented by Kwon *et. al.* [13]. The dual-band antenna is designed to direct its radiation into the human body over the MICS band and directed toward the outside at ISM band. This offers the opportunity to transmit information collected from an implanted device to an external monitoring system with one antenna. In addition, the return loss property of the antenna is insensitive to human body effects. This is achieved by utilizing the epsilon negative zeroth-order resonance property.

Figures 8 (a) and (b) show the layout of the dual-band antenna [13]. It is fabricated on FR4 substrate with ε_r =4.4 and has dimensions of 40 mm x 40 mm x 3.2 mm. The antenna is comprised a top patch to transmit signals to external devices in the ISM band and a bottom patch to communicate with the implanted devices in the MICS band. The bottom patch is fed by CPW on the bottom ground. The human body phantom used in the simulation is defined with ε_r = 56.7 and σ = 0.94 S/m at 403.5 MHz, and ε_r = 52.7 and σ = 1.95 S/m at 2.450 GHz.

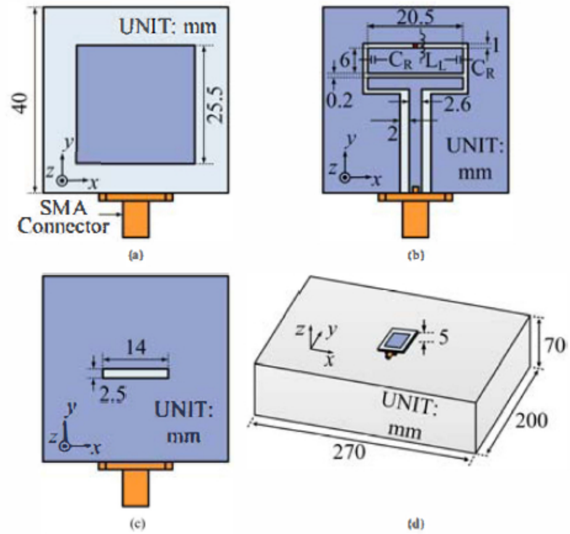


Figure 8: Configuration of the proposed antenna: (a) top plane; (b) bottom plane; (c) middle ground plane; (d) simulation setup for the proposed antenna on a human body phantom

Figure 9, shows the measured return loss characteristics. The measured data agrees well with the simulated results. The measured 10 dB return loss bandwidths of the antenna in the MICS and ISM bands were 7 MHz (400 MHz-407 MHz) and 85 MHz (2.4 GHz-2.485 GHz), respectively. The antennas return loss insensitivity to various environments can be clearly seen in Figure 9. Measurements made in an anechoic chamber, showed radiation efficiencies of 1.92% and 35.85% and peak gains of -17.17 dBi and -4.46 dBi of at 403.5 MHz and 2.45 GHz, for the MICS and ISM band designs respectively. The measured 1 g-averaged peak SAR values were 0.977 W/kg at 403.5 MHz and 7.237 W/kg at 2.45 GHz.

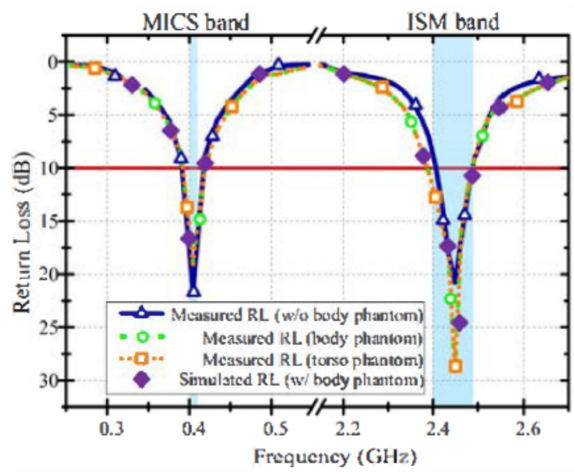


Figure 9: Measured return losses of the fabricated antenna

III. CASE STUDY

The tactical vest antenna system (TVAS) in Figure 10 is an application example of a wearable antenna system designed for the United States military. It consists of two antenna inserts, two interconnecting cables, and a cable for radio connection. It is of light weight and is concealable. This type of wearable antenna helps conceal the identity of the radio operator, providing a crucial link between ground troops, support units, aircraft and quick reaction forces, etc. It can also improve troop mobility by reducing the amount of equipment attached to the body armor. The weight of the vest is 255.14 grams and the antenna impedance is 50 Ω. It has a size of 12” x 9” [14][15].

The main distinction of a wearable patch antenna from a regular patch is that the antenna substrate is often a textile fabric, because fabric antennas can be easily integrated into clothes. Textiles with a low dielectric constant can reduce the surface wave loss and improve impedance bandwidth [16].

However, the use and design of wearable antenna is a relatively newly established field and as such there are still many design factors to be explored. Since the antenna should be suitable for wear, it should have a small size, a low profile and be flexible. It also needs to have a performance which can withstand significant bending caused by human body movement. It should also be noted that in addition to their flexibility, textile materials are compressible, so their density and thickness may change with pressure, which can also lead to performance issues. The operation frequency of the wearable antenna is set at 2.4 GHz, within the ISM band. [17].

Figure 10: Tactical vest antenna system [15]

The wearable antenna proposed in this paper is based on microstrip technology. Microstrip is a kind of electrical transmission line used to transmit microwave-frequency signals. It consists of three layers and can be fabricated on printed circuit board (PCB). The ground plane is on the bottom followed by a substrate which separates the ground plane and radiating metallic strip located on the top surface [18]. The antenna will be designed to operate at 2.4 GHz, at which its input impedance should be 50 Ω.

Microstrip antennas are also referred to as patch antennas. The shape of the patch can be square, rectangular, dipole, circular, elliptical, circular rings or ring sectors [19]. In this paper, the patch is rectangular.

Patch antennas have a metalized deposit on a plane dielectric substrate which allows for a very thin printed-conductor topology of any shape. Microstrip is much less expensive than traditional waveguide technology, as well as being far lighter and more compact. Low profile planar configurations can be made conformal. In addition, they have low fabrication costs and are amenable to mass production.

To design a textile antenna, knowledge of electromagnetic properties such as permittivity and loss tangent of the textile material is required. Conductive textiles such as Zelt, Flectron and pure copper polyester taffeta fabrics are commonly used as radiating elements while non-conductive textiles such as silk, felt and fleece are used as substrates [20].

This section aims to examine the performance of a rectangular microstrip antenna fabricated on various textile based substrates. There are four different substrate materials examined, namely, wash cotton, curtain cotton, polyester and poly-cotton. The size of the ground plane is equal to the fabric substrate used, 120 mm x 120 mm. The thickness of the top metallic layer is 0.1 mm, while that of the ground plane is 0.5 mm. The material used for these two planes is annealed copper. The design parameters are shown in table III.

The configuration of the patch antenna is shown in Figure 11.

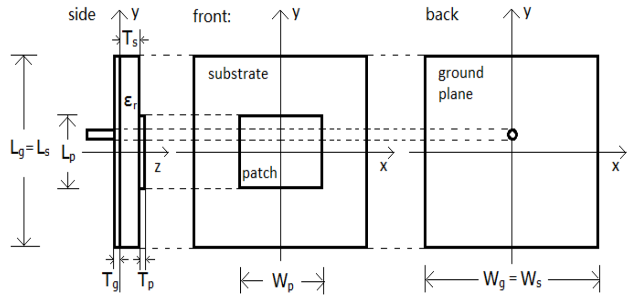


Figure 11: The configuration of the patch antenna.

The wearable antenna is manufactured as shown in Figure 11. After optimizing the feed position of the source, simulations are carried out over the frequency range 2 GHz to 3 GHz. The return loss results obtained for the four textile material substrate based antennas are shown in the next page.

In Figure 12 the resonant frequency of the patch antenna with wash cotton as a substrate is 2.396 GHz and the return loss is -42.125 dB.

In Figure 13 the resonant frequency of the patch antenna with curtain cotton as a substrate is 2.398 GHz and the return loss is -41.572 dB.

In figure 14 the resonant frequency of the patch antenna with polyester as a substrate is 2.398 GHz and the return loss is -30.152 dB.

In figure 15 the resonant frequency of the patch antenna with curtain cotton as a substrate is 2.404 GHz and the return loss is -33.3792 dB.

TABLE III. The antenna design specifications

Design parameters	Antenna 1	Antenna 2	Antenna 3	Antenna 4
Insulating fabric material employed	Wash cotton	Curtain cotton	Polyester	Polycot
Resonant frequency (GHz)	2.4	2.4	2.4	2.4
Substrate dielectric constant (ε_r)	1.51	1.47	1.44	1.48
Loss tangent of the substrate	0.02	0.02	0.01	0.02
Substrate thickness (Hs: mm)	3.0	3.0	2.85	3.0
Patch length (L) in mm	46.9	47.4	47.9	47.5
Patch width(W) in mm	54.65	55.06	55.43	55.20
Ground plane and substrate dimension(W x L: mm x mm)	120x120	120x120	120x120	120x120

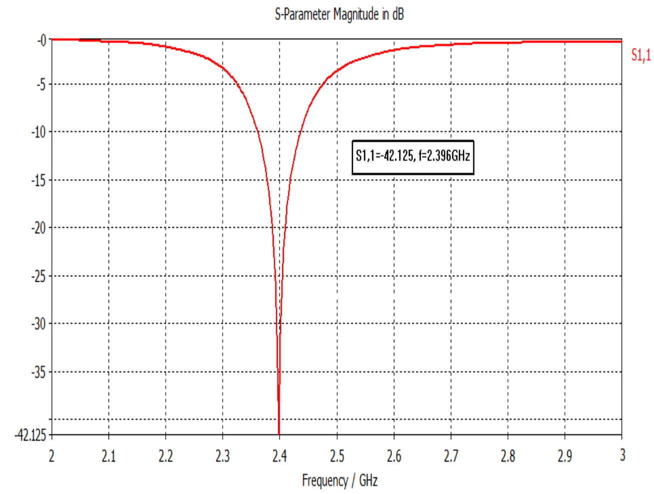


Figure 12: The simulated return loss of patch antenna with wash cotton as a substrate.

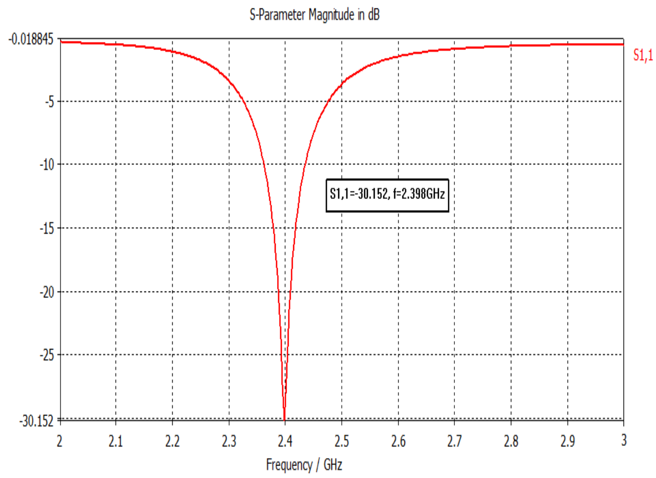


Figure 14: The simulated return loss of patch antenna with polyester as a substrate.

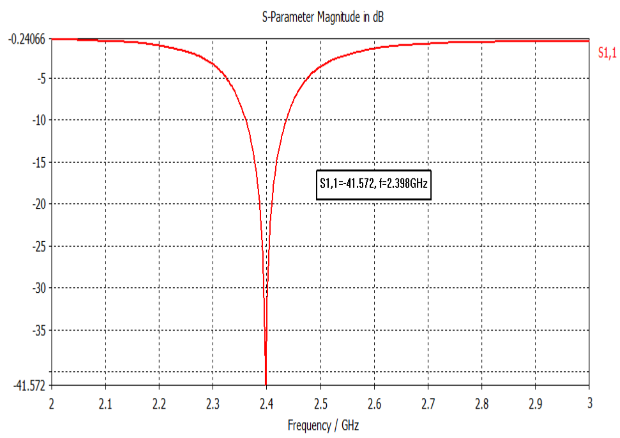


Figure 13: The simulated return loss of patch antenna with curtain cotton as a substrate.

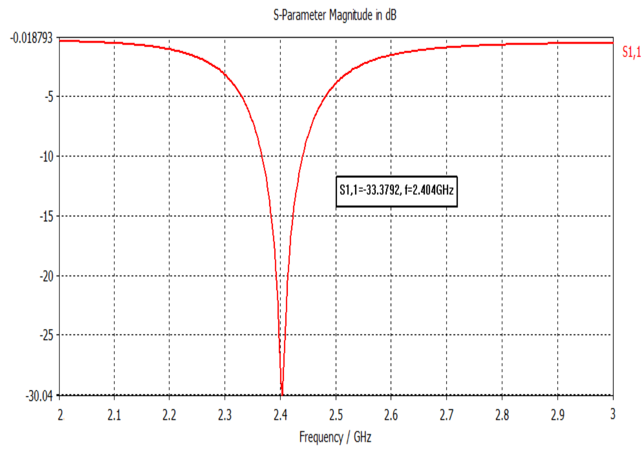


Figure 15: The simulated return loss of patch antenna with polycot as a substrate.

From these simulation results, it can be seen that at the resonant frequencies, all of around 2.4 GHz, the return losses of these antennas with polycot and polyester as the substrates are about -30 dB, while those with wash cotton and curtain cotton are about -40 dB. Hence, curtain cotton and wash cotton show better performance for the same antenna configurations.

Despite this variation, from a return loss perspective, all four antennas can be considered well matched, each exhibiting similar performance. Based on this result, only the antenna with curtain cotton as a substrate will be used to design the desired compact antenna.

Reducing patch size, increases the resonant frequency. This is then compensated for by inserting shorting pins between the top of the patch and ground plane as shown in Figure 16.

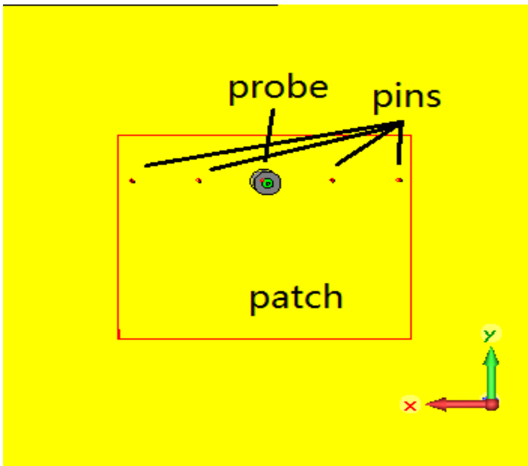


Figure 16. Patch antenna with four inserted pins.

When pins (or pin) are inserted to the left, right or on both sides of the probe (in the x-axis), the resonant frequency and return loss are significantly altered. Conversely, inserting pins along the y-axis results in only small changes in resonant frequency and return loss. For the reduced patch size, the pint positions must be optimized to shift the resonance point back to the desired frequency.

With the help of the short circuit pins as shown in Figure 16, the patch width *Wp* has been reduced from 55.06 mm to 41 mm, while the length *Lp* is reduced from 47.4 mm to 20 mm (on the origin centred x-y coordinate, $Lp_{\max}$ = 10.9 mm and $Lp_{\min}$ = -9.1 mm). The patch size is reduced to around 32% of its original size. The simulation results of this size-reduced design are shown in Figure 17, which shows that the resonant frequency has been shifted to 2.396 GHz with a return loss of -42.125 dB.

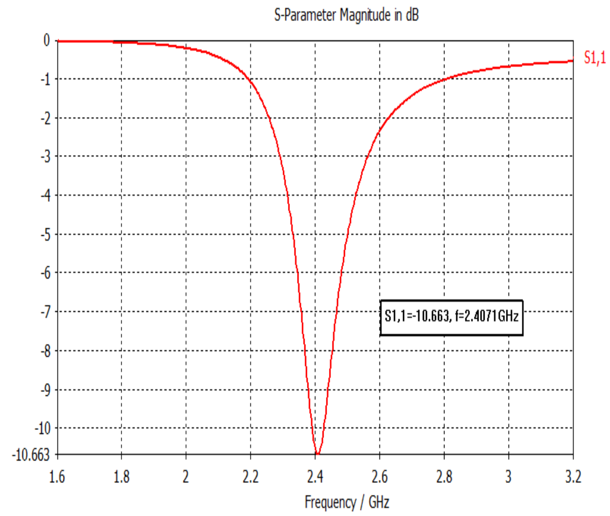


Figure 17. Return loss of patch antenna with four inserted pins.

IV. Conclusion

This paper reviewed a selection of state-of-the-art wearable antennas of varying types. All of which displayed omnidirectional radiation patterns.

In the case study, the return loss characteristics of patch antennas fabricated on 4 textile substrates were investigated. At the resonant frequency of approximately 2.4 GHz, the return losses of both wash cotton and curtain cotton were better than -40 dB, while those of polyester and polycotton were in the region of -30 dB. Ideally, the return loss should be $-\infty$ dB, hence, the antennas with substrates of wash cotton and curtain cotton seem better than those with polyester and polycotton.

By introducing metal shorting pins, connecting the top patch and ground plane, the resonant frequency of the antenna has been changed. When the pins are inserted through the plane to the left or right side or on both sides of the antenna feeding point, the resonant frequency and return loss were changed significantly. However, when pins are inserted above or below the antenna feed point, changes were negligible. Patch size remains the dominant influence on the resonant frequency of the antenna, but can be shifted in a controlled manner to obtain the desired response. In this case the pins are used to shift the resonant frequency down as the patch size reduction shifts it up. With the proposed method, the antenna size has been reduced from 47.4 mm x 54.06 mm to 20 mm x 41 mm (approximate 32% reduction)

In this case study, only four textile materials have been examined and the antennas are modeled in free-space. In the future, more materials will be examined. The effects of the human body on the radiating properties of the antenna as well as body movement (resulting in antenna deformation) also need to be considered.

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