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Performance Evaluation Of Wearable Antennas For Body Area Network Applications

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Abstract: In this paper, we present the performance evaluation of wearable antennas for body area network applications. Wearable antennas developed on various substrate materials such as cotton, silk, and jeans are designed and developed and their performance under various constraints is measured to validate the simulated results and use in body area network applications. The proposed antennas operate at a fundamental frequency of 2.45 GHz which facilitates the unlicensed operation in the ISM band making wearable antennas usable in various industry, scientific, and medical applications.

Keywords: Wearable antennas, ISM, Cotton, Jeans, WBAN

1. INTRODUCTION

Wearable devices are becoming popular in the field of wireless body area network applications. The heart of these devices is an antenna. Most wearable devices demand flexible antennas for wireless transmission/ reception of electromagnetic waves. This has increased the interest of researchers towards the design of wearable antennas and study the various parameters and find opportunities to comprehend how the size of the antenna may be minimized, make it more compact, lightweight, and most importantly reduce the cost of antenna. These microwave antennas are widely used in the wireless communications system. In the last few years, tremendous research is done on wearable antennas by various authors/researchers. These antennas must be designed to have proper shape and size and fabricated using highly flexible robust material. The important consideration while mounting the antenna on the surface of the human body is to reduce the interaction of the human body with the antenna and also reduce SAR. The wearable antennas are fabricated by using a highly flexible material that is both conducting material and substrate. For fabricating wearable antennas various types of substrate material are used like clothing material, resin material, FR4, etc. The clothing material includes cotton, jeans, silk, etc. can also be used depending upon the applications.

A Wireless Body Area Networks (WBAN) system essentially consists of a sensing system, actuators, processor for computation, power supply and, IoT nodes which can be embedded inside the human body for in-body communication, or on the clothes for on-body communication. Wearable antennas can be for continuous monitoring of vital signs such as oxygen level, heart rate, stress level and, temperature and can be deployed for various applications such as patient monitoring in medical systems, home health care systems, security personnel, military guards, and first-line [1]. As mentioned earlier, wearable antennas can be utilized for Wireless Body Area Networks (WBANs) applications such as healthcare, military, sports, and identification systems. Wearable antennas operate in close proximity of the curved human body therefore, the performance of wearable/ flexible antenna needs to be measured in terms of reflection coefficient, bandwidth, directivity, gain, radiation characteristic, Specific Absorption Rate (SAR), and efficiency that are anticipated to be influenced by the coupling and absorption by the human body tissues [2].

A compact wearable antenna fabricated on Rogers substrate that facilitates dual-band, dual-polarized operation at 2.45 GHz for indoor/outdoor applications is presented in [3]. In another communication reported in [4], a dual-band antenna operating at 400 MHz and 2.4 GHz is developed using a flexible folded-shorted patch (FSP). In [5], a highly compact, flexible, and lightweight antenna for medical wearable applications is proposed. The antenna is fabricated on a flexible conductive cloth MKKTN260 with felt acting as a good isolation substrate. The antenna facilitates operation over the frequency range 5.578 to 5.898GHz, which can cover the whole ISM 5.8GHz band (5.725–5.825GHz) and provide good wearable radiation characteristics.

A wearable textile antenna that facilitates dual-band operation at 2.45 GHz for WBAN and WLAN application and, 1.575 GHz band for Global Positioning System (GPS) is presented in [6]. The antenna consists of an artificial magnetic conductor (AMC) plane that reduces back-lobe radiation and improves antenna gain.

A compact grounded asymmetric coplanar strip (GACS)-fed flexible multiband frequency reconfigurable antenna with two PIN diodes is proposed in [7]. The investigated antenna offers triple-band operation at 2.4 GHz, 3.8 GHz, and 5.6 GHz. The antenna consists of a monopole patch in the radiating structure that facilitates the wireless LAN operation at 5.6 GHz. Further, inverted L-shaped and F-shaped monopoles are embedded near the monopole patch that facilitates operation for Bluetooth and 5G NR applications at 2.4 GHz and 3.8 GHz respectively. The two PIN diodes deployed in the radiating structure facilitates four modes of operations that include single-band operation at 5.6 GHz, two dual-band operation at 3.8/5.6 GHz and 2.4/5.6 GHz, and multiband operation at 2.4, 3.8 and, 5.6 GHz.

The effects of textile weaving and finishing processes on the performance of textile-based wearable antennas are presented in [8]. Several textile-based patch antennas operating at 2.4 GHz were designed and fabricated for evaluation. All of them had the same geometry comprising a 1-mm-thick felt substrate in the middle, and silver ink screen-printed polyester fabric as the ground and patch at the bottom and on top. However, polyester fabric, the bare textile material for the conductive ground and patch was subjected to different weaving and finishing (tendering, scouring, and calendaring) processes. It was observed that the antenna resonant frequency, bandwidth, radiation efficiency, and peak gain were varied by these processes, although the antenna geometry and screen-printing method were identical to each other. The best antenna exhibits a peak gain of 5.2 dBi and radiation efficiency of 42.4%, while the worst shows corresponding values of 4.17 dB and 34.8%. This implies that the weaving and finishing processes considerably impact textile-based wearable antenna performances.

The compact and robust high-impedance surface (HIS) integrated with the antenna is designed to operate at a frequency of 2.45 GHz for wearable applications. They are made of highly flexible fabric material. The overall size is 45 × 45 × 2:4 mm3 which is equivalent to 0.37λo×0.37λo×0.02 mm3. The value of using HIS lies in protecting the human body from harmful radiation and maintaining the performance of the antenna, which may be affected by the high conductivity of the human body. Besides, setting the antenna on the human body by itself detunes the frequency, but by adding HIS, it becomes robust and efficient for body loading and deformation. Integrated antenna with HIS demonstrates excellent performance, such as a gain of 7.47 dBi, an efficiency of 71.8%, and FBR of 10.8 dB. It also reduces the SAR below safety limits. The reduction is more than 95%. Therefore, the presented design was considered suitable for wearable applications [9].

A compact antenna having size 30×20×0.7 mm^3 (75% smaller than the conventional antenna) that consists of an inverted E-shaped antenna demonstrated an impedance bandwidth of 15% and efficiency of 79% at 2.4 GHz in the ISM band is suitable for incorporation into wearable systems is presented in [10]. In another communication, Ultra-wideband (UWB) technology that can offer broad capacity, short-range communications at a relatively low level of energy usage, which is very desirable for wireless body area networks (WBANs) is presented [11].

This work proposes more realistic parameters for evaluating RF-powered Body Area Networks (BANs) and utilizes them to analyze and compare the performance of an RF-powered BAN based on 915 MHz and 2.4 GHz rectennas. Two fully-textile antennas: a 915 MHz monopole and a 2.4 GHz patch, are designed and fabricated for numerical radiation pattern analysis and practical forward transmission measurements. The antenna outperforms the 2.4 GHz high gain antenna when powered by an RF–powered BAN at 915 MHz where the antenna offers mean gain and omnidirectional radiation characteristics, despite lack of shielding, by 15:4× higher DC power. Furthermore, a transmitter located above the user can result in 1× and 9× higher DC power at 915 MHz and 2.4 GHz, respectively, compared to a horizontal transmitter. Finally, it is suggested that the mean and angular gain should be considered instead of the peak gain [12].

A highly flexible wearable antenna with a high degree of isolation and wide bandwidth for Medical Body Area Network Applications that consists of an asymmetrical e-slot antenna is presented in [13]. The Electromagnetic Band- Gap (EBG) offers a high degree of isolation whereas the Defected Ground Structure (DGS) provides wideband characteristics.

The design process for fabrication via screen printing on fabric substrates for commercially available conductive inks is presented in [14] that can be used for the development of in-body and outside the body sensors. The effects of non-conductive, paint-based inks as interface layers between conductive elements and fabric substrates of coplanar keyhole fabric antennas are presented along with wash sustainability and its effects on antenna resonance at 5.8 GHz over time. Fabrication of screen-printed radio frequency identification tag antenna includes placement of the tag chip. Accessibility of the tag is assessed by comparing reader data to the distance between the reader and the tag at 915 MHz.

Millimetre-wave antennas have applications in several sensing and communication systems. Such antennas, designed for modern miniaturized devices and systems, must be low profile, flexible, and low cost. Some applications also require beam steering for detection purposes. Combining all these features into an antenna system and delivering decent antenna performance is challenging. In the study reported in [15], the researchers have combined parasitic patch array antenna with partially reflective surfaces to create a flexible, low-profile, and simple beam-switching wearable antenna detection system. To ensure lower costs as well as compatibility with wearable systems, screen printing was utilized on a flexible substrate. The antenna array was optimized for the 77 GHz band and had a high gain of 11.2 dBi.

The difficulty of antenna design applied to glasses is that the structure of glasses is too single, and the space available for antenna design is greatly limited. In this background, the integrated design of 4G antennas and 5G antennas applied to glasses is proposed in this paper. The most important highlight of this design is that it makes full use of the limited three-dimensional space structure provided by glasses and achieves the perfect combination of the antenna and glasses in the physical structure. Specifically, two antennas for 4G communication are arranged on two glasses frames, and four antennas for 5G communication are arranged on two glasses legs. In this way, we can make full use of the space provided by the glasses to design antennas and ensure that there is a certain distance between the 4G antennas and 5G antennas so that the performance of both 4G antennas and 5G antennas can be guaranteed. The 4G antenna consists of a loop structure printed on the frame and leg of the glasses and a parasitic branch strip printed on the front of the leg of the glasses. The resonance modes of the 4G antenna are mainly loop, monopole, and dipole modes, which can cover two 4G bands of 0.824-0.96 GHz and 1.71-2.69 GHz. Each 5G antenna mainly comes from the open slot mode etched on the metal ground surface of an FR4 substrate of the glasses leg. In addition, the slot antennas operate in two 5G bands of 3.3-3.6 GHz and 4.8-5.0 GHz. Finally, the glasses and the antennas are fabricated based on FR4 substrates and measured. The measured results show that the proposed antennas perform well and have the potential to be used in 4G/5G communications through glasses [16].

A novel pattern and polarization reconfigurable wearable slot antenna suitable for smart glasses is proposed. The antenna is designed and fabricated on glass and reconfiguration is realized using four PIN diodes. It operates in the 2.4 GHz Industrial, Scientific, and Medical Band. It consists of an equilateral L-shaped slot fed by a single coplanar waveguide feed. The slot is manipulated with switches to generate two modes of operation. Each mode corresponds to one of the two states of the switches which result in different L-shaped slots with unequal legs creating patterns that are polarized perpendicular to each other [17].

A flexible wearable antenna fabricated on Polytetrafluoroethylene (PTFE, also known as Teflon) using inkjet-printed that facilitates superior performance for cross-body communication is proposed in [18]. The researchers have coupled the antenna with machine learning techniques powered by Google’s Tensor flow is used for recognizing human activities that provides an accuracy of about 92% while tracking human activities based on RF signal recognition techniques in variable environments and users.

A multiple-input multiple-output (MIMO) antenna that consists of four elements, which are placed orthogonally to the adjacent elements offers a wideband response [10-dB bandwidth of 2210 MHz (fractional bandwidth (FBW) = 92.08%) in free space and 10-dB bandwidth of 2200 MHz (FBW = 91.66%) when worn on human-body] is deployed for wearable bio telemetric devices applications [19].

A high gain antenna having a gain of 2.50 dBi and efficiency of 93% at 2.4 GHz is designed on semi-flexible RT/Duroid 5880 substrate is deployed for wearable biomedical telemetry applications. The investigated antenna offers wideband, low-profile, and semi-flexible characteristics [20].

2. MATERIALS FOR WEARABLE ANTENNAS

Designing wearable antennas is not exactly like conventional antennas and hence they demand special designing approaches. Although the requirements of wearable antennas may vary according to the application, a few common requirements of all wearable antennas are:

- Lightweight,
- Low-cost,
- Low maintenance,
- No set-up requirements,
- Robust or flexible, and
- Conformity.
- Low resistivity
- High conductivity
- Low deformability such as bending, crumpling, and stretching
- Weatherproof
- Tensile strength
- Ease of integration with on-body fabrics.

Thus, when designing wearable antennas several considerations are to be addressed. In [8], the authors have developed a process for designing wearable antennas which are illustrated in Fig 1.

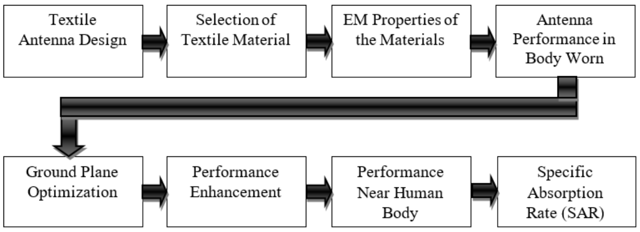


Figure 1: Wearable Antenna Designing [8]

2.1 Conductive materials for wearable antennas

Similar to conventional antennas, the flexible-wearable antenna comprises of two parts:

1. The conductive element which comprises the ground plane and radiating element and
2. The dielectric material is usually the substrate that acts as a platform for the conductive elements.

In this section, a detailed classification of these two groups is provided and illustrated in Fig. 3. The conductive materials used for designing wearable antenna must suffix the following requirements:

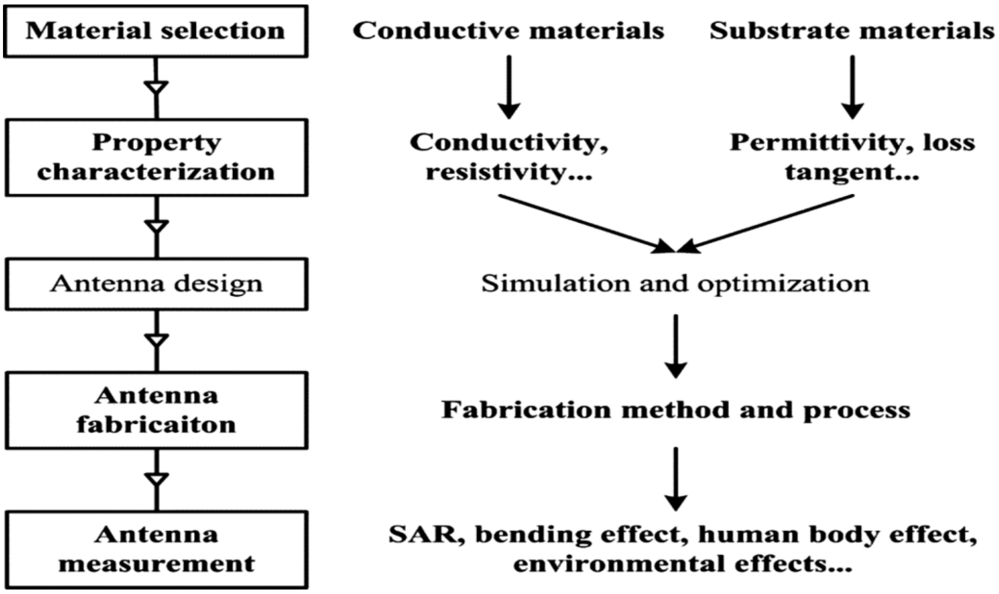


Figure 2: Design procedure

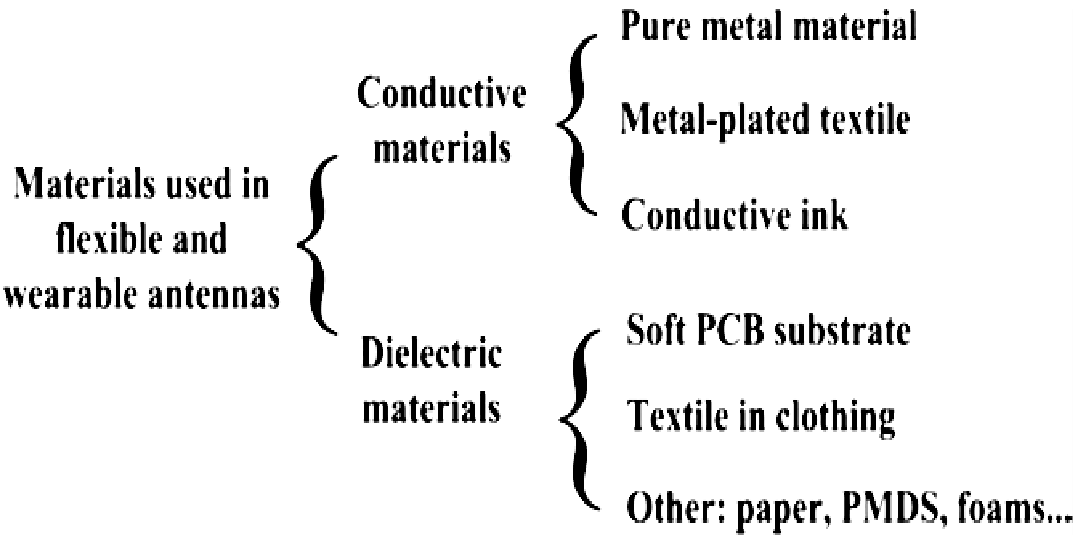


Figure 3: Material classification.

Pure metallic materials such as silver paste [1], copper gauze [2], and copper foils [3] are widely used for fabrication in wearable textile-based antennas. The advantages of using such materials include:

- High conductivity,
- Cost-effectiveness, and
- Simplicity in fabrication (for example: using soft PCB fabrication process [4]).

It is worth mentioning that adhesive laminates or supporting foams are usually used as binding material when integrating antenna in clothing material instead of sewing and embroidering.

Another conductive material that is widely used for the fabrication of wearable and flexible antennas is the metal-plated textile. Metal plated textiles are often also termed “electro-textile” or “E-textile”. Materials such as Kevlar, Nylon, and Vectran are often coated with metal-plated textile conductive material which can offer electrical conductivity of about 1E+6S/m. The advantage of using this material include:

- High Ductility
- High Conductivity, and
- Can be embedded directly onto the cloth using textile yarns

The E-textile materials are created from the conductive thread using the process of weaving or knitting. The conductive thread used for weaving the antenna onto the cloth are:

- Multifilament
- Monofilament

Different kinds/ brands of E-textiles are exploited in recently published literature, such as Nora [6], Flec Tron [7], less EMF [8], and Zelt [9].

An alternative promising material for the fabrication of a flexible antenna that is made of carbon or metal particles is conductive ink. The main advantages of using conductive inks are:

- Simplicity of fabrication
- Compatibility with standard screen printing or inkjet printing process, and
- Low cost.

However, the conductivity of conductive ink depends on the intrinsic property of the material in use; add solvent impurities, and the thermal annealing process.

2.2 Substrate materials (Dielectric Material)

The substrate material in an antenna is mainly utilized to provide support to the conductive elements of the antenna. Various flexible substrates are available in the market which is adopted for flexible wearable antenna fabrication based on the properties of the conductive material used. Here, a few of such substrate materials and films both conventional and cutting edge which are widely used for fabrication of flexible wearable antenna design is represented in Table 2.

Table 1: Commonly used fabric Tested along with their electrical properties [22]

Fabric under test	Dielectric Constant (εr)	Loss Tangent (tanδ)
Cordura	1.90	0.0098
Cotton	1.60	0.0400
100% Polyester	1.90	0.0045
Quartz Fabric	1.95	0.0004
Lycra	1.50	0.0093

The major core materials used as supporting overlays for the soft PCB manufacturing process are:

- Polymide (PI) films
- Polyester, also commonly referred to as Polyethylene Tere Phthalate (PET) films, and
- Liquid Crystal Polymer films (LCP)

The main advantages of using these materials are:

- High flexibility
- Low loss tangent
- Low thickness of the substrate

Table 1 summarizes the advantages and disadvantages of each material [4].

Table 2: Properties of Film Materials

Property	PI films	PET films	LCP films
Thermal rating	200°C	70°C	90°C
Soldering	Applicable	Difficult	Possible
Wire bonding	Possible	No	Difficult
Moisture absorption	High	Low	Low
Dimensional stability	High	High	High
Cost	Moderate	Low	Low

3. FABRICATION METHODS FOR WEARABLE ANTENNAS

Line patterning: The line patterning technique was proposed by Hohnholz and MacDiarmid in 2001 [23]. In this technique, firstly the negative image of the desired antenna is developed using suitable design software. This is followed by decomposing a conductive polymer onto the substrate. In the last step, the printed mask is sonicated on the substrate by applying ultrasonic energy in a toluene solution for about 10 seconds. This technique is widely used for developing components such as flexible field-effect transistors, filters, resistors, RFIDs, etc... The advantages of using this method are:

- Extremely simple fabrication methods
- Low-cost method

3.1 Flexography

Flexography is widely used of fabrication of RFID antennas by the manufacturers due to its following advantages:

- Higher resolution,
- Cost-effective fabrication, and
- The capability of Roll-to-roll production.

Flexography technique for fabrication can yield dry patterned films having a thickness of about 2.5 µm which results due to the use of ink that has a lower viscosity than inks used in screen printing. Furthermore, the ink used in flexography must provide a higher degree of conductivity to compensate for the sheet resistance. This is because the antenna efficiency is largely dependent on the electrical conductivity of the radiating element of the antenna. Furthermore, the sheet resistance largely depends on that the consistency of ink flow and ink line width [24].

3.2 Screen-printing

Screen printing is another cost-effective technique that is widely used by flexible electronics manufacturers. In this process, a mask of the desired pattern is developed. Then the mask is directly applied to the substrate material or the film. It is further treated thermally to remove the excess solvent retaining the desired pattern of the antenna. In [25, 26], flexible transparent antennas and RFID antennas manufactured using the screen-printing technique have been reported.

The advantages of this technique are as follows:

- Simple mechanism
- Additive manufacturing process
- Cost-effective
- Eco-friendly manufacturing

However, a few drawbacks associated with this technique are:

- No effective mechanism to control the amount of ink deposited
- Multilayer manufacturing is critical
- Poor resolution of pattern developed

3.3 Photolithography

Another widely used manufacturing process that evolved in the 1960s and is widely used for PCB manufacturing is photolithography. This technique consists of the use of photoresist and chemical agents such as $FeCl_3$. In this technique, the desired pattern is UV exposed which is etches away the unwanted area due to the corrosion process to produce the desired metallic pattern. It involves using a photo-resist and chemical agents to etch away the unwanted area corrosively to produce the desired metallic patterns.

The advantage of using photolithography for manufacturing flexible wearable antennas are as follows:

- Highly accurate in developing finely detailed antennas
- Multilayer manufacturing is possible
- Low cost, additive manufacturing process

The major drawbacks associated with this technique are:

- Low throughput,
- Involvement of hazardous chemicals, and

Production of by-products, hence it is not suitable for commercial production.

Other techniques used for manufacturing flexible wearable antennas are inkjet printing, sewing and embroidering, and thermal evaporation.

4. ANTENNA DESIGN

The design of wearable antennas used for performance evaluation in the next section is presented in [21]. A comparison of wearable antennas simulated on various substrates is presented in Table 3.

Table 3: Comparison of Compact Monopole Circular Wearable Antennas on Various Substrates

Parameter	**Compact monopole circular wearable antenna on a substrate**		
	Cotton	Jeans	Silk
Relative permittivity	1.6	1.7	1.05
Dielectric loss tangent	0.04	0.03	0.08
The radius of the circular patch	7 mm	6.75 mm	7 mm
Operational bands and bandwidths	-12dB reflection coefficient bandwidths of 1.2622 GHz at 2.41 GHz (2.062 – 3.3244 GHz), 2.7022 GHz at 6.2 GHz (4.089 – 6.7911 GHz), and,	-11dB reflection coefficient bandwidth of 2.89 GHz (2.12 – 5.00 GHz) at 2.6 GHz and 1.83 GHz (5.931 – 7.765 GHz) at 6.8 GHz.	-10dB reflection coefficient bandwidths of 3.3056 GHz (1.8 – 5.13 GHz) at the first resonant frequency of 2.4GHz/4.00 GHz while 0.6136 GHz

	0.7556 GHz at 8.3 GHz (7.9733 – 8.7289 GHz)		(7.64 – 8.25 GHz) at the second resonant frequency of 7.9 GHz.
Type of operations	Narrowband and multiband along with wideband operation	Dual-band with the wideband operation	Dual-band with the wideband operation
Simulated gains	6.2252 dBi, 0.7500 dBi, and 2.5817 dBi at operational frequency bands of 2.41 GHz, 6.2 GHz and, 8.3 GHz	4.91 dBi and 4.307dBi at operational frequency bands of 2.6 GHz and 8.6 GHz	7.48dBi and 6.08 dBi at 2.4/4.0 GHz, and -3.612 dBi at 7.9 GHz

Figure 4: Fabricated prototypes: (a) Compact monopole circular patch wearable antenna is fabricated on cotton substrate (b) Compact monopole circular patch wearable antenna is fabricated on jeans substrate.

5. PERFORMANCE EVALUATION OF WEARABLE ANTENNAS

5.1 Measured results of compact monopole circular patch wearable antenna presented in section 4 is fabricated on a cotton substrate

Figure 5: Measurement of compact wearable patch antenna fabricated on cotton material carried out using Agilent Fieldfox N9916A Dual Port Vector Network Analyzer in an open environment at Department of Electronics and Telecommunication, Amrutvahini College of Engineering, Sangamner.

The compact wearable patch antenna fabricated on cotton textile material is measured in an open area network as shown in Fig 5. The measured return loss (dB) is as shown in Fig. 6 The proposed antenna offers measured 10 dB return loss bandwidths of 0.131 GHz at 2.39 GHz (2.354 – 2. 485 GHz). Narrow bands at other frequencies are generated which can however be discarded due to narrow bandwidths. The measured results show large variations in antenna performance when compared with simulated results. These variations may have been raised due to the following reasons:

1. Effect of EM wave radiation available in the atmosphere since measurements is carried out in an open area environment.
2. Discrepancies are generated by the substrate material itself since the textile material is not accurately cut. Any change in the dimension of the substrate material can degrade the performance of the antenna.
3. Since the antenna is glued using adhesive material, the presence of this material may also alter the performance of the antenna.
4. Discrepancies while installing the SMA connector can also generate losses. Also, the length of the cable used for connecting the antenna to the port of VNA may alter the performance of the antenna.
5. **Table 4: Comparison of simulated and measured results for antenna fabricated on a cotton substrate**

Parameter under consideration	**Simulated**	**Measured**
Operational bands and bandwidths	-12dB return loss bandwidths of 1.2622 GHz at 2.41 GHz (2.062 – 3.3244 GHz), 2.7022 GHz at 6.2	-10dB return loss bandwidth of 0.131 GHz at 2.39 GHz (2.354 – 2. 485 GHz) with several narrow

	GHz (4.089 – 6.7911 GHz), and, 0.7556 GHz at 8.3 GHz (7.9733 – 8.7289 GHz)	bands which are discarded due to narrow bandwidths
Type of operations	Narrowband and multiband along with wideband operation	Narrowband single band operations

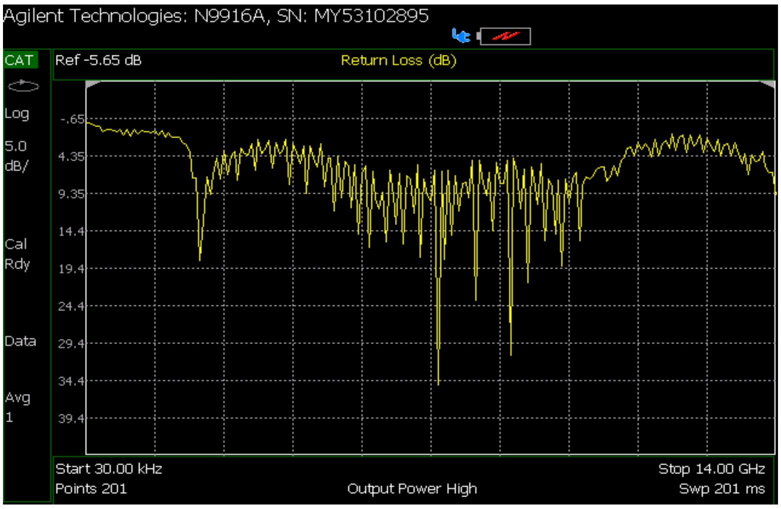


Figure 6: Measured return loss (dB) of compact wearable patch antenna fabricated on cotton material using Agilent Fieldfox N9916A Dual Port Vector Network Analyzer.

5.2 Measured results of compact monopole circular patch wearable antenna presented in section 4 is fabricated on jeans substrate

Figure 7: Measurement of compact wearable patch antenna fabricated on jeans material carried out using Agilent Fieldfox N9916A Dual Port Vector Network Analyzer in an open environment.

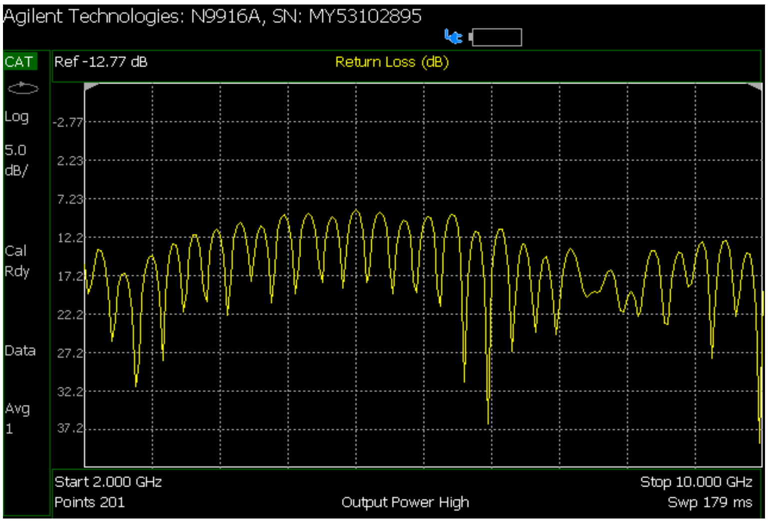


Figure 8: Measured return loss (dB) of compact wearable patch antenna fabricated on jeans material using Agilent Fieldfox N9916A Dual Port Vector Network Analyzer.

The compact wearable patch antenna fabricated on jeans material offers an exceptional dB return loss wideband bandwidth of 8 GHz operating over the frequency range of 2 GHz to 10 GHz. The presented antenna has the first resonant frequency at 2.56 GHz with a return loss of 31.9 dB and the second resonant frequency at 6.8 with a return loss of 36.8 dB as shown in Fig 8.

Table 5: Comparison of Simulated and Measured Results for Antenna Fabricated On a Jeans Substrate

Parameter under consideration	Simulated	Measured
Operational bands and bandwidths	-11dB return loss bandwidth of 2.89 GHz (2.12 – 5.00 GHz) at 2.6 GHz and 1.83 GHz (5.931 – 7.765 GHz) at 6.8 GHz	-10 dB return loss wideband bandwidth of 8 GHz operating over the frequency range of 2 GHz to 10 GHz (first resonant frequency at 2.56 GHz with a return loss of 31.9 dB and the second resonant frequency at 6.8 with a return loss of 36.8 dB)
Type of operations	Narrowband and multiband along with wideband operation	Wideband multi-band operation

6. PERFORMANCE OF WEARABLE ANTENNAS UNDER DIFFERENT CONSTRAINTS

As wearable antennas are embedded on or inside the human body it is important to understand the performance and effects of the antenna. To serve the numerous requirements of body-centric communication systems, the wearable antenna must ensure that they maintain good communication links always. However, while designing wearable antenna designers have to consider several other conditions other than the conventional design parameters, as the human body is not a perfect rigid planar surface, and mobility of parts is expected. Hence, other parameters such as bending, crumbling must be taken into account.

6.1 Performance of wearable antenna on-body area

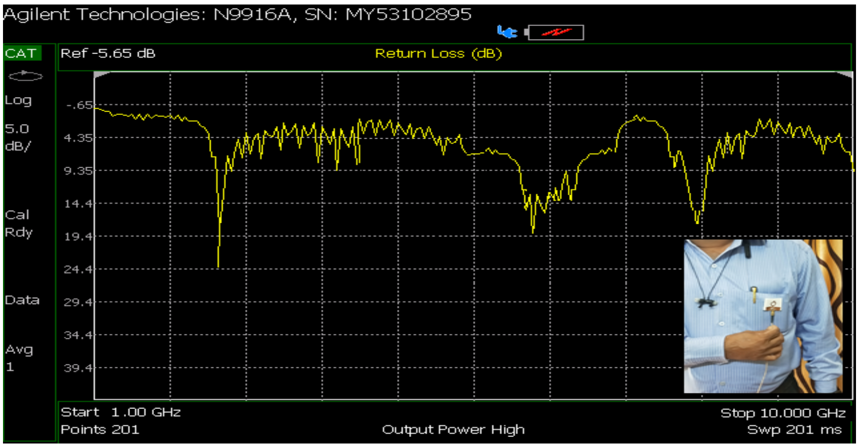
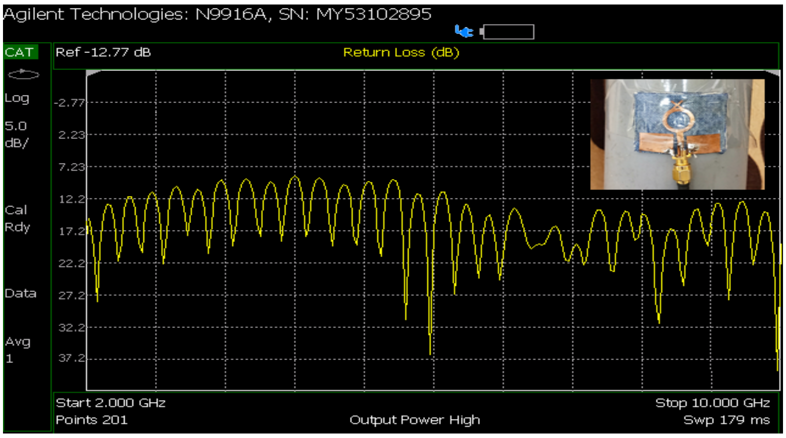


Figure 9: Performance of compact wearable patch antenna fabricated on cotton material on-body area

Fig. 9 shows the performance of a compact wearable patch antenna fabricated on cotton material when placed in close vicinity of the human body. As wearable antennas are aimed to work in close vicinity of the human body, the interaction of an antenna with the human body should not hamper the performance of wearable antennas. The measured results in Fig. 9 indicate that the wearable antenna when placed in close vicinity of the human body does not affect the performance of the proposed wearable antenna. The antenna resonates at the fundamental frequency of 2.45 GHz while providing another narrowband at 7.5 GHz.

6.2 Performance of wearable antenna under bending effect

As in most applications of wearable antennas, flat surfaces for embedding the antenna cannot be guaranteed. Curves and bends are expected when embedding wearable antennas. Therefore, it is necessary to evaluate the performance of wearable antennas in various bending conditions.


Agilent Technologies: N9916A, SN: MY53102895

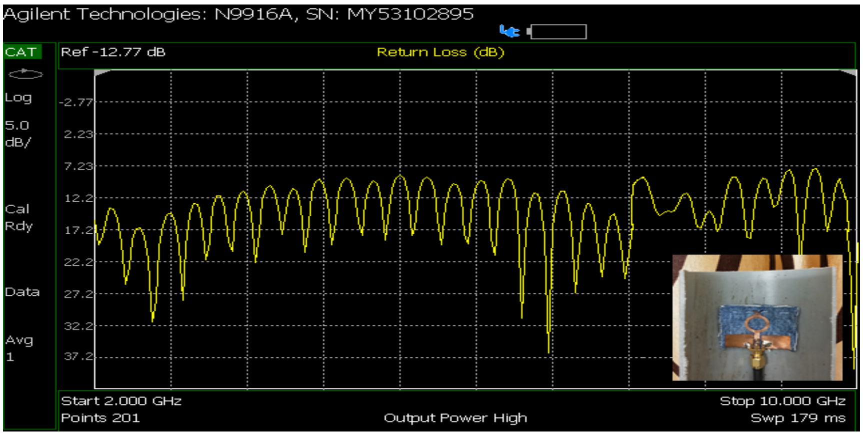
CAT Ref -12.77 dB Return Loss (dB)

Log 5.0 dB/ Cal Rdy Data Avg 1

Start 2.000 GHz Stop 10.000 GHz
Points 201 Output Power High Swp 179 ms

Figure 10: Performance of compact wearable patch antenna fabricated on jeans material under bending effect (concave bending)

The performance of compact wearable patch antenna fabricated on jeans material when subjected to concave bending is shown in Fig. 10. When the antenna was subjected to concave bend on a cross-sectional piece of pipe of radius 3.18 cm, the antenna showed a shift in resonant frequency as well as a change in bandwidth. The fundamental resonant frequency shifted from 2.45 GHz to 2.09 GHz with a 10% reduction in bandwidth at the new resonant frequency. Contrarily, when subjected to convex bending, no significant change in antenna performance at lower frequencies was reported as shown in Fig. 11. However, at a higher frequency, a change in bandwidth of 10-15% was reported.


Agilent Technologies: N9916A, SN: MY53102895

CAT Ref -12.77 dB Return Loss (dB)

Log 5.0 dB/ Cal Rdy Data Avg 1

Start 2.000 GHz Stop 10.000 GHz
Points 201 Output Power High Swp 179 ms

Figure 11: Performance of compact wearable patch antenna fabricated on jeans material under bending effect (convex bending)

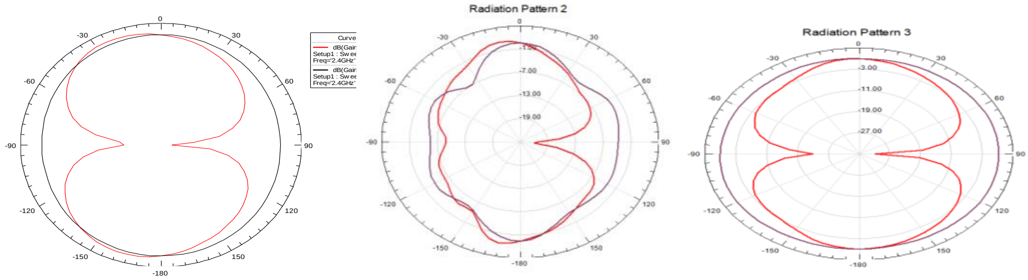


Figure 12: Simulated radiation characteristics along E-plane and H-plane at (a) 2.41 GHz (b) 6.2 GHz and (c) 8.3 GHz

7. CONCLUSION

The research conducted shows that wearable antennas (simple and monopole) fabricated on the cotton substrate have measured results deviating from simulated results. There are various reasons which can alter the performance of the wearable antennas as enlisted in the thesis. However, wearable antenna fabricated on jeans material offers more correlated simulated and measured results under the same constraints. Wearable antenna fabricated on jeans material offers excellent wide bandwidths along with multiband operation. Also when the same antenna was subjected to various constraints (such as deformations, bending, or on body antenna placement), it still offered excellent measured electrical characteristics as compared to wearable antenna fabricated on the cotton substrate.

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