WEARABLE ANTENNAS FOR ON - BODY COMMUNICATION SYSTEMS

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ABSTRACT

A wearable antenna is meant to be a part of the clothing used for communication purposes, which includes tracking, mobile computing, navigation and public safety. The rapid development of body area network (BAN) concepts has spawned a considerable research interest over the past decade due to their promising applications in a wide variety of diverse areas including health monitoring, patient tracking, wearable computing, battlefield survival, and so on. Several frequency bands have been identified for research and commercialization of BAN communication systems, such as the 402 - 405 MHz Medical Implant Communication Services (MICS) band, the 2.4 – 2.48 GHz industrial, scientific and medical (ISM) band, the 3.1 – 10.76 GHz ultra-wide band (UWB) range and others. More recently, a new medical BAN (MBAN) band, which operates from 2.36 to 2.4 GHz, has been considered by the Federal Communication Commission (FCC) for its clean spectrum and low interference sources. There is currently much interest in body-worn communication systems whether for off-body communications or on-body communications to fixed and mobile networks. Such systems are of interest for detecting motion on the body during exercise, monitoring functions such as pulse rate and blood pressure, use by the emergency services, and for general network connection.

1. INTRODUCTION

The wireless body-centric communication within personal area networks and body-area networks can be classified as off-body, on-body, or in-body as shown in Fig. 1. The first class of communication takes place from off-body to an on-body device or system. The second class forms the wireless communication link within on-body networks and wearable systems. The third class is the wireless communication to medical implants and sensor network (Rao et al., 2014). Consequently, antennas for applications such as airwave at 400 MHz, mobile telephones 800–2200 MHz and network communications at 2.45 GHz and 5–6 GHz are of great interest. Body-worn antennas may be made from textiles and attached on body or integrated into clothing, or may be worn as a button antenna (Zhu and Langley, 2009). Emerging military applications are focused on integrating these devices into military clothing in an attempt to enhance soldier performance, awareness and survivability on the battle field (Winterhalter et al., 2005). Recently, biomedical sensor networks mounted on or implanted within the human body have drawn greater attention for healthcare monitoring. As population grows, the demand on healthcare resources increases and many governments are looking for remote healthcare solutions. Wearable monitoring systems have capability to examine medical data in home or ward, facilitating disease prediction, diagnosis and, in some cases, even control of condition (Kiourti and Nikita, 2012).

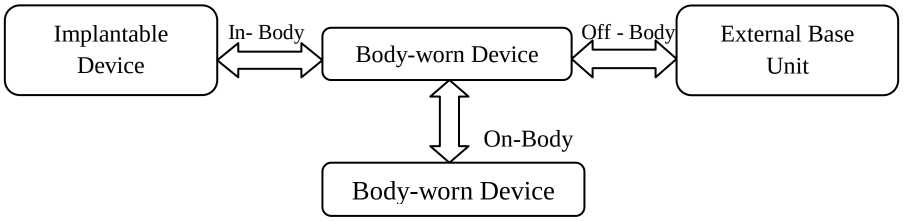


Fig.- 1: Classification of Wireless Body-Centric Communication

By reducing clinical face-to-face consultations and shortening hospital stays, such technology can help compensate for limited healthcare and medical resources. Regardless of the application area, an important aspect of wearable communications is the preservation of antenna performances, yet antennas must be small, light weight, least affected by human body, unobtrusive to the users and ideally comfortable to the body (Wang et al., 2013). Fabric antennas are more prone to discontinuities in substrate material and fabrication related performance variations in comparison to antenna constructed using available high quality rigid substrates. Secure feed connections to textile antennas still remain a significant problem in robust wearable system design (Conway et al., 2007).

When communicating wirelessly in the proximity of a human body, the propagation channel is dependent upon the body condition, the human activity being performed, the antenna orientation, the immediate surrounding environment, the interaction between the human body and the antenna. Therefore, the radio propagation channel in this (on-body) scenario directly includes the body effects (Hall et al., 2007). It becomes important therefore to be able to characterize any antenna, specifically designed for use “on-body,” in a realistic scenario (i.e., on a human being) to attempt to accurately quantify the effect of the human body on any associated antenna parameters of interest. The wearable antenna placed conformally onto the right arm is shown in Fig. 2.

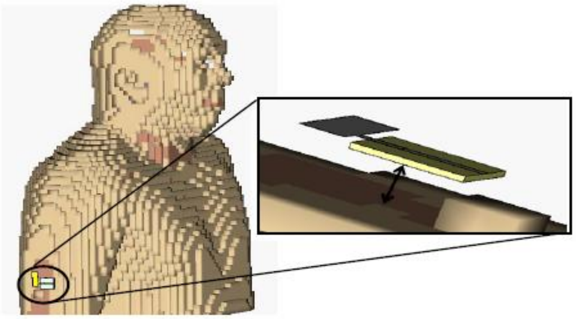


Fig.- 2: Antenna Setup on Human Arm

2. STRUCTURE OF WEARABLE PATCH ANTENNA

Microstrip patch antenna consists of a radiating patch on one side of a dielectric substrate which has a ground plane on the other side as shown in Fig. 3. The patch is generally made of conducting material such as copper or gold and can take any possible shape. The radiating patch and the feed lines are usually photo-etched on the dielectric substrate. In case of fully wearable antennas, the dielectric substrate is fabric such as polyester or jeans cloth and for partially wearable antennas, the dielectric substrate is not cloth based. Thus, partially wearable antennas are implanted onto the clothes and are less flexible than fully wearable antennas.

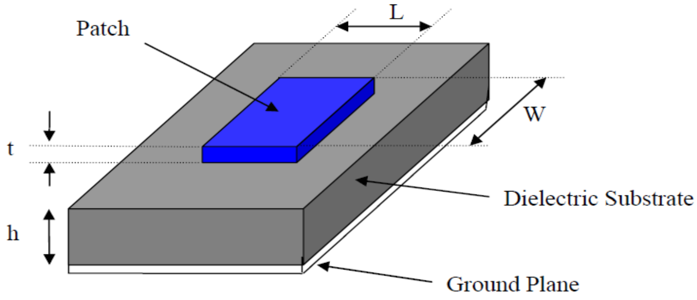


Fig.- 3: Structure of Microstrip Patch Antenna

3. SELECTION CRITERIA OF SUBSTRATE FOR WEARABLE ANTENNAS

3.1 PERMITTIVITY

The permittivity (ε) is expressed in terms of relative permittivity (ε_r) as : $\varepsilon = \varepsilon_0\ \varepsilon_r$, where ε_0 is the permittivity of vacuum, which is 8.854×10^{-12} F/m. In general, the dielectric properties depend on the frequency, temperature, and surface roughness, and also on the moisture content, purity and homogeneity of the material. The real part of the relative permittivity, is called the dielectric constant and is not constant in frequency. For the design of patch antenna dielectric constant of substrate is in the range of $2.2 \leq \varepsilon_r \leq 12$. But for textile material dielectric constant is less than 2. The lower dielectric constant reduces the surface wave losses which are tied to guided wave propagation within the substrates. Therefore, lowering the dielectric constant increases spatial waves and hence increases the impedance bandwidth of the antenna, allowing the development of antennas with acceptable efficiency and high gain (Jarvis et al., 2010).

3.2 LOSS TANGENT

Loss tangent tanδ (also known as dissipation factor) characterizes the amount of power turned into heat in the material. The higher the loss tangent values, the more lossy the dielectric substrate will be. Higher losses means reduced radiation efficiency (Jarvis et al., 2010).

3.3 THICKNESS OF THE DIELECTRIC SUBSTRATE

The bandwidth and efficiency of a patch antenna is mainly decided by the substrate dielectric constant and its thickness. The thickness h of substrate is usually in the range of $0.003\lambda \le h \le 0.005\lambda$ where λ is a wavelength. For a fixed relative permittivity, the substrate thickness may be chosen to maximize the bandwidth of the patch antenna. However, this value may not optimize the antenna efficiency. Therefore, the choice of the thickness of the dielectric material is a compromise between efficiency and bandwidth of the antenna (Sangakaralingam and Gupta, 2009). The influence of the thickness on the bandwidth (BW) of the antenna and the antenna quality factor (Q) may be explained by Equation (1.1).

$$BW \sim 1/Q \qquad (1.1)$$

For thin substrates the quality factor associated with radiation is inversely proportional to the height of the substrate. Therefore, increasing the height of the substrate lowers the Q factor. As the Q-factor decreases with an increased aperture between the patch and the ground planes of the antenna, a thicker substrate allows a larger antenna bandwidth. Fig. 4 shows the samples of Taffeta, Shieldit, Flectron, Zelt electro-textile material.

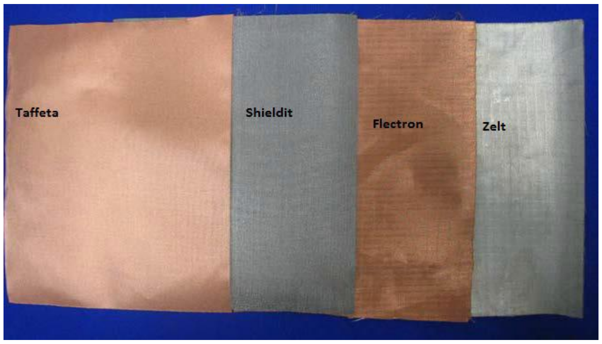
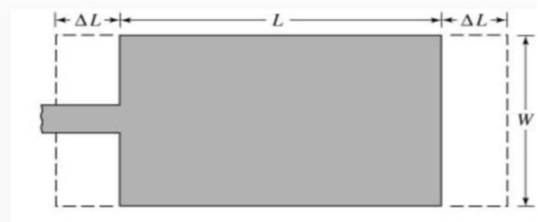


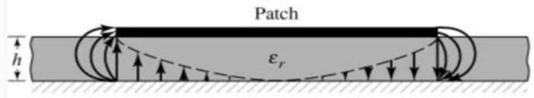
Fig. -4: Samples of Taffeta, Shieldit, Flectron, Zelt Electro-Textile Material

4. DESIGN CRITERIA OF WEARABLE PATCH ANTENNA

To design, a rectangular microstrip patch antenna which has the given fabric material as its substrate is to be designed assuming an approximate value of dielectric constant. The value of the dielectric constant of this fabric substrate material may be computed by simply measuring the resonant frequency of the patch radiator. The design of the microstrip patch antenna involves the calculation of its patch dimensions (Balanis, 1997).



(a) Top view



(b) Side view

Fig.- 5: Physical and Effective Length of the Microstrip Patch

The patch width (w) has a minor effect on the resonant frequency (f_r) , and it is calculated using the following formula:

$$w = \frac{c}{2fr}\sqrt{\frac{2}{(\varepsilon_r+1)}} \qquad (1.2)$$

Where c is the speed of light in free space and εr is the relative permittivity of the fabric material under test. The microstrip patch lies between air and the dielectric material, and thus, the EM wave sees an effective permittivity (εreff) given by equation (1.3):

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2\sqrt{1+12\frac{h}{w}}} \qquad (1.3)$$

Where h is the thickness of the substrate. The patch length (L) determines the resonant frequency and it is a critical parameter in design because of the inherent narrow bandwidth of the patch. The design value for L is given by (1.5).

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{reff}}} \qquad (1.4)$$

$$L = L_{eff} - 2\Delta L \qquad (1.5)$$

Where εreff is the effective permittivity of the material under test. The additional line length on ΔL both ends of the patch length, due to the effect of fringing fields, is given by (1.6).

$$\Delta L = 0.412h\frac{(\varepsilon_{reff}+0.3)\left(\frac{w}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{w}{h}+0.8\right)} \qquad (1.6)$$

5. FABRICATION OF WEARABLE ANTENNA

Authors have been improving the manufacturing processes to construct textile antennas and some of the guidelines for their fabrication are summarized as follows:

1. The geometrical dimensions of the patch should remain stable while connecting to the dielectric substrate as the mechanical stabilization of both materials is essential to preserve the desired antenna characteristics.
2. The techniques used to connect the various layers must not affect the electrical properties of the patch, such as its surface resistivity, nor the properties of the substrate. This process of attachment of the superposed layers is very simple to perform by a simple ironing operation. However, attention should be made to the ironing process, in special if the patch is made of a fabric with metallic components.
   Indeed, the oxidation of the metallic component, due to the hot moistening of the fabric, may increase the surface resistance of the fabric and so decrease the efficiency of the textile antenna.
3. The heterogeneities introduced in the substrate due to the extra layers of air between the fabrics, influencing its dielectric properties must be minimized.
4. Finally, the connections at the antenna terminals may also be critical as in wearable and flexible antennas these connections have to be mechanically robust.

6. DIFFERENT TYPES OF ANALYSIS REQUIRED FOR WEARABLE ANTENNA

6.1 EFFECT OF HUMAN BODY INTERACTION ON ANTENNA PERFORMANCE

The human body is an irregularly shaped medium with frequency dependent permittivity and conductivity. The distribution of the electromagnetic field inside the body and the scattered field depends largely on the body physiological parameters, geometry, frequency and polarization of the incident field. To verify antenna performance in wearing conditions, the antenna can be implanted on cotton coat. Measurements are then taken with and without human body as shown in Fig. 6 and Fig. 7 respectively.

Due to high permittivity of body tissues the antenna resonant frequency will change and detune to a lower one. Another important parameter is the antenna Gain that directly affects the power transmitted in a maximum radiation direction. Due to lossy human body, some part of radiating power of an antenna will be absorbed by it and it will result in lower Gain.

Thus, variations in resonant frequency and radiation characteristics must be negligible, when wearing on high loss human body. This proves that antenna is suitable for wearable applications (Wang et al., 2013).

Fig.- 6: Antenna Implanted on Cloth

Fig. -7: Antenna Performance Measurement in Chamber with Human Body

Also, a cylindrical multilayer human tissue model can be employed to mimic human arm, which consists of four layers each representing skin, fat, muscle and bone. For each layer, typical permittivity, conductivity, thickness and mass density values are given in Table 1. The distance between the antenna and the tissue model is varied in order to study the loading effects of the human body (Jiang et al., 2014).

Table- 1: Material Properties of Multilayer Human Tissue Model

Tissues Properties	**Skin**	**Fat**	**Muscle**	**Bone**
ε_r	37.95	5.27	52.67	18.49
σ (S/m)	1.49	0.11	1.77	0.82
Density (Kg/m^3)	1001	900	1006	1008
Thickness (mm)	2	5	20	13

6.2 BENDING EFFECTS ON ANTENNA PERFORMANCE

Due to flexibility, wearable antenna is subjected to bending and crumpling when wearing. It may cause frequency shift and performance deterioration (Bai and Langley, 2012). Under an on-body environment it is difficult to keep the antenna in a flat condition especially for elements made of textile materials. Comparing with pure textile antennas, the Ethylene Vinyl Acetate (EVA) based antennas are rigid enough to resist against crumpling. However, bending along body surface is still unavoidable. To validate the performance and stability in bending conditions, a study on bending effects should be performed (Wang et al., 2013).

The yz-plane bending and xz-plane bending of antenna must have minor effects on antenna performance in terms of return loss of antenna.

The radiation characteristics of antennas should be measured for two orthogonal bending planes E-plane and H-plane (Salonen and Samii, 2007).

Polystyrene formers of two different diameters of 80 and 140 mm, respectively, can be chosen, corresponding approximately to the typical size of a human arm and leg. The H-plane bending causes the resonance to move up in frequency by 75 MHz for the 80 mm former, and slightly less for the larger 140 mm former of about 65 MHz. For an E-plane bend, the resonance moves downward by 75 MHz for the 140 mm former and 120 MHz for the 80 mm former. There should be no significant changes in the gain and beam-width of bent and planar antennas (Zhu and Langley, 2009).

Fig. 8 shows typical application scenery when wearing. Three different conditions, which include flat no bending (R ∞), moderate bending (R = 500 mm) and severe bending (R = 125 mm) needs to be analyzed.

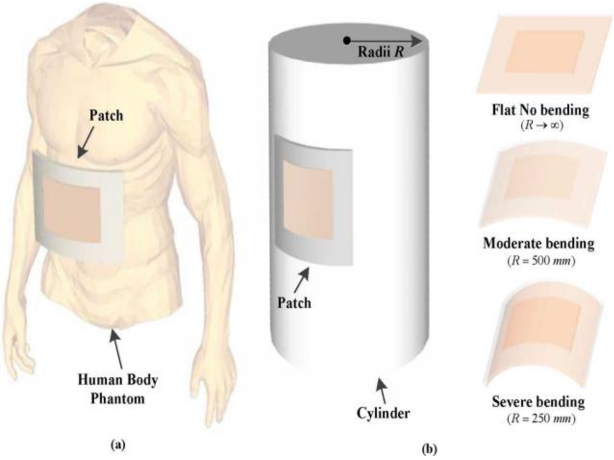


Fig.- 8: (a) Typical Application Scenery when Wearing Antenna (b) The Model and Different Bending Conditions used in Simulations

6.3 SAR MODELING

For wearable antenna design, the Specific Absorption Rate (SAR) is an important measure criterion for safety considerations. Lower SAR indicates that less radiation is absorbed by the body. Public concern regarding the health effects of radiation and legal requirements around the world have urged engineers and researchers to always consider the amount of power absorbed by the human body. Therefore, specific absorption rate (SAR) by wireless devices has been defined. The two most commonly used SAR limit are those of IEEE 1.6W/kg averaged over 1g of tissue (Wang et al., 2013) and IEC (International Electrotechnical Commission) 2W/kg averaged over 10g of tissue (Sundarsingh et al., 2014).

6.4 ANTENNA PERFORMANCE IN ADVERSE CONDITIONS

Antennas are expected to work in all kinds of environments and conditions. Designed antennas must meet this criterion, especially at very high, very low temperatures and in humid conditions. Measurements should be taken to investigate heat resistance and low water absorption characteristics of the fabricated antenna.

For this, the antenna can be placed in front of a heater at about 160ºC - 180ºC for 20 minutes, and later be placed in water for 30 minutes to test absorption factor. In both scenarios, Return Loss is measured and results should be comparable to the free-space result (Abbasi et al., 2013).

7. SOME RECENTLY DEVELOPED WEARABLE ANTENNAS

7.1 EMBROIDERED WEARABLE ANTENNA

Previous textile antennas were usually composed of materials that were not possible to allow washing and reusing of the wearable suite. Thus, embroidery based new antenna is made entirely from textile materials as shown in Fig. 9 along with new features provided by being easily and directly integrated into clothing, guarantees washing of the wearable device and accordingly reuse of it. Jeans fabric and flannel fabric are used as substrate materials. Both fabrics are made from 100% cotton materials with a smooth and firm surface and suitable for wearable applications. A high quality conducting thread is embroidered onto the fabric substrates. According to manufacturer specifications, this conducting thread is made from a silver plated Nylon thread to ensure superior strength and conductivity along with the ability to resist the normal conditions of use such as multiple deformations. Additionally, the conducting thread can be washed as well as its ability to resist temperature up to 150ºC (Osman et al., 2011).

Fig. 9: Embroidered Wearable Antenna Prototype

7.2 FABRIC KNITTED WEARABLE ANTENNA

In this type of antennas, knitting is used as a technique of fabricating antennas. These antennas are fully fabric with a knitted ground plane, a knitted substrate and a knitted patch element. They are fabricated using industrial knitting machinery and hence could potentially be scaled up to mass-manufacture. Four different versions are considered (all have a knitted ground plane and substrate):

i) A conducting material coated nylon fabric knitted patch.

ii) A knitted patch with a high fiber density.

iii) A knitted patch with a medium fiber density.

iv) A knitted patch with a coarse fiber density.

The resulting antennas are extremely flexible and soft to the touch (Zhang et al., 2013).

7.3 WEARABLE RFID SENSOR TAGS

A new tag geometry combining folded conductors and tuning slots can be achieved, having size comparable with a credit card, and can be applied to any part of the body. The measured performance indicates a possible application of these body-worn tags for the continuous tracking of human movements in a conventional room (Occuhiuzzi et al., 2010). Recently the durability of embroidered passive UHF RFID dipole tag antennas is explored using various kinds of washing procedures. The embroidered RFID antennas are fabricated on 0.25-mm-thick cotton fabric using a computer-aided sewing machine and conductive sewing thread as shown in Fig. 10.

Also, protection technique can be used to reinforce the embroidered tag's durability and should be hydrophobic to protect the conductive thread, the tag's IC, and the antenna-IC interconnection from water. Moreover, it should maintain the softness and flexibility of the tag antenna without impairing the tag's performance. Polydimethylsiloxane (PDMS) polymer is a potential candidate that fulfills these requirements. It is a soft, hydrophobic, heat-resistant, low-loss, and flexible material (Rao et al., 2014). Embedding an embroidered tag in PDMS thus protects it from environmental stress, while maintaining the flexible structure. In addition to achieving totally garment integrated antennas, the transparent PDMS can be used to coat tags that have been embedded in very decorative embroidered figures.

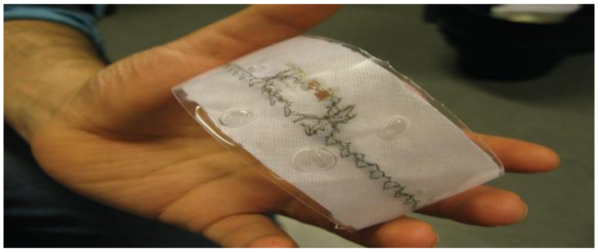


Fig. 10: PDMS Coated Embroidered RFID Tag

7.4 HELMET AND VEST ANTENNA

Soldier, police, firefighter, forest worker, etc. in the field need "hands free" operation for their wireless equipment. A solution is to use antennas worn on their helmet (as helmet antenna) or on their upper torso (as vest antenna) as shown in Fig.11. The design of body-wearable antennas has become increasingly more challenging as its frequency bandwidth escalates. Furthermore, the larger the bandwidth required, the more difficult it is to meet regulatory mandate of radiation safety and user mandates for body-wearability, light-weight, cost etc. Consequently, helmet and vest antennas thus far have large bandwidth, and meet all regulatory and user mandates. The antenna is connected with a flexible feed cable embedded in a lightweight energy absorbing material, which can serve as impact protection for wearer's head. Thus, the antenna fills a portion of the previously void space within the helmet with no loss in safety to the wearer. It is worth noting that some new military helmet designs use energy absorbing foam instead of air gap to protect wearer's head (Wang and Triplett, 2007).

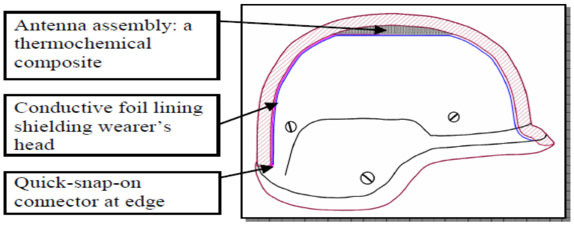


Fig. 11: Helmet Antenna

7.5 WEARABLE MONOPOLE ZIP ANTENNA

A zip is used to realise a monopole antenna. This element is very often present in garments, often in pockets and it can be an easy way to hide antennas. Preferably a pocket zip will be used for practical considerations. This novel zip antenna can be used in Wi-Fi communication systems**.** The zip antenna is manufactured using felt as dielectric and electro-textile as the conductor as shown in Fig. 12.

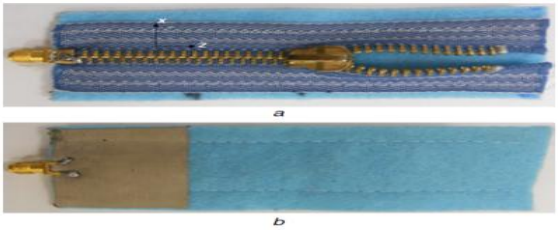


Fig. 12(a): Zip Antenna Prototype Upper Side (b) Back Side

8. CONCLUSION

From the review, it is concluded that there are several aspects to be taken into consideration when designing a wearable antenna, in comparison to a conventional antenna design. It showed that there exists several of potential materials that could be used in designing wearable antennas. SAR analyses, measurements with different antenna bending effects and on body measurements have to be done in order to obtain an antenna design that meets the wearable antenna specification. Wearable antennas are promising, and boast a great future alongside the development of the rapidly growing wireless communication technology.

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