COMPACT PLANAR WEARABLE ULTRA WIDEBAND ANTENNA FOR ON-BODY APPLICATIONS

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ABSTRACT

The increasing growth in using body area networks (BANs), wireless personal area networks (WPANs), and medical sensors has given an interest in wearable antennas that are made for operation on the living bodies. Engineers have not stopped at creating a remarkable technology such as wearable systems, but also involved in understanding the interaction of electromagnetic (EM) waves with the body. Studying the interaction between EM waves and the body requires modeling of the body with physical phantoms or with numerical phantoms embedded in numerical electromagnetic codes. In this project, two ultra-wideband (UWB) planar monopole antennas have been reported in this thesis. The substrates of the proposed antennas have been made of jeans while radiators were made of copper tapes. Simulated and measured performances of the antennas in terms of return loss and radiation patterns have been discussed in this work. Recorded results have shown that the operating frequency ranges from 3.04 GHz to 10.3 GHz and from 3.04 GHz to 11.3 GHz with respect to -10 dB for the first and second antennas respectively. The antennas have been tested under severe conditions such as operating in water and aggregates, and results have been presented and discussed. Moreover, an extended study on the safety concerns of the antennas by means of specific absorption rate (SAR) has been included in this work. The approximated SAR has been found to be within the safety guidelines set by Federal Communications Commission (FCC).

ABSTRAK

Pertumbuhan yang semakin meningkat menggunakan rangkaian kawasan badan (BANs), rangkaian kawasan peribadi tanpa wayar (WPANs) dan sensor perubatan telah memberikan kepentingan kepada antena boleh pakai yang direka untuk operasi kehidupan. Jurutera tidak berhenti untuk mewujudkan satu teknologi yang luar biasa seperti sistem boleh pakai, tetapi juga terlibat dalam memahami interaksi elektromagnet (EM) gelombang dengan badan. Mengkaji interaksi antara gelombang EM dan badan memerlukan pemodelan tubuh dengan model fizikal atau dengan model berangka tertanam dalam kod elektromagnet berangka. Dua reka bentuk antena eka kutub ultra jalur lebar telah dilapor dan dibincangkan di dalam tesis ini. Substratum rekabentuk antena yang dicadangkan dihasilkan daripada fabrik jeans manakala radiator pengujaan dihasilkan daripada pita tembaga. Persembahan simulasi dan pengukuran antena dari segi kehilangan balikan dan radiasi corak telah dibincangkan di dalam thesis ini. Keputusan yang dicatatkan telah menunjukkan bahawa antena beroperasi pada jalur frekuensi lebar 3.04 GHz – 10.3 GHz dan 3.04 – 11.3 GHz dengan pekali pantulan < -10 dB untuk antena pertama dan kedua. Antena telah diuji di bawah beberapa keadaan seperti yang beroperasi di dalam air dan agregat, dan keputusan kajian telah dibentang dan dibincangkan. Selain itu, satu kajian lanjutan terhadap kebimbangan keselamatan antena melalui kadar penyerapan tertentu (SAR) juga telah dibincangkan di dalam penyelidikan ini. Nilai SAR yang diperolehi didapati telah mengikut garis panduan keselamatan yang ditetapkan oleh Suruhanjaya Komunikasi Persekutuan (FCC).

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LIST OF SYMBOLS AND ABBREVIATIONS

ᴗ	-	Mass density
±	-	Conductivity
£$_{r}$	-	Permittivity of the substrate
£$_{reff}$	-	Effective permittivity of the substrate
AB	-	Absolute bandwidth
BANs	-	Body area networks
CST MWS	-	Computer Simulation Technology Microwave studio
EM	-	Electromagnetic
FB	-	Fractional bandwidth
FR-4	-	Flame Retardant 4
GHz	-	Giga Hertz
ICNIRP	-	International Commission on Non-Ionizing Radiation Protection
IEEE	-	Institute of Electrical and Electronics Engineers
LOS	-	Line-of-sight
MRI	-	Magnetic resonance imaging
PCB	-	Printed circuit boards
RAM	-	Radar absorbent material
RF	-	Radio-wave
SAR	-	Specific absorption rate
UHF	-	Ultra high frequency
UWB	-	Ultra-wideband
UWEN	-	UWB wireless embedded networks
WLAN	-	Wireless local area network
WPANs	-	Wireless personal area networks

LIST OF PUBLICATIONS

Journals:

(i) Waddah A. M. A. Khairun N. R. and Abdirahman M. S. (2015). Performance of Ultra-Wideband Wearable Antenna under Severe Environmental Conditions and Specific Absorption Rate (SAR) Study at Near Distances, *ARPN Journals*

Proceedings:

(i) Ashwal, W. A. M. Al, & Ramli, K. N. (2013). Compact UWB wearable antenna with improved bandwidth and low SAR. In 2013 IEEE International RF and Microwave Conference (RFM) (pp. 90–94). Kuala Lumpor: IEEE. doi:10.1109/RFM.2013.6757225

(ii) Ashwal, W. A. M. Al, & Ramli, K. N. (2014). Small Planar Monopole UWB Wearable Antenna with Low SAR. In 2014 IEEE Region 10 Symposium (TENSYMP 2014) (pp. 235–239).

CHAPTER 1

INTRODUCTION

1.1 Research Background

‘Ultra-wideband’ (UWB) describes that the system/signal possesses a large bandwidth (Allen et al., 2006). UWB systems offer high data rate, low cost equipments, multipath immunity and both precise ranging (object location) and high speed communication at the same time. Before UWB technology was commercialized, it has been developed mainly in military radar systems. Today, UWB technology is changing the wireless industry and competing with narrowband technology with its method of spreading signal across a wide range of frequencies instead of broadcasting on separate frequencies (Ghavami, Michael, & Kohno, 2004).

Consumer markets present most exciting opportunities for commercializing applications that are part of our daily life. UWB can play a part in enhancing and enriching these applications more efficiently.

As the applications in communication come in two categories, low and high data rate, both share the two best qualities of UWB, which are low power and high capacity. Low data rate devices, like home intruder detector usually attached by wires and cables, can be developed into wireless device, but such solution on today’s market is restricted by line-of-sight (LOS) interference and power issues. UWB is not bound by LOS as is infrared light, since wavelengths are long by comparison and can generally bend around or transmit through objects without impeding the connection. It is also immune against shades and light-related interferences. The intermittent low power fashion of UWB makes it possible to operate hundreds of devices in the same space without interfering one another.

Indoor devices like computer peripherals can be improved in an innovative way. They can be made wireless and utilized to share the space. This shared space can include a wireless printer, monitor, audio speakers and more of computer accessories such as wireless mouse and keyboard.

Medically, sensors are used to monitor the critical life signs of a patient. Monitoring systems come with wires and cables connected to these sensors which are attached to the patient's body. This creates uncomfortable scenario for the patient surrounded by wires in constant matter. UWB wireless sensor network makes that choice avoidable.

There is the so-called UWB wireless embedded networks (UWEN) project that is working on developing systems with low rate communication for location and tracking applications. Such application targets to improve security of material goods, find our keys, keep pace with children, find people in situations, including fire fighters in burning building, police officers in distress, and track people at recreational activities such as cross country skiing and athletics. The key concept is to develop carried low power UWB devices and data from users transmitted to fixed nodes and exchange signal time of arrival information which enables to determine the location of the device (Siwiak & McKeown, 2004).

The increasing growth in using body area networks (BANs), wireless personal area networks (WPANs), and medical sensors has given an interest in wearable antennas that are made for operation on the living bodies. They are found in portable radio equipments used by the military, the pager and mobile phones. The introduction of body worn medical sensors and wireless medical sensor networks has enabled doctors and specialists to monitor patients at a distance (Guha & Antar, 2010).

Engineers are not done with only creating remarkable technology such as wearable systems, but also involved in understanding the interaction of electromagnetic

(EM) waves with the body in body-centric communications and wireless systems that operate close to the body. This helps understand the nature of electromagnetic properties of body tissues and how they vary significantly with tissue type and frequency. This understanding enables the development of antennas and transceivers for such communications systems. Studying the interaction between EM waves and the body requires modeling of the body with physical phantoms or with numerical phantoms embedded in numerical electromagnetic codes.

A phantom is defined as a simulated biological body or as a physical model mimicking the characteristics of the biological tissues. The aim of modeling a phantom is to predict and explore the interaction between the human tissue and the electromagnetic fields. For this purpose, phantoms have been used extensively in medical research on the effects of electromagnetic radiation on health, as well as in development of various methods of medical diagnosis and treatment, such as X-ray, magnetic resonance imaging (MRI) scan, and hyperthermia.

With the increase of communication devices that will be worn or operating close to the human body, the phantoms became an essential tool for testing safety of such devices. Various safety standards specify the acceptable limits of radiation in terms of specific absorption rate (SAR), which can be measured using a number of methods involving phantoms. Phantoms are also a useful tool in studying the EM wave propagation around and inside the human body. Such studies are necessary to help design powerful, robust, reliable, wearable low-cost communication devices. Phantoms can also provide a steady, controllable propagation environment, which cannot be easily realized with human subjects.

Many numerical phantoms have been modeled for theoretical analyses and computational simulations. Theoretical phantoms are simple-shaped phantoms and generally used in theoretical analyses. However, it is necessary to use voxel phantom, a more realistic numerical phantom, in order to calculate the characteristics of antennas close to the human body, which is composed of many voxels.

Therefore, it still remains as an engineering challenge to explore the area of wearable application in all aspects and produce suitable, reliable, and safe technology for these applications.

1.2 Problem Statements

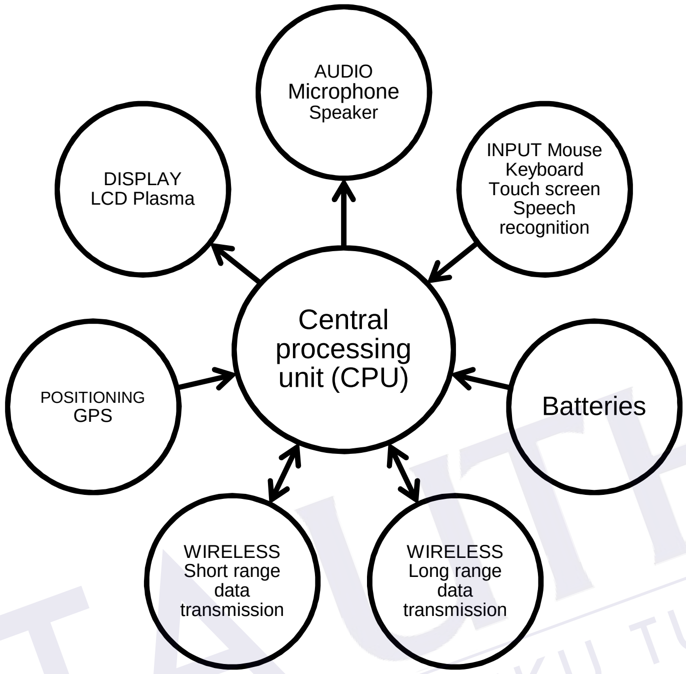
Body worn system consists of electronic devices normally situated on or in close proximity to the human body. Figure 1.1 shows that both short range and long range wireless communication plays an important role in mobile wearable systems. However these communication systems consist of several subparts of which antenna is the most essential one and the quality and reliability of a connection will depend a great deal on optimal design of antennas.

The wired connection between devices in a body area network (BAN) may be inconvenient for a user. This may be due partly to weight and partly to restriction in movement and prescriptions placed on clothing design and manufacture. Therefore, the need for comfortability is pushing the trend of wireless communication in place of wired one.

The making of wearable UWB antenna requires an operating frequency in the range of 3.1 GHz – 10.6 GHz, flexible radiators and substrates and consideration of safety limits standards by providing low readings of the specific absorption rate (SAR).

The size of the antenna is one of the critical issues in UWB system design, because it greatly affects the bandwidth and gain. Therefore, the miniaturization of antennas capable of providing abroad impedance matching bandwidth and offering an acceptable gain is a challenging task (Chen & Yang, 2008).

The human body is composed of a large variety of tissue types, each having different dielectric properties, and this data is important for the design of wearable antennas (Guha & Antar, 2010). Body-centric communication systems involve the interaction between electromagnetic waves and the body tissues. It is most important to account for the overall performance of the antenna in the vicinity of human body. At the same time, it is an engineering task to optimize the design of the antenna in order to comply with safety guidelines, such as those standardized by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) (Ahlbom et al., 1998) and the Institute of Electrical and Electronics Engineers (IEEE) (“IEEE Recommended


AUDIO
Microphone
Speaker
DISPLAY
LCD Plasma
INPUT Mouse
Keyboard
Touch screen
Speech
recognition
Central
processing
unit (CPU)
POSITIONING
GPS
Batteries
WIRELESS
Short range
data
transmission
WIRELESS
Long range
data
transmission

As for wearability, textiles are good candidates for making the proposed antennas flexible. As textiles have low permittivity, which contributes to the bandwidth improvement, jeans has been elected for the substrates of the proposed antennas. A low reading of SAR is also one of the concerns of wearable systems. Therefore, the proposed four-layer numerical phantom model (bone, muscle, fat and skin) can provide an acceptable accuracy for the performance of the antennas as well as the computation of SAR.

1.3 Objectives

The main objectives of the proposed work are:

i. To design a compact planar antenna that covers the range of ultra wideband spectrum (3.1 GHz – 10.6 GHz).
ii. To explore the utilization of textile materials in making wearable UWB antennas.
iii. To study the effect of a numerical phantom on the proposed designs and ensure that the specific absorption rate (SAR) comply with the safety limit standards.

1.4 Scope of Study

This study will focus on the performance improvement in terms of bandwidth for the ultra wideband antenna designed using jeans as a substrate. In order to succeed, a number of procedures have been identified as listed below:

i. Focus on designing small sized planar UWB antenna.
ii. Obtain the characteristics of jeans substrate, tangent loss and permittivity ε_r, by means of measurement.
iii. Use the finite difference time domain method (FDTD) to study the performance the proposed UWB antenna before the actual prototype is built.

iv. Develop four-layer (bone, muscle, fat and skin) numerical phantom model to approximate the performance of the proposed antennas for on-body condition and evaluate the SAR.

1.5 Thesis Organization

The thesis is organized in four chapters as follows:

Chapter 1 gives a brief background of the research and defines the objective, problem statement and scopes.

Chapter 2 contains the literature review, which examines a comprehensive background of other related research works and the fundamental antenna parameters that should be considered in designing UWB antenna. It also summarizes some studies on narrowband and wideband wearable antennas, especially on their physical construction. Finally, a brief study of phantoms and specific absorption rate (SAR) is also included.

Chapter 3 is about the design methodology applied in this proposed work and discusses in details the methodology of the literature review, UWB antenna design process, design techniques, numerical phantom model, and fabrication and measurement setup.

Chapter 4 analyzes the results yielded from the proposed work. There is a brief section on the measurement setup and results for the selected material jeans. The proposed slotted-beveled planar monopole antenna with notched ground-plane has been studied in details. The second proposed design, off-center fed planar monopole, has also been studied widely. Results of the antennas operating under external forces such as bending, and applied environmental conditions such as wetness were examined in depth. This chapter also studies the phantom model proposed for SAR computation and antenna performance on-body.

Chapter 5 concludes the researches that have been done in this thesis. Suggestions for future work are also given in this chapter.

CHAPTER 2

LITERATURE REVIEW

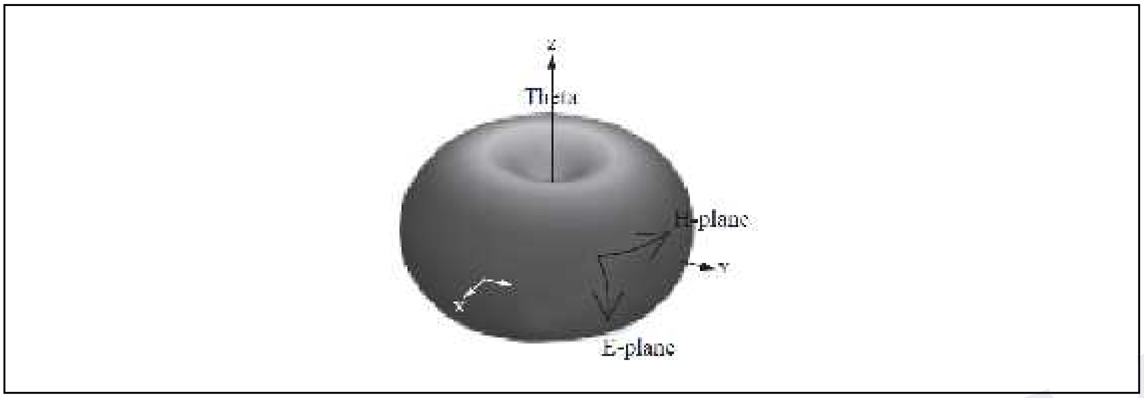
This section of the report summarizes some of the fundamental theories on antennas parameters, introduction to body area networks (BANs), brief study on bandwidth enhancement techniques, and some previous works in the area of UWB antennas as well as wearable antennas in general. Part of the study focuses on the methods used to evaluate wearability of the antennas in terms of flexibility and safety concerns.

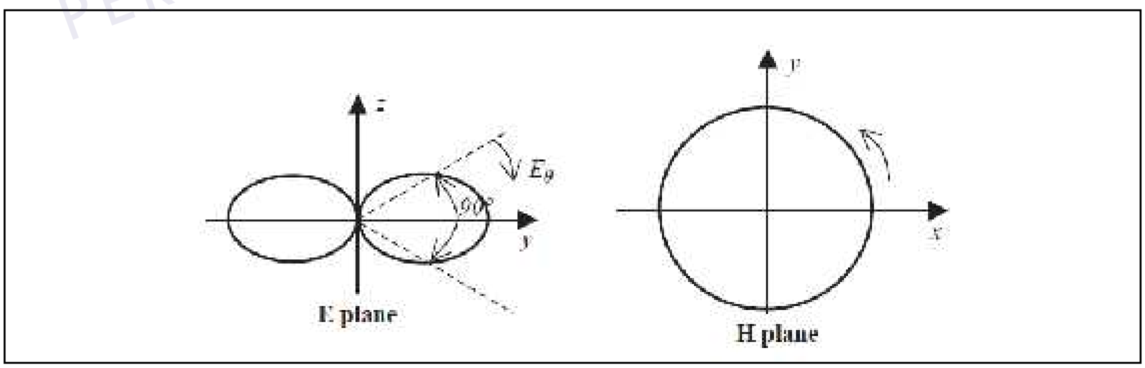
2.1 Antenna Parameters

An antenna is a basic component of systems where it is used as a link between transmitter and free space or free space and receiver. The basic parameters of the antenna include the radiation pattern, radiation intensity, gain, directivity, antenna efficiency, beamwidth the bandwidth. (Huang & Boyle, 2008; Seybold, 2005) discuss some of the important parameters of the antenna in the following section.

2.1.1 Radiation Pattern

The radiation pattern of an antenna is a plot of the radiated field/power as a function of the angle at a fixed distance, which should be large enough to be considered far field. The three-dimensional (3D) radiation pattern of the electrically short current element is


z
Theta
H-plane
y
x
E-plane


z
E_θ
90°
y
E plane
y
x
H plane

The E-plane (at φ = 0) and H-plane (at θ = π/2) patterns of the short current element are shown in Figure 2.2. This antenna has an omni-directional pattern in the H-plane; this is a desirable feature for many mobile antennas since the antenna is not sensitive to orientation. Another special case is called the isotropic antenna, which has the same radiation power at all angles. This is a hypothetical case and cannot be realized in practice, but sometimes it is used as a reference for analysis (Huang & Boyle, 2008).

2.1.2 Gain and Radiation Efficiency

For a real antenna, there will be certain angles of radiation, which provide greater power density than others (when measured at the same range). The directivity of an antenna is defined as the ratio of the radiated power density at distance, d, in the direction of maximum intensity to the average power density over all angles at distance, d. This is equivalent to the ratio of the peak power density at distance d, to the average power density at d:

$$D = \frac{\text{Power density at } d \text{ in direction of maximum power}}{\text{Mean power density at } d} \tag{2.1}$$

Thus an isotropic antenna has a directivity of D = 1. When the antenna losses are included in the directivity, this becomes the antenna gain

$$G = \eta \frac{\text{Power density at } d \text{ in maximum direction}}{P_T / 4\pi d^2} \tag{2.2}$$

where P_T is the power applied to the antenna terminals

$4\pi d^2$ is the surface area of a sphere with radius d

η is the total efficiency, which accounts for all losses in the antenna, including resistive and taper losses ($\eta = \eta_T \eta_R$)

Antenna gain can be described as the power output, in a particular direction, compared to that produced in any direction by an isotropic radiator. The gain is usually expressed in dBi, decibels relative to an ideal isotropic radiator (Seybold, 2005). While the radiation efficiency factor of the antenna is the ratio of the radiated power to the input power accepted by the antenna (Huang & Boyle, 2008):

$$\eta_e = \frac{P_t}{P_{in}} \tag{2.3}$$

2.1.3 Impedance

An antenna presents load impedance or driving point impedance to whatever system is connected to its terminals. The driving point impedance is ideally equal to the radiation resistance of the antenna. In practical antennas, the driving point impedance also includes resistive losses within the antenna and other complex impedance contributors such as cabling and connectors within the antenna. The driving point impedance of an antenna is important in that a good impedance match between the circuit (such as a transceiver) and the antenna is required for maximum power transfer. Maximum power transfer occurs when the circuit and antenna impedances are matched (Seybold, 2005).

2.1.4 Bandwidth

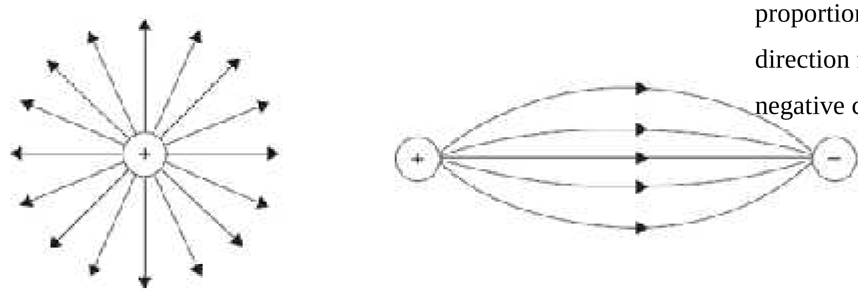
The bandwidth of an antenna may be defined in terms of one or more physical parameters. As shown in equation 2.4, the bandwidth may be calculated by using the frequencies f_u and f_l at the upper and lower edges of the achieved bandwidth:

$$\mathrm{BW} = \begin{cases} \dfrac{2(f_u - f_l)}{(f_u + f_l)} \times 100\% & \text{bandwidth} < 100\% \\ \dfrac{f_u}{f_l} :1 & \text{bandwidth} \geq 100\% \end{cases} \tag{2.4}$$

The bandwidth of an antenna can be defined for impedance, radiation pattern and polarization. First, a satisfactory impedance bandwidth is the basic consideration for all antenna design, which allows most of the energy to be transmitted to an antenna from a feed or a transmission system at a transmitter, and from an antenna to its load at a receiver in a wireless communication system. Second, a designated radiation pattern ensures that maximum or minimum energy is radiated in a specific direction. Finally, a defined polarization of an antenna minimizes possible losses due to polarization mismatch within its operating bandwidth (Z. Chen & Chia, 2006).

2.1.5 Permittivity

Since the electric or E-field depends not only on the flux density, but also on the permittivity of the material or environment through which the wave is propagating, it is valuable to have some understanding of permittivity. Permittivity is a property that is assigned to a dielectric (conductors do not support static electric fields). The permittivity is a metric of the number of bound charges in a material and has units of farads per meter. Permittivity is expressed as a multiple of the permittivity of free space, ε_0. This term is called the relative permittivity, ε_r, or the dielectric constant of the material (Seybold, 2005).



Flux lines have magnitude proportional to the charge and direction from positive charge to negative charge or infinity

$$\pounds = \pounds_r \pounds_0$$

$$\pounds_0 = 8.854 \times 10^{-12}\ F\ /\ m$$

Material	**Relative Permittivity**
Vacuum	1
Air	1.0006
Polystyrene	2.7
Rubber	3
Bakelite	5
Quartz	5
Lead glass	6
Mica	6
Distilled water	81

2.1.6 Loss tangent

In a practical sense, most materials lie on a continuum of properties. The characterization of a material as a conductor or dielectric is based on the dominant property of the material. For lossy dielectrics, the permittivity or dielectric constant is given by

$$£ = £' \left(1 - \frac{j±}{µ£'} \right) \tag{2.6}$$

where σ is the conductivity of the dielectric. Thus the dielectric constant is a complex value with the imaginary part representing the loss characteristics of the material. The loss tangent is defined as σ/(ωε') and represents the ratio of conductive current to the displacement current in the material. A material can be considered low loss if the loss tangent is less than 0.1, and it is considered high loss if the loss tangent is greater than 10 (Seybold, 2005).

2.2 Body Area Networks (BANs)

Current communication systems are driven by the concept of being connected anywhere at any time. An essential part of this concept is a user-centric approach in which services are constantly available and systems provide reconfigurability, unobtrusiveness and true extension of the human's mind. Body area networks (BANs) consist of a number of nodes and units placed on the human body or in close proximity, such as on everyday clothing. Currently, they are used to receive or transmit simple information which requires very low processing capabilities, e.g. patient monitoring systems that transmit low data rate information (heart rate, blood pressure, etc.). However, some high performance and complex units are needed in the future to provide the facilities for powerful computational processing with high data rates for applications such as video streaming and heavy data communications. A major drawback of current body-worn systems is the wired communication which is often undesirable because of the inconvenience for the user. Other connection methods have been proposed for solving this problem, including the use of smart textiles and communication by the currents on the user's body (B Allen et al., 2006).

The radio propagation around the human body is a complex phenomenon, although it takes place over only very short distance ranges. For communication between two devices placed on the human body, transmitted signals can arrive at the receiver in three ways (Hao & Alomainy, 2008):

- propagation through the body,
- diffraction around the body, and
- reflections from nearby scatterers in the radio environment.

Signals in the Gigahertz frequency range diffracting around the body attenuate due to absorption by human tissue. In addition, the original transmitted signal spreads out in time, due to the frequency-dependent dispersion by the antenna-body system. This attenuation and signal spreading likely depends on a number of random factors, including the curvature of the body, the exact position of the antennas, the position of the arms, the type of materials along the various signal paths, and so forth.

The ultra wideband low transmit power requirements allow longer battery life for body-worn units. This leads to UWB being a potential candidate for BAN. The possibility of transmitting data with various requirements in short range communication with low power consumption offered by UWB introduces an attractive solution for wireless BAN (WBAN) and implant radio system designers (B Allen et al., 2006).

2.3 UWB Antennas and Design Techniques

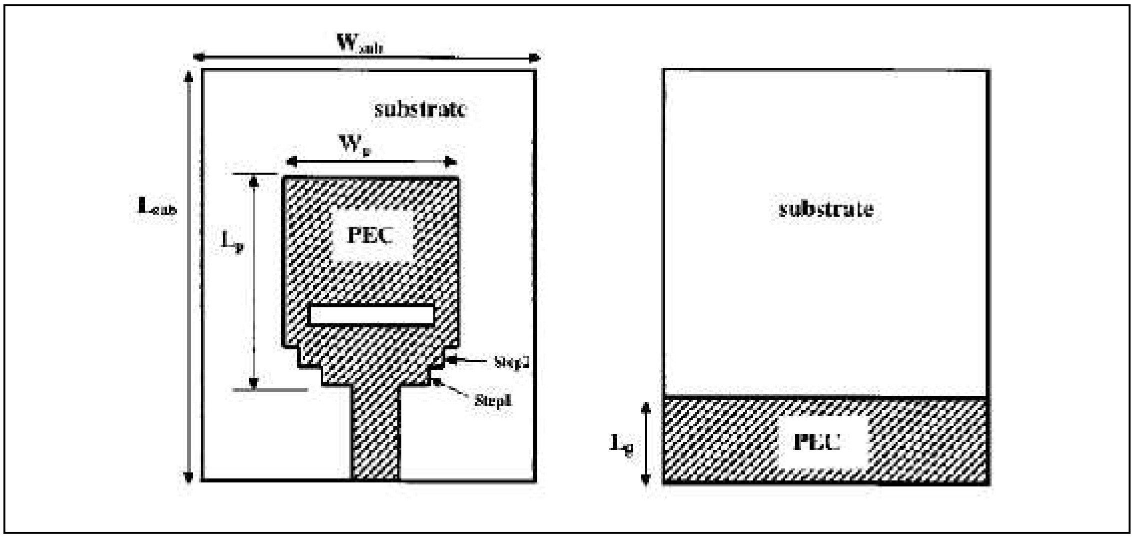
Recently, a variety of UWB antennas have been experimentally investigated and reported with different geometries. But very few people have discussed about how flexible the antenna is, especially when attachment to the body is demanded such as in

UWB body centric communications. There are some techniques that have been experimentally examined which have resulted broadband antennas. The following is a list of some of design techniques used for achieving wide bands (Gouda & Yousef, 2012):

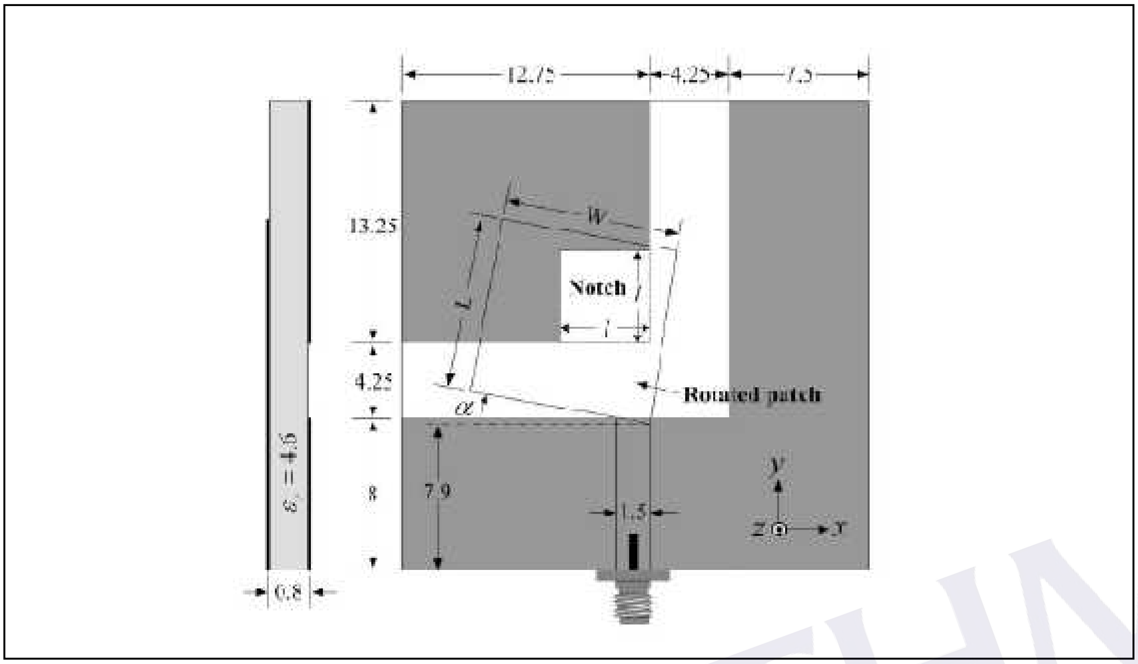
- Slots: wide rectangular slot, square-ring slot, E-slot, multi-inverted cone slot, L- and T-slot, V-slot, double U-slots, etc.
- Beveling the bottom edges of the radiating element.
- Using steps on the patch.
- Notches at the feeding position in the ground plane.

Large number of proposed antennas is patch type due to their performances for a variety of UWB applications compared to wire antennas. Planar antennas are attractive due to their simple geometric structures and ease of fabrication. Most of UWB antennas mainly focus on the slot and monopole antennas for their ability of providing a wide operating bandwidth. Considerable attention has been paid to broadband planar monopole antennas for their attractive merits, such as ultra wide frequency band, good radiation properties, simple structure and ease of fabrication. Broadband planar monopole antennas have taken many shapes such as half-disc, circle, ellipse, and rectangle.

There are many types of broadband directional antennas such as the Vivaldi, log-periodic, cavity-backed, waveguide, horn, and dish antennas that cover the entire 3.1–10.6 GHz band (109%). The undesirable fact about them is that they are electrically large, and have a high profile, while planar monopoles, disc cone, and slot antennas provide omni- and bi-directional radiation patterns and have a low gain and back radiation pattern, therefore they are not suitable for unidirectional communication (Azim, Islam, & Misran, 2010).



W_sub
substrate
W_p
L_sub
L_p
PEC
Step2
Step1
substrate
L_g
PEC



12.75
4.25
7.5
13.25
W
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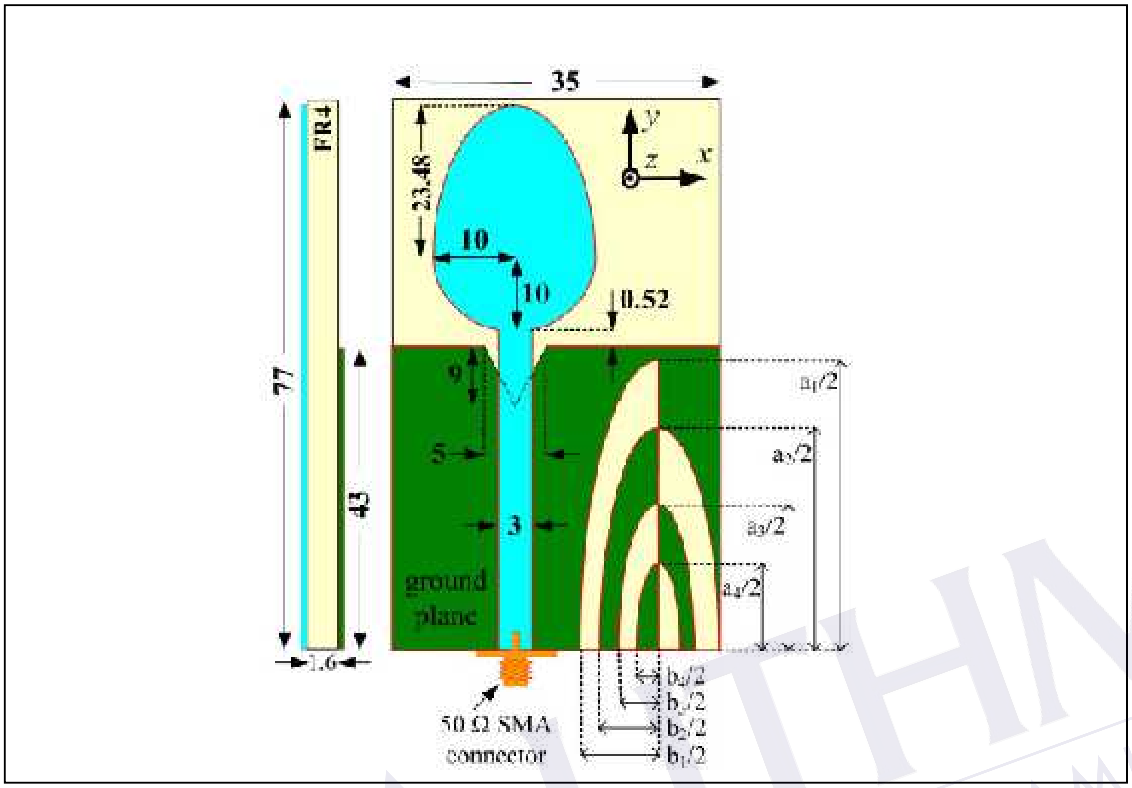
l
4.25
Rotated patch
α
8
7.9
1.5
y
z
x
0.8


35
FR4
77
43
1.6
23.48
10
10
0.52
9
5
3
y
z
x
ground plane
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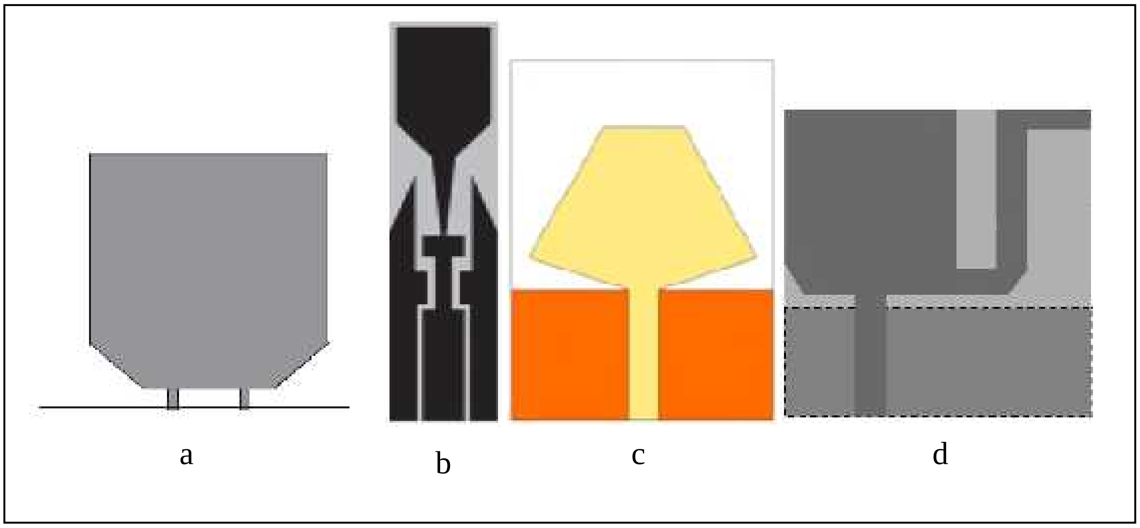
a1/2
a2/2
a3/2
a4/2
b4/2
b3/2
b2/2
b1/2


a
b
c
d

2.4 Wearable Antennas

The introduction of body-centric networks has led to the development of body worn wireless devices. The body-centric network consists of a number of nodes and units placed on the human body or in close proximity such as on clothing. As low-power transmission is required for operating body worn wireless devices, the human body can provide a communication channel between wireless wearable devices to and from a wireless body-centric network (Alomainy, Hao, Hu, Parini, & Hall, 2006).

Body-worn applications require flexible surfaces and circuit components to provide superior electrical and mechanical performances. This has led to the creation of a new technology using embroidered conductive fibers on polymer. Flexible conductors are constructed from silver-coated p-phenylene-2, 6-benzobisoxazole (PBO) fibers (e-fibers). The e-fibers provides inherent mechanical strength (due to their polymer core), together with high electrical conductivity owed to the silver coating. Lightweight and conformal electro-textiles based on conductive threads and fabrics provide compelling means to fabricate seamlessly garment-integrated antennas substrates (L. Zhang, Wang, & Volakis, 2012), (Koski et al., 2013).

Wearable tags are meant to be used near the body. As a result, the human body absorbs RF energy, reducing the overall antenna performance. In this application, also humidity, bending, and stretching likely affect the performance of the antenna. Sewing pattern and thread densities can also affect the overall performance of an embroidered antenna as investigated in (Moradi, Bjorninen, Ukkonen, & Rahmat-Samii, 2012).

Transmission in body area networks for proposed dual-band wearable metallic button antenna has been studied in (Sanz-Izquierdo, Miller, Batchelor, & Sobhy, 2010). The design was proposed to operate at 2.4 GHz WLAN and the HiperLAN/2 bands. The study focuses on on-body propagating line of sight and non-line of sight channels and how the body attenuates the channel.

Davis & Stutzman, 2005, have investigated the feasibility of the ultra-wideband half-disk structures based on camouflage cloth (substrate) and compared the performance of solid copper and woven versions (radiators). The study has concluded that solid copper version has shown good measured return loss characteristics, omni-directional patterns, and acceptable transient response.

Antenna mounting for ultra-wideband on-body communication has been studied in (Thompson, Cepeda, Hilton, Beach, & Armour, 2011). The authors have proposed a means of modifications made to the mounting procedure for two UWB antennas suitable for BAN applications, one commercially available antenna and one fabric antenna to reduce their coupling with the body. The proposed antenna modification employs radar absorbent material (RAM) to shield the antenna from the user. This alteration decreases the amount of radiation passing into the body, but still allows the principal propagation mechanisms of UWB BAN.

In (Osman, Rahim, Samsuri, & Ali, 2011), the authors proposes three different antenna structures. The substrate of the designed antennas was made from two types of fabrics: jeans and flannel. The dimensions of the proposed antennas are 40 mm × 40 mm for antenna I, and 60 mm × 60 mm for antenna II and III.

Most of the studies of wearable antennas have not stepped into the area of Specific Absorption Rates (SAR) test, which is required for studying the power absorption issues and meet the standards in order to avoid harm to human body. The aim of this study includes producing antennas with compact geometries and low SAR.

2.5 Specific Absorption Rate (SAR) and Phantoms

SAR is the time derivative (rate) of the incremental energy (dW) absorbed by (dissipated in) an incremental mass (dm) contained in a volume element (dV) of a given density (ρ).

$$SAR = \frac{d}{dt}\left(\frac{dW}{dm}\right) = \frac{d}{dt}\left(\frac{dW}{\rho dV}\right)$$

SAR is expressed in units of watts per kilogram (W/kg) or equivalently milliwatts per gram (mW/g). Some refer to it as a so-called volume-SAR, expressed in units of mW/cm^3, where mass density has been set to unity. SAR can be related to the E-field at a point as in equation 2.7

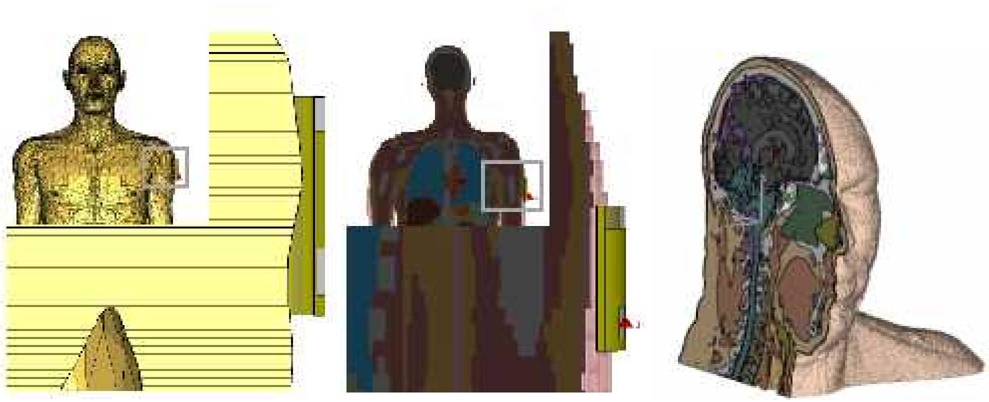
$$SAR = \frac{\sigma |E|^2}{\rho} \quad (2.7)$$

where σ is conductivity of the tissue (S/m), ρ is mass density of the tissue (kg/m^3) and E is the electric field strength (V/m).

Specific absorption rate—peak spatial-average is determined by the maximum local SAR averaged over a specified volume or mass, e.g., any 1 g or 10 g of tissue in the shape of a cube. SAR is expressed in W/kg or equivalently mW/g.

A considerable attention has been given to the impact of the interaction between electromagnetic (EM) fields and the human body as in (Chatterjee, Gandhi, Hagmann, & Riazi, 1980; Chatterjee, Hagmann, & Gandhi, 1980; Rosen, Stuchly, & Vander Vorst, 2002; Stuchly, 1993). The interaction between human head and cellular phones has been studied in (Kuster & Balzano, 1992; Meier, Hombach, Kastle, & Kuster, 1997), while interaction between human head and terminal antennas has been studied in (Christ & Kuster, 2005; Gandhi, Lazzi, & Furse, 1996). These works have been conducted in order to examine whether or not the antenna radiation exceed the limits set by the standards (Ahlbom et al., 1998), (ANSI, 1992).

CST STUDIO SUITE developers have also shared a note on "Body Wearable Antenna: Simulation Challenges" of RFID, ISM and UWB antennas (Rütschlin, 2013). The note discusses construction and body model handling when dealing with complex geometries. The note has also included a comparison between homogenous and voxel phantoms in terms of S11 and SAR considering full and partial body. The difference was found to be in small fractions (according to the example studied in the note: SAR: 0.667 W/kg for homogenous model and SAR: 0.883 W/kg for voxel model). It also studied the same example on full and reduced model. The result was found to be very close (SAR: 0.667 W/kg for full homogeneous body model and SAR: 0.644 W/kg for partial homogeneous body model).



(a) (b) (c)

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