Performance Investigations of a Quad-band Microstrip Antenna for Body Wearable Wireless Devices

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Abstract **─** This research work proposes a microstrip-based quad-band monopole antenna for body Wearable Wireless Devices (WWD) for Wireless Body Area Network (WBAN) applications. Ultra high frequency (UHF) and Ultra wide band (UWB) technology have been known for their efficiency to meet power, size and distance considerations for WBANs. The designed antenna resonates at four frequencies, 1.8, 2.4, 5.0 and 8.9 GHz covering licensed and license-free wireless technologies. The antenna design considers the electromagnetic (EM) effects due to the interaction of body tissues with the radio frequency (RF) waves, which are very different when compared to their interaction with free space. The performance of the antenna is investigated in terms of radiation efficiency, total gain, specific absorption rate (SAR), and thermal effects (short and long term). A simplified, human body tissue layer model is used for simulations utilizing EM computations. Simulated and experimental results are paralleled and are found to be in good agreement.

Index Terms **─** Microstrip antenna, quad-band, specific absorption rate, thermal effects, ultra wideband, WBAN, wearable wireless devices.

I. INTRODUCTION

The goal of wearable technology is to create expedient and portable access to information in real time. With the use of body Wearable Wireless Devices (WWD), Wireless Body Area Networks (WBANs) find extensive applications in health care, rescue and emergency missions, augmented reality, ambient assisted living setups, smart entertainment and much more due to its multi-frequency capability. It has been anticipated that wearable technology would be a vital supporter of consumer electronics industry. Wearable devices interconnect with the help of wearable antennas. The field of wearable antennas is a multidisciplinary one that combines electromagnetics, material science, and bioelectronics. The parameters that impact the design of in-body and on-body antennas have been enumerated in [1]. A review paper [2] has revealed research on wearable, body mounted antennas for various applications at different frequencies over a decade. A wide assortment of antennas ranging from monopole, dipole, PIFA, microstrip, U slot, coplanar, circular, triangular patch antenna, EBG textile antennas, antennas for dual bands and those mounted on a button, belt and helmet have been studied.

In recent years, antennas for health care systems, effects of planar fabric substrate antenna, dual polarized printed antenna, tripod kettle antenna, and several antennas when placed near to human body has been studied by [3-7]. Diverse antenna types working at GHz frequencies has been discussed [8-11]. Antennas that are wearable and which work at multiband are in trend. A fractal shape multiband antenna that can operate from 1-20 GHz has been proposed [12]. A WiMax and C band antenna of compact size has been designed [13] and compared with other dual and triple band antennas. A triple band fractal Koch dipole denim antenna has been studied for its performance and its suitability has been tested for wearable applications [14].

The human body is inhomogeneous with high loss and permittivity that are frequency dependent and which affect the properties of an antenna. The interactions of electromagnetic (EM) waves with the body using single and multi-layered tissue models have been discussed [15]. A good antenna design is essential for limited SAR values as the SAR depends on directivity, orientation, and gain of the antenna [16]. The effect of human body on RF transmission of biotelemetry and portable radio antennas at 10-1000 MHz has been discussed [17]. Recent research in wearable textile antennas that work under bending conditions on body has been carried out by [18]. Researchers [3] have investigated wearable antenna performance using human modelling for gain and diversity. In [19] authors have designed wearable fractal antenna and have worked on SAR as a useful parameter for wearable application. Safe use of the antenna on the body is more related to temperature

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changes than power density [20]. Emphasis has been made on thermal and biological aspects when it is RF waves interactions with the body [21]. In this context, elevation of temperature measurements for the compliance evaluation of mm-wave wireless devices operating close to the body has been suggested [22].

In this work, a quad-band microstrip based monopole antenna that works efficiently at four bands within UHF (30-3000 MHz) and UWB (3.1-10.6 GHz) frequencies on the human body has been proposed for WBANs utilizing WWDs. The antenna is offered to communicate from WWD to a personal digital assistant device / smart digital device. Due to the growth of wireless technology, several wireless systems operate simultaneously in a given scenario. The four bands chosen enable the antenna to be used along with the existing wireless technologies licensed and license-free bands. The UWB sub-bands selected allow the antenna to be used for low and high data rate applications, for varying power levels of reception and realistic environments when the full UWB cannot be utilized [23-24]. The antenna designed is proposed to work in proximity to the human body. The effects of the body on the antenna performance and vice versa have to be taken into account. The performance of the designed antenna for varying skin thickness and its heating effects are studied and analyzed utilizing Ansys HFSS [25] and Sim4Life by SPEAG [26]. Sim4Life is used for simulations on-body for the designed antenna at various body sites utilizing its high-fidelity computable human phantoms with advanced tissue models, and HFSS (based on finite element method) is used for antenna design and fabrication.

II. MODELLING HUMAN BODY TISSUES

A. Effect of electromagnetic field on human tissues

The human body consists of different types of material, each differing in the way they interact with the EM fields. The geometry of the human body and its different parts has been described to be very complex [27]. The electrical properties of the biological tissues are the result of the electromagnetic radiations interacting with constituents of the body at the cellular and molecular level [28]. Understanding the interaction and the electrical properties of body tissues is the primary need in the design work of antennas for body wearable devices. The biological effects of antennas working in the UWB frequency ranges are proportional to the rate of energy absorption given in terms of SAR and the ability to heat human tissues. Both these effects can be hazardous if exposure is sufficiently intense or prolonged. Since the magnetic permeability of body tissues is same as that of free space, the electrical permittivity and conductivity are the important properties that determine the electric field distribution in the body and the power dissipated in it [29]. These properties change with frequency. Tissues with the highest water content have the highest relative permittivity (e.g., skin and muscle), decreasing with increasing frequency. The tissue's water content results in the specific permittivity value, which affects the wavelength inside tissues [30].

B. Layered model of human tissue

The antenna has been designed for wireless devices, where the influence of the outermost body tissues has to be considered. There are different simplified tissue models like homogeneous models, three layered body model with different cross sections as flat, rectangular and elliptical used in literature. There are also detailed 3D complex voxel body models that use a lot of computational resource and time. For computational simplicity and considerable accuracy, a four layered rectangular biological tissue model made up of skin, subcutaneous fat, muscle and bone has been chosen as it represents most of the body regions [31]. The designed antenna is proposed to be placed over the stacked tissues with an average thickness of 2 mm, 3.5 mm, 10 mm and 10 mm for skin, fat, muscle and bone layer respectively, as in Fig. 1.

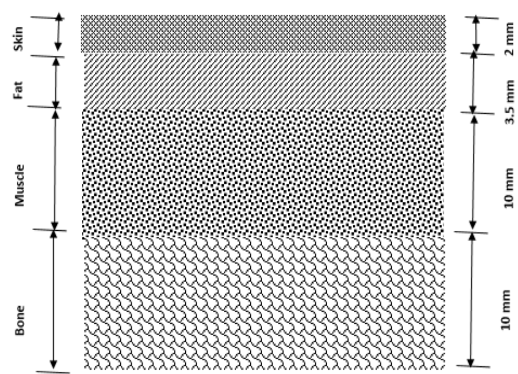

Fig. 1. Layered rectangular phantom model of human tissues.

The electrical properties of the tissues at the various resonating frequencies of the designed antenna have been based on the works of Italian National Research Council, which is available online [32] and are tabulated in Table 1. The calculation of these electrical properties have been based on the data available [28], where the variation of the electrical properties of tissues over a frequency range of 10 KHz-10 GHz around a body temperature of 20˚C to 40˚C has been considered. Skin, due to its inhomogeneous structure has inhomogeneous dielectric properties. Muscles, bones have intermediate dielectric properties when compared to fat which has poor dielectric properties.

Table 1: Electrical properties at the desired frequencies

Frequency (GHz)	Tissue	ε_r	σ (S/m)	Tan θ (Loss Tangent)
1.8	Skin	38.8	1.18	0.30
	Fat	5.30	0.07	0.14
	Muscle	53.5	1.34	0.25
	Bone	19.3	0.58	0.30
2.4	Skin	38.0	1.44	0.28
	Fat	5.28	0.10	0.14
	Muscle	52.7	1.70	0.24
	Bone	18.6	0.78	0.31
5.0	Skin	35.7	3.06	0.30
	Fat	5.02	0.24	0.17
	Muscle	49.5	4.04	0.29
	Bone	16.0	1.81	0.40
8.9	Skin	32.3	6.78	0.42
	Fat	4.68	0.50	0.21
	Muscle	44.2	9.05	0.41
	Bone	13.2	3.42	0.52

III. ANTENNA DESIGN

It is critical that the antenna has a compact design for use on the human body. The antenna design requirements differ from that of a conventional antenna that is designed for free space because of the tissue environment. Microstrip model design equation [33] has been used to design the antenna. The antenna has a dimension of 35 x 32 x1.57 mm^3 and is made of Rogers RT/ Duroid 5880 substrate with relative permittivity of 2.2 and loss tangent of $9x10^{-3}$. The selection of the substrate is due to its low electric loss along with low moisture absorption. An optimized design of the antenna with a partial ground plane and staircase rectangular shaped patch has been used. The step size of 1mm followed by 1.5mm from both the top and bottom edges is used for the staircase pattern. Horizontal slots each measuring 6 mm in length and 0.5 mm in width are used on the right and left sides of the radiating patch. A 50Ω microstrip line was used to feed the radiating patch. The power input at the port was 1 mW. Good impedance matching has been achieved by a microstrip tapered line. The prototype of the antenna along with the dimensions is shown in Fig. 2.

Strips of conducting material at top and bottom have been used to provide a defected ground plane. The design has been optimized to make the antenna work at four bands with S_{11} less than -10 dB at all the bands. The return loss plot for the various slot size of antenna design and optimization is shown in Fig. 3. It has been learnt that the defected ground plane helps to achieve the multiband operation of the antenna. The slots on the patch tend to align the shifted bands to the required resonant frequencies and the steps offer a greater value of return loss at the four bands. A quad band operation has been chosen to offer better EM compatibility with existing wireless communication technologies and unlicensed UWB and to be used for both low and high data rate applications.

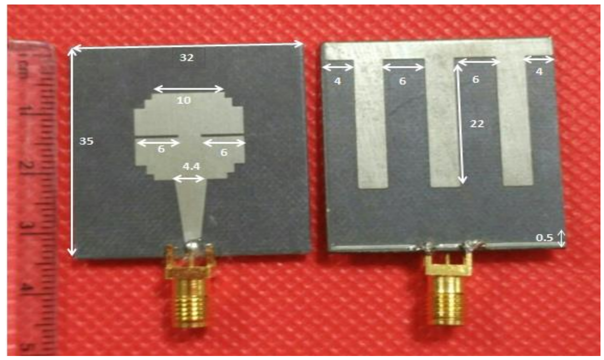

Fig. 2. Photograph of the prototype of staircase microstrip antenna with the dimensions in mm for: (a) radiating patch and (b) ground plane respectively.

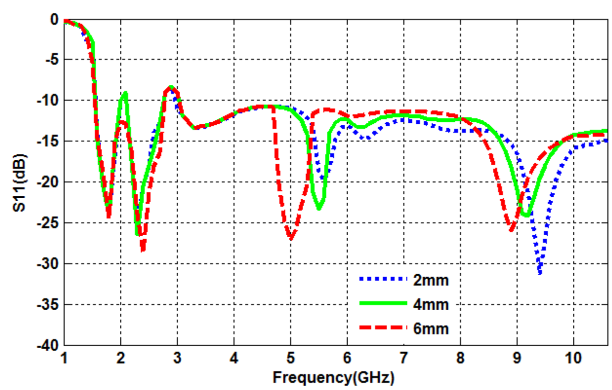

Fig. 3. S_{11} plot for various simulated length of the horizontal slot on the radiating patch of the antenna.

IV. SIMULATION AND MEASURED RESULTS

A. Antenna simulations and measurements in free space

The antenna has been simulated and measured for its performance in free space before placing it on the body to understand the influence of human body proximity on the working of the microstrip antenna. Performance metrics of the antenna considered are total gain, radiation efficiency, and SAR. Measurements of return loss were made using RS-ZVL Vector Network Analyzer of frequency range 9 KHz-13.6 GHz.

B. Antenna simulations on rectangular phantom model and measurements on human body

Placement of the antenna in direct contact with the body has resulted in decrease in gain and radiation efficiency with due effects on the impedance matching due to the dielectric loading provided by the lossy human tissues. A frequency shift in the resonating frequency of 100 MHz from 1.8 to 1.9 GHz, 80 MHz from 2.4 to 2.48 GHz, 140 MHz from 5.0-5.14 GHz, 100 MHz from 8.9 to 8.8 GHz was observed between simulated and measured results in the four bands respectively. Measurements of return loss when the antenna is placed on the body were made using RS-ZVL Vector Network Analyzer of frequency range 9 KHz-13.6 GHz. The designed antenna was kept on the human body with cotton padding of 5 mm between them. The performance of the antenna on the body has been enhanced due to the bio and electromagnetic compatibility nature of the chosen fabric which makes it realizable for real-time use when compared to the few mm of air gap used in previous designs. The measured return loss plot for free space and on body operation of the antenna is shown in Fig. 4.

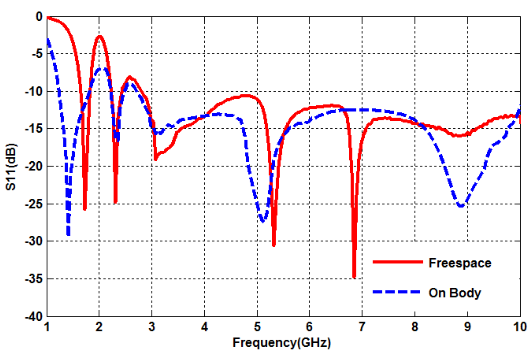

Fig. 4. Measured return loss plot for free space and on body placement of the antenna.

The performance of the quad bands has been studied and tabulated in Table 2. It is seen from the table that the upper bands perform well when compared to lower bands. This is important while considering the EM waves (thus also antennas) interaction with the body [28]. Major reflections occur due to the wave impedance mismatch between low (fat) and high water content (skin, muscle) tissues. The performance of the antenna at the four bands is dependent on the electrical properties of the tissues at those frequencies. It has been observed that the electrical permittivity decreases with increasing frequency and the electrical conductivity and loss tangent increase with increasing frequency for the tissues. Negative gain values at lower bands were due to the near omnidirectional radiation pattern of the antenna.

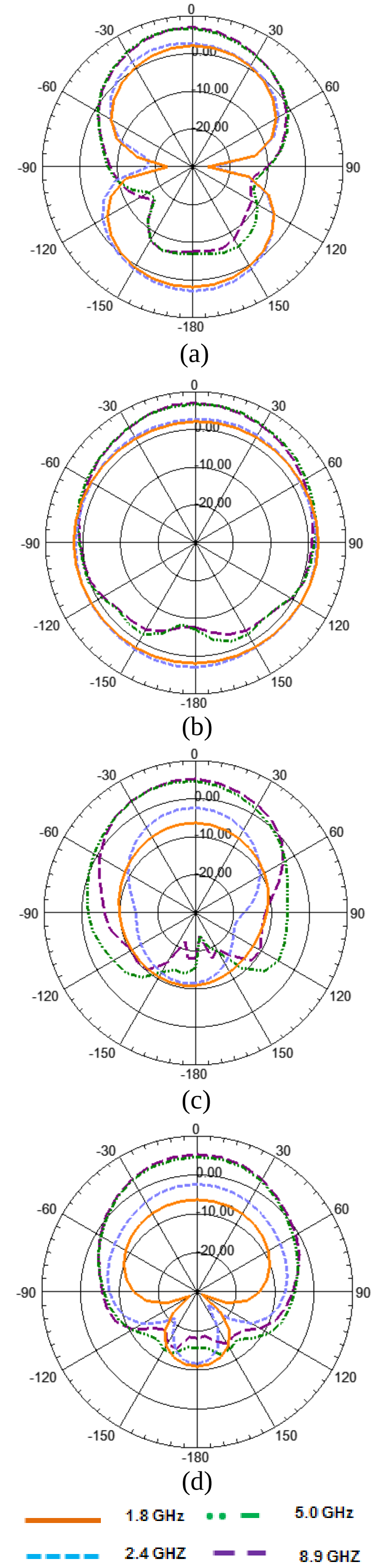

Fig. 5. Radiation pattern (simulated gain in dB): (a) free space E plane, (b) free space H plane, (c) on body E plane, and (d) on body H plane.

As frequency increases, there is less penetration into the body and hence an increase in radiation efficiency of the antenna. It is observed that there is better performance in the third band. This is due to the combination of the change in electrical properties of the tissues at this band when compared to the other bands.

The quasi-omnidirectional radiation pattern of the antenna that has been obtained considering the thickness of the layers of skin, subcutaneous fat, muscle and bone as 2, 3.5,10, 10 mm respectively at the four bands are shown in Fig. 5. The patterns have been compared with free space radiation patterns of the antenna. The radiations are seen away from the body ensuring less absorption of radiations by the body. The simulated radiation parameters for on-body placement of the antenna are tabulated in Table 3. It has been observed that there is increase in main lobe level, peak directivity at higher frequencies due to lesser penetration of RF waves into body and hence more radiations away from the body. The values of half power beam width (HPBW) and side lobe levels are also given. This makes it suitable for on-off body communication as from a wearable device to a mobile phone. In case of free space operation, the absence of body tissue influence has ensured near omni- directional radiation pattern as seen in Fig. 5.

Table 2: Performance of quad band in free space and on body

Frequencies	Total Gain (dB)		Radiation Efficiency (%)	
	Free Space	On Body	Free Space	On Body
1.8 GHz	2.7	-6.7	98	9.0
2.4 GHz	3.2	-2.3	98	14.4
5.0 GHz	7.0	5.2	99	55.9
8.9 GHz	6.8	5.0	99	48.1

Table 3: Radiation properties (simulated) for on-body placement of the antenna

Radiation Parameter	1.8 GHz	2.4 GHz	5.0 GHz	8.9 GHz
Main lobe magnitude (dB)	-6.4	-2.3	5.2	5.0
Peak directivity (dB)	2.5	4.0	5.9	6.1
Side lobe level (dB)	-4.5	-9.3	-15.3	-15.0
HPBW (degree)	130	117	79.5	81.5

C. Robustness study of the antenna on the body

The antenna has been analyzed for its robust performance on the human body by considering the scenario of varying skin thickness and placement of the antenna at random sites on the body. The thickness of skin increases with age. In that view, the thickness of the skin layer used in the model has been varied from 1-2 mm, depicting a scenario of young to aged skin. The return loss plot for the same is seen in Fig. 6. It is observed that the quad band operation is maintained for all skin thickness. With a decrease in skin thickness, for the second band, there is a right shift towards higher resonating frequencies.

The proposed antenna has been simulated at ten different anatomical sites on the body. This was to analyze the performance of the antenna on any site on the body where the thickness of the layers of tissue varies with the placement site. The body sites that were considered are forehead, neck, biceps, triceps, chest, wrist, anterior abdomen, anterior thigh, posterior thigh, calf of legs as shown in Fig. 7 and named in Table 4. They are the most familiar and comfortable sites on body for monitoring vital bio-signals. The anatomical sites have been chosen considering a scenario of sports training or general health monitoring where the sensors and transceivers can be placed for the specific application. They are best sites for picking up physiological parameters like body temperature, pulse rate, blood pressure, respiration rate, ECG, heart rate, EMG, glucose level, motion and perspiration. The thickness of skin and subcutaneous fat layer for these body sites measured using ultrasonography have been referred from literature [34-40].

The performance of the antenna for various tissue layer combinations considering the muscle and bone thickness as 10 mm is given in Table 4. As frequency increase, they have shorter wavelengths and hence smaller penetration into the tissues. This results in lesser absorption of EM waves, and low values of SAR as frequency increases.

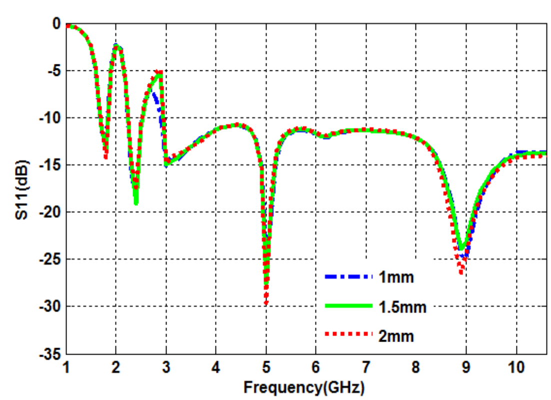

Fig. 6. Comparison of simulated S_{11} plot for varying skin thickness.

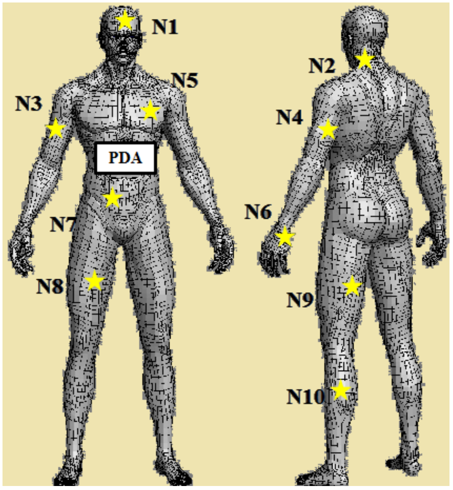

Fig. 7. Anatomical sites of the body (anterior and posterior) considered for simulations along with PDA that serves as a gateway for WBAN applications.

D. SAR and on body thermal effects

Specific Absorption Rate (SAR) is a good dosimetric quantity that measures the rate of energy absorption by human body when exposed to radio frequency EM field. SAR is calculated as:

$$SAR = \frac{\sigma.|E|^2}{\rho_m}, \quad (1)$$

where, E is the RMS value of induced field in (V/m), σ is the conductivity of tissue in (S/m), ρ_m is the mass density of tissue in kg/m^3. A high level of SAR, in any tissue, above standard limits, can prove dangerous for human use. The effect has been measured as an increase in tissue temperature related to the time of exposure of tissues to the EM field. It has been observed from literature that an increase of tissue temperature equal to or greater than 1K would ascertain danger.

The temperature rise of tissues have a linear relationship with the time of exposure for short-term exposure of a few seconds to minutes. This is because of the little significant contribution made by conductive or convective heat distribution to the temperature rise. A time duration of seconds to minutes has been taken as short term and minutes to hours has been taken as long term. The temperature rise in tissues (K) for short time exposure has been obtained from the following equation [41] by knowing the heat capacity of the tissue (J/kg/K), average SAR value for 1 gram of tissue and the time of exposure (Δt) in seconds:

$$\Delta T = SAR.\frac{\Delta t}{c}. \quad (2)$$

The short time temperature rise for a period of 60 seconds of radiation from the designed antenna on the human body has been calculated for the outer three tissues. Adiabatic conditions were assumed for heat exchange with the environment. Adiabatic conditions give the worst case temperature increase [42] in a state where no heat is exchanged with the environment.

To obtain the relation between temperature rise and time, in the case of long time exposures, the Pennes Bio Heat equation considering the role of blood in thermoregulation of the body has been used. Simplification of the Bio heat differential equation has yielded equation (3) [43] that gives the maximum temperature rise over an extended period of time in the order of minutes. In the equation, S is average SAR for 1 gram of tissue in W/kg, ρ is the mass density of tissue in kg/m^3, K is thermal conductivity of the tissue in W/m/K, and w is blood perfusion rate in ml/g/min, c_b is the heat capacity of blood in J/kg/K, λ is the wavelength of the EM wave in m. The parameter values for the considered body tissues and the average SAR values for the tissues at the four bands considered are given in Table 5.

Table 4: Performance of the quad bands at different body sites using simulations

Performance Metrics	Total Gain (dB)				Efficiency (%)				SAR (W/Kg)			
Site (Node)	**I**	**II**	**III**	**IV**	**I**	**II**	**III**	**IV**	**I**	**II**	**III**	**IV**
Forehead (N1)	-4	0.5	4.6	3.7	12.5	25.5	48.0	47.8	0.23	0.20	0.17	0.15
Neck (N2)	-4.3	-0.7	4.7	3.5	13.3	21.9	47.7	46.8	0.22	0.20	0.16	0.13
Forearm (N3)	-6	-2.1	5.2	3.8	9.3	15.3	53.4	50.7	0.21	0.20	0.14	0.13
Triceps (N4)	-6.7	-2.7	5.3	3.9	9.1	14.2	55.6	50.6	0.20	0.17	0.14	0.12
Chest (N5)	-6.9	-1.7	4.8	3.7	8.5	15.3	53.9	50.1	0.17	0.14	0.13	0.10
Wrist (N6)	-5.3	-1.4	4.2	2.5	10.5	16.4	16.4	39.6	0.25	0.19	0.15	0.14
Abdomen (N7)	-9	-6.6	5.1	3.5	6.1	7.4	58.1	46.4	0.21	0.17	0.16	0.09
Ant. Thigh (N8)	-6.8	-3.2	5.2	3.9	9.1	13.3	55.9	50.0	0.20	0.17	0.13	0.10
Posterior thigh (N9)	-7.9	-4.7	5.3	3.8	7.6	10.4	57.3	49.3	0.18	0.16	0.10	0.09
Calf (N10)	-7.3	-3.0	5.7	3.9	8.7	13.5	57.8	50.6	0.14	0.17	0.11	0.11

Table 5: Parameter values of body tissues used for temperature calculations

Tissue/ Parameters	Mass Density (kg/m^3)	Thermal Conductivity (W/m/K)	Heat Capacity (J/kg/K)	Average SAR (W/kg)			
				1.8 GHz	2.4 GHz	5.0 GHz	8.9 GHz
Skin	1109	0.37	3391	0.22	0.17	0.15	0.11
Fat	911	0.21	2348	0.03	0.02	0.01	0.01
Muscle	1090	0.49	3421	0.09	0.05	0.02	0.02
Bone	1908	0.32	2065	0.0003	0.0002	0.0001	0.0001

The maximum SAR values among them has been used to calculate the maximum temperature rise for the particular tissue and the temperature rise are tabulated in Table 6 using (2) and (3). It is observed that the highest temperature increase has been found in the skin, with 0.004 K for short term and 0.134 K for long term exposure. The temperature increase has been found to be indeed less of about fraction of a kelvin. The value of blood parameters considered are blood perfusion rate (w) and heat capacity of blood (c_b) whose values are taken as 0.5 ml/g/min and 3617 J/kg/K respectively:

$$Tmax = \frac{q}{\lambda'}[1 - \left(\sqrt{\lambda'}\,A + 1\right)e^{-\sqrt{\lambda' A}}\ ], \qquad (3)$$

where, $q = \frac{\rho S}{K}$; $\lambda' = \frac{w\,c_b}{K}$; $A = \frac{\lambda}{4}$.

Table 6: Maximum SAR values at different tissues and their heating effects

Tissue	Average SAR (Max.) (W/Kg)	Short Term Temp Increase (K)	Long Term Temp Increase (K)
Skin	0.22	**0.004**	**0.134**
Fat	0.03	0.001	0.016
Muscle	0.09	0.002	0.056
Bone	0.0003	0.0001	0.0003

V. DISCUSSIONS AND CONCLUSIONS

The performance of the quad-band based microstrip monopole antenna for WBAN applications has been studied in free space and on the body for the use of WWDs. The effects of the human body on the performance of the proposed antenna and the effects of the performing antenna on the human body in terms of thermal effects were analyzed. The antenna's S_{11} satisfies less than -10 dB in free space and on body simulations at all the four bands. Less value of gain at lower bands is due to the omnidirectional radiation pattern at these bands. Investigations have been made on the performance of the antenna at various human body sites and for varying skin thickness. It was observed from Table 4 that the location of placement of the antenna on the body has an effect on the performance of the antenna. Sites with lesser fat thickness (wrist, forehead, neck) had less reflections, greater absorption by the body, hence higher SAR values. Higher bands performed better due to a change in permittivity leading to less penetration into the tissues as frequency increases. Radiation absorption is less and efficiency of the antenna is more at higher frequencies. However, the performance of the antenna at all the considered body sites was reasonably good regarding gain and radiation efficiency.

It is also analyzed from Table 6 that the short term and long term exposure of the body to the EM field due to the irradiating antenna was found to produce a temperature increase of a fraction of a kelvin which is indeed a small value. The thermal effect was found to be maximum on the skin which is the outermost tissue with a value of 0.134 K temperature rise under long term exposure. The maximum SAR value was observed to be 0.22 W/kg over 1 g of tissue. SAR values were found to be far less than the maximum allowable SAR values limits 2 W/kg averaged over 10 g of tissue exposed to EM radiations given by International Council on Non-Ionizing radiation protection [44] and 1g averaged SAR value of 1.6 W/kg provided by IEEE/ICES C95.1-2005 [45]. These observations indicate that the proposed antenna module can be used as a candidate for WWDs for WBAN applications which will proliferate very widely in near future as a promising way of monitoring signals in all walks of life where the antennas performance is greatly affected by the dielectric properties of body tissues.

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