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Posted Date: 28 April 2025

doi: 10.20944/preprints202504.2369.v1

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Article

Effects of Dielectric Properties of Human Body on Communication Link Margins and Specific Absorption Rate of Implanted Antenna System

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Highlights

This is the first work where the carrier link margin and the data link margin of a muscle-implanted antenna system with an external monitoring device were performed. Variation of Specific Absorption Rate (SAR) was also investigated for wide range of variations of the effective relative permittivity and conductivity of the human body.

What are the main findings?

- The performance matrices [including signal radiation (gain) and reflection (S_{11})] within the body model are comparable with the leading implantable antennas. The SAR value (220.26 W/kg) for a 1-g tissue at 1W input power ensures the patient's safety after implantation compared with the existing work.
- ANN modelling was performed to analyze the accuracy of the dependence. The innovative use of ANN in this field further underlines the pioneering nature of this research.

What is the implication of the main finding?

- The reported research findings will aid the innovative development of 5G/6G IoMTs devices for existing and/or emerging wearable technology use cases and/or applications.

Abstract: This paper presents the effects of effective dielectric properties of human torso on carrier-link-margin (CLM) and data-link-margin (DLM) of an experimentally validated miniaturized corner-chamfered meander-line implantable antenna placed within an implantable system prototype consisting of battery, PCB, camera and sensor encapsulated by biocompatible gelatin at 2.5 GHz. Specific Absorption Rate (SAR) and link margin performances of the implanted antenna are analyzed for 2500 scenarios ($\pm 20\%$ variations in reference to the mean values of the effective relative permittivity, ϵ_{eff} , and conductivity, σ_{eff} , of the human body). For accurate dependence analyses, an artificial neural network (ANN) with two input variables (ϵ_{eff} , σ_{eff}) and five output variables (SAR_1g, SAR_10g, fractional bandwidth, CLM and DLM) is trained by 80% and tested by 20% of the total scenarios. Compared with the reference effective electrical properties of the homogeneous human body model, respective maximum variations of 63%, 41.6%, 17.97%, 26.79%, and 5.89% are observed in 1 g SAR value, 10 g SAR value, fractional bandwidth, CLM and DLM at 4 m distance for 100 Kbps. This work pioneers accurate dependences of link margins of body-implantable antenna system on effective relative permittivity and conductivity analyses.

Keywords: Biotelemetry; Carrier Link Margin; Data Link Margin; Implantable Antenna; Meander-line; Specific Absorption Rate

1. Introduction

In the last two decades, the popularity of medical bio-telemetry devices has escalated interest in therapeutic and diagnostic functions for continuous patient monitoring in applications like temperature, heartbeat, glucose level detection, heart rate regulation, drug delivery and pain control [1–3]. Implantable antennas embedded in these medical devices can transfer the patients' health-related sensed data to the doctor's end wirelessly to save them from a sudden death or a critical condition with the help of the emerging Internet of Medical Things (IoMT) technology [4]. Erroneous communication link characterization may cause data loss, which leads to the misinterpretation of the patient's health condition and wrong diagnosis. The quality of communication (or link margin), includes the gains of the implantable antenna and the external monitoring device's antenna, operating frequency, transmitted power, path loss, polarization of the antennas, data rate, and signal-to-noise ratio (SNR) [5]. Figure 1 shows a schematic of wireless telemedical communication between an implantable antenna and an external monitoring device. Previously, inductive coupling was utilized for an implant communication. However, this communication technique has some limitations, viz: low data rates (1-30 kbps), low communication range (less than 10 cm) and low sensitivity of the coils [6,7]. To overcome these restrictions, medical implant communications are performed at different frequencies, such as Medical Implant Communication Service (MICS) (402 – 405 MHz); Wireless Medical Telemetry Service (WMTS) (608 – 614, 1395 – 1400 and 1427 – 1432 MHz), and Industrial, Scientific and Medical (ISM) bands (such as 2.4-2.5 GHz, 5.73-5.88 GHz etc.) [8,9].

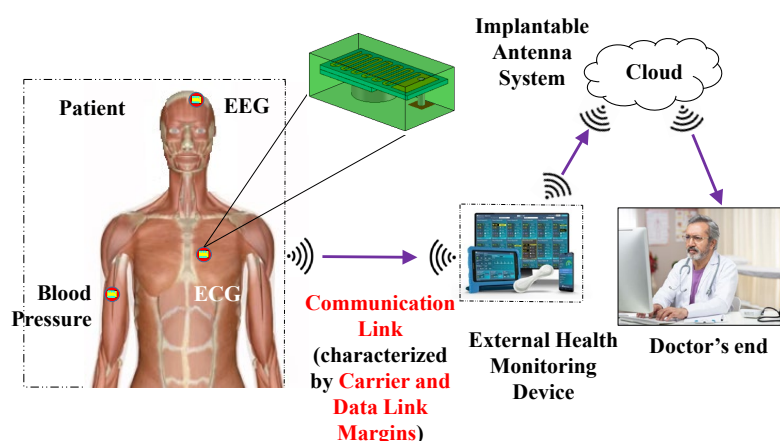


Figure 1. Overview of a wireless communication link between an implantable antenna system and an external health monitoring device.

Implantable antennas have significant challenges, including developing miniaturized prototypes, achieving an agreement with safety guidelines regarding Specific Absorption Rate (SAR) and measuring the dielectric properties of tissues [10–12]. According to electromagnetic regulatory guidelines [13–17], SAR averaged over 1 g and 10 g of contiguous cubical tissue should be less than 1.6 W/Kg and 2 W/Kg respectively at 2.5 GHz. As the wireless communication link of the implantable antenna with the monitoring device is established through the human tissue, this communication performance depends on the bioelectric properties of tissue, viz: relative permittivity and conductivity. Relative permittivity of human tissues is dependent on factors like age, gender of patients, location of implant, thickness of skin and fat layers and hormonal variations in patients' bodies. [18–23]. It is also dependent on the water and oil content, the structure of fibers, etc. 0.4 – 0.6 mm thick stratum corneum (a part of the epidermis of the skin layer) contains comparatively lower water content (around 10%) [24]. Hwang et al. [25] and Boric-Lubecke et al. [26] showed that the effective complex permittivity of different body parts is not the same. The generation of tumors in any layer may increase effective complex permittivity by about 20%. The effective dielectric properties can also change due to pathological changes in the liver due to cirrhosis, steatosis and,

hepatocellular carcinoma. [27]. Therefore, it is enough to study the possible variation in link performance by considering $\pm 20\%$ variations in mean bioelectric properties of the overall human body.

Effective loss in channels can change due to variations in the electrical properties of the biological environment of the implanted antenna, which may lead to varying communication link performance metrics. For small size and low mass anatomical models, the realized gain and the radiated power of the implanted antenna are low. The impact of anatomical variations in the relative permittivity and conductivity of the human body model due to skin and fat thickness variations on reflection coefficient (S_{11}) and fractional bandwidth of an implantable antenna at MICS (402-405 GHz) was assessed in [28]. Authors in [29] studied the dependence of S_{11} and bandwidth of an implantable rectangular patch antenna on the relative and conductivity of different tissues such as fat, kidney, liver, muscle, gray matter, white matter, different ages, gender, height and mass of the patients. In the literature survey, the dielectric parameters of human tissue also influence the performance of implantable antenna. The detuning of an implantable antenna in terms of reflection coefficient due to relative permittivity and conductivity of the human body was studied in [30]. In [3], the authors investigated the dependence of S_{11} , resonant frequency, gain and SAR of the implantable antenna on the variations of the dielectric constant of the human head and body model. They performed their investigations by taking a very small number of samples, which were not sufficient to analyze their dependencies. The communication link is also dependent on the variation of the data rate, the uncertainties of channel properties etc.

In this article, a corner-chamfered meander-line implantable antenna was designed within an equivalent homogeneous human body model (mean tissue permittivity = 52.7 and mean conductivity = 1.95 S/m) and exhibited communication performance was studied at 2.45 GHz ISM band (dedicated for medical investigations by FCC). A frequency shift of 25 MHz from reference frequency was observed for $\pm 20\%$ variation in mean relative permittivity and conductivity values of the human body. Due to this possible variation of the bioelectrical properties, peak SAR and its distribution due to the placement of implantable antenna are changed, which has been studied here. To limit the SAR value as per safety guidelines, input power should be controlled properly, and the input power is one of the main parameters for the link margin to characterize the communication quality. The bandwidth of an implantable antenna is another important parameter for communication because it can characterize the channel capacity of wireless communication based on Shannon’s channel capacity theorem. Link margin includes a gain of the implanted antenna, the distance between the implanted antenna and monitoring device, a gain of the antenna of the monitoring antenna, different communication characteristics in terms of signal-to-noise ratio, type of modulation and data rate. There are two parts of Communication link margin – (a) carrier-link-margin (CLM) related to carrier signal-to-noise ratio and (b) data-link-margin (DLM) related to data signal-to-noise ratio [30],[31]. There is no reported work related to the dependences of the CLM and DLM along with SAR profile to ensure a reliable and safe wireless patient monitoring on the effective body electrical properties. This paper closes the research gap by developing an artificial neural network (ANN) to train and validate the effective properties with respect to the CLM and DLM. The ANN was trained by 80% of 2500 scenarios ($\pm 20\%$ variations in the referenced mean relative permittivity, ϵ_{eff} , and conductivity, σ_{eff} , of the human body) and validated by 20% of them. The ANN predicted with 99.24% average accuracy with respect to the simulated and the measured responses. Compared with the referenced effective electrical properties of the homogeneous human body model, respective maximum variations of 63%, 41.6%, 17.97%, 26.79% and 5.89% are observed in 1 g and 10 g SAR value, fractional bandwidth, CLM and DLM at 4 m distance for 100 Kbps.

Table 1. Comparison with Previously Reported Works.

Ref.	Freq. (GHz)	S_{11} (dB)	Gain (dBi)	SAR_1g (1W) (W/Kg)	CLM (dB)	DLM (dB)	Comm. range (m)	Uncertain Parameters	Samples	Variation Analysis Techniques	Variation in parameters Tested
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							17 (7kbps), 4.3 (100 kbps) and 1.4 (1 Mbps)				
[32]	2.4	-25	-24.7	697.5	No	No		No	No	No	No
[33]	0.4	-20	-18.9	No	No	No	No	No	No	No	No
[34]	0.915, 2.45	-25, -40	30.47, - 24.71	658, 589	No	No	2	No	No	No	No
[35]	0.915, 2.45	-20, -37	-36, -30.1	333	No	No	No	No	No	No	No
[36]	0.915	-20	- 23.23	270.3	No	No	13	Effective permittivity	6	Cartesian plot	Sensing Performance
[37]	0.915, 2.45	-19, -15	26.30, -20.9	306.19, 252.36	No	No	8	No	No	No	No
[38]	0.402, 2.45	No	-37, -24.5	No	No	No	No	Phantom Size Relative Permittivity	2	Cartesian plot	Gain, efficiency S ₁₁ and frequency
[39]	2.45	-11	No	No	No	No	No		6	Cartesian plot	
This Work	2.5	- 45.9	- 38.42	220.26	20.73 (d = 1m, Ts =13K) (First)	9.28 (d = 1m, Ts =13K) (First)	15 (7kbps), 10 (100 kbps) and 3.5 (1 Mbps)	Effective permittivity and Conductivity	2500	ANN modeling (First)	CLM, DLM, bandwidth and SAR performance (First)

The novelty of this work compared with previous works reported in [32–39] is highlighted in Table 1. The significance and timeliness of this work are summarized below.

- (i) Table 1 concludes that this is the first work where the carrier link margin and the data link margin of a muscle-implanted antenna with an external monitoring device were performed.
- (ii) The SAR value (220.26 W/kg) for a 1-g tissue at 1W input power ensures the patient’s safety after implantation compared with the existing work.
- (iii) The performance matrices [including signal radiation (gain) and reflection (S₁₁)] within the body model are comparable with the leading implantable antennas.
- (iv) The authors in [36] designed an implantable antenna which could communicate up to 13 m variation. In [38], the effect of phantom size on the gain and the efficiency of the spiral-implanted antenna were discussed. The possibility of variations in S₁₁ and frequency of an implanted antenna due to variation in relative permittivity of the body was observed in [39] based on only 6 samples of permittivity values. Our work takes a comprehensive approach to investigate and validate the impact of both human body electrical parameters (including effective relative permittivity and conductivity) on the link margins (CLM, DLM). The prevailing performance matrices for potential IoMTs applications include operating frequency, realized gain, data rate, channel loss, range of communication, bandwidth, and SAR signature of the implanted antenna.
- (v) 2500 samples of effective body models were considered, and ANN modelling was performed to analyze the accuracy of the dependence. The innovative use of ANN in this field further underlines the pioneering nature of this research.
- (vi) This work presents the first extensive human body electrical properties dependence analysis of the SAR profile and communication link performance of implantable antennas.
- (vii) The reported research findings will aid the innovative development of 5G/6G IoMTs devices for existing and/or emerging wearable technology use cases and/or applications.

Table 2. Parameters of Implantable Antenna.

Parameters	Values	Parameters	Values
l	20 mm	$w2$	4.397 mm
w	10 mm	$w3$	1.46 mm
$l1$	8 mm	$w4$	0.86 mm
$w1$	3.6 mm	φ	45°
$l2$	7.4 mm	P	(7.25 mm, 2 mm)

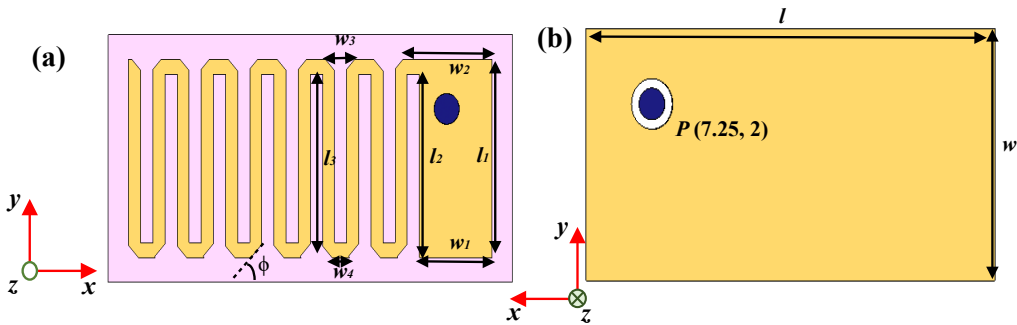


Figure 2. Geometry of the corner-chamfered implantable antenna: (a) Top view and (b) Bottom view.

2. Models and Methods

2.1. Implantable Transmitting Antenna System Design

2.1.1. Design Procedure

The geometry of designed 152.4 mm³ antenna within implantable medical device is illustrated in Figure 2 and the parameters of the antenna are listed in Table 2. The radiator part of this antenna was printed on Arlon AD 430 dielectric substrates with a thickness of 0.762 mm. Meandering was performed here to lengthen the effective current path, which led to an increase in the effective wavelength with miniaturized structure. Corner-chamfering was performed to reduce the stray radiated emission to minimize losses and unwanted reactance [40]. For proper analysis of the communication and SAR performance, a prototype of implantable medical device (shown in Figure 3) containing the corner-chamfered antenna, camera, PCB and sensor encapsulated by 0.5 mm thick biocompatible coating made of 10 g gelatin and 15 g deionized (DI) water which has relative permittivity of 41.57 and loss tangent of 0.39 at 2.45 GHz, was taken. A coaxial probe with 0.63 mm probe radius providing input impedance of 50 Ω was used for exciting the antenna system.

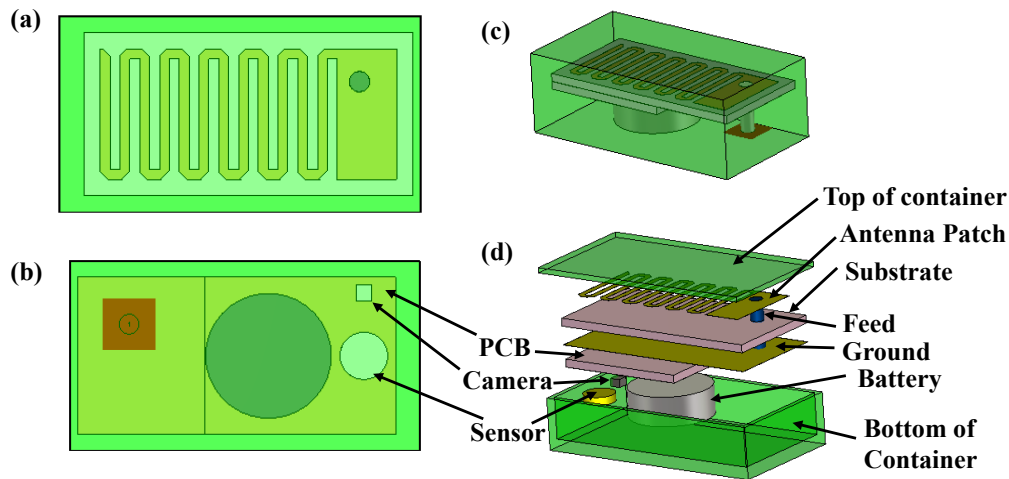


Figure 3. Detailed architecture of Implantable device: (a) Top view, (b) Bottom view, (c) Isometric view and (d) Exploded view.

2.1.2. Simulation Setup

The corner-chamfered antenna was implanted within a 100 mm X 100 mm X 100 mm cubical mean Homogeneous Human Body Model (HHBM) at the center as shown in Figure 4. The HHBM has a relative permittivity of 52.7 and conductivity of 1.95 S/m based on FCC guideline [41]. HHBM was enclosed by an airbox which is considered as radiation boundary of the implanted system. Numerical simulations were performed using Finite Element Method (FEM) method using CST MWS 2019 commercial software. Here, a Gaussian source was fed to the implanted antenna and frequency response was measured at 2.5 GHz.

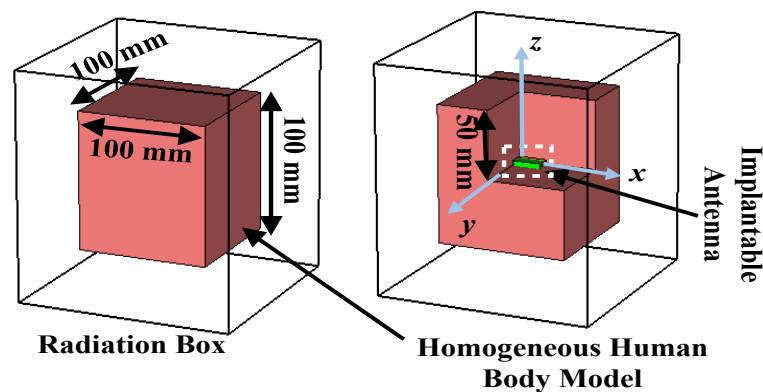


Figure 4. Homogeneous human body model consider to simulate implantable antenna system.

2.1.3. Design Evolution

The design steps of the implantable antenna are shown in Figure 5. An initial patch with size of 18 mm X 8 mm was designed on substrate, resulting in poor S_{11} response at operating frequency of 3.18 GHz. In Step 2, a meander-line was created at the opposite edge of excited part by etching two 0.6 mm slots as shown in Figure 5. The operating frequency was shifted to 2.82 GHz and S_{11} was improved to -18.05 dB. The incorporation of slots increased effective guided wavelength by increasing equivalent capacitance. To tune the operating frequency within 2.45 GHz ISM band (2.4-2.5 GHz), more symmetrical slots were etched to increase meander-line numbers. After creating six meander-line slots as shown in Figure 5, the operating frequency was tuned at the desired band. The reflection coefficient (S_{11}) of this antenna architecture was observed as -15.59 dB. The realized gain of

this antenna was -47.28 dBi. To improve the antenna responses in terms of S_{11} and gain, the chamfering of the corners were performed. Operating frequency was not varied due to chamfer; however, reflection coefficient was improved to -45.87 dB and realized gain was increased to -38.42 dBi. The simulated antenna possessed a fractional bandwidth of 5.67%.

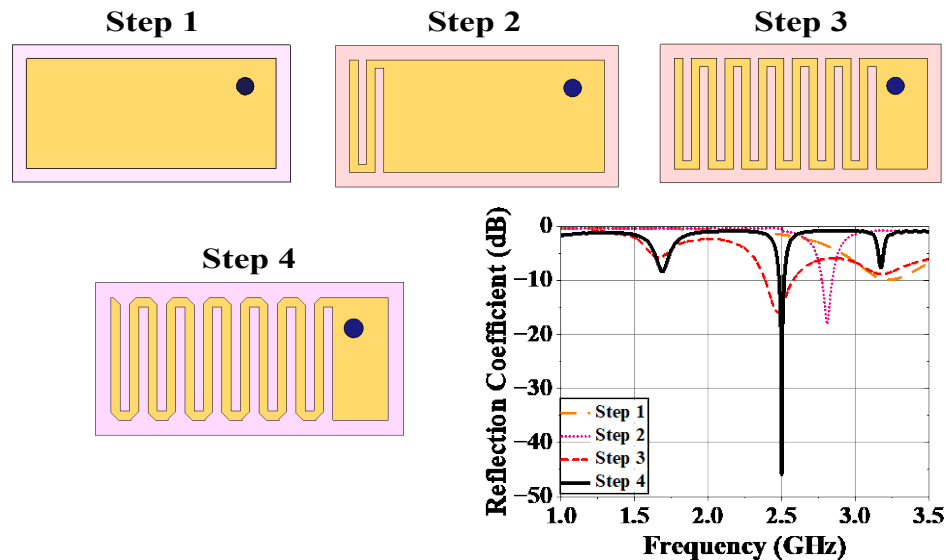


Figure 5. Design Evolution steps of implantable antenna within human body model and their reflection coefficients (dB).

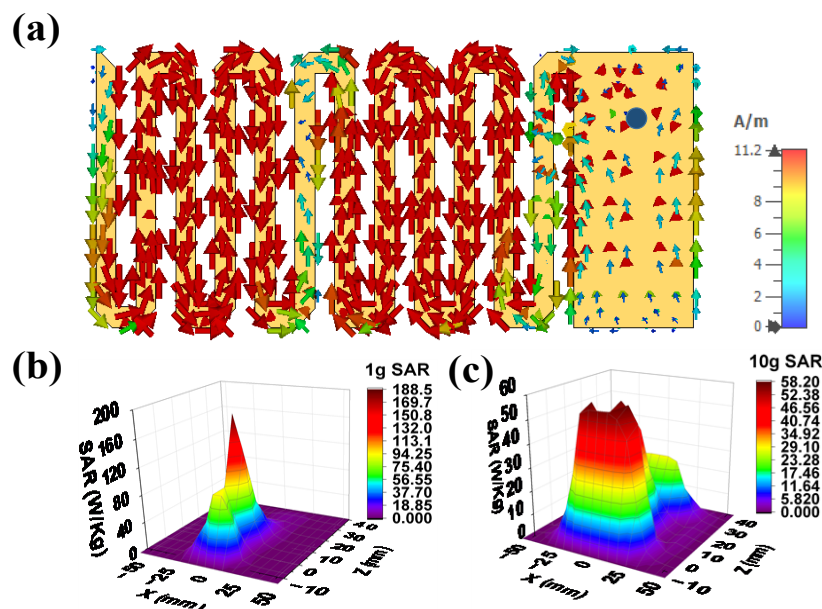


Figure 6. (a) Surface current distribution on patch of antenna at 2.5 GHz; 3D 1W SAR plots (Y=0 calibration) for (b) 1g and (c) 10g tissue.

2.1.4. Current Distribution and SAR profile

Figure 6 (a) shows the surface current distribution of the final antenna radiator at 2.5 GHz. This current was injected through 50Ω coaxial probe from RF source. From this figure, the current was distributed from connector to the patch surface. The currents were highly dense at the edges of meander-lines. The safety performance of the implanted antenna was evaluated in terms of compliance with international safety guidelines, the IEEE Std. C95.1-2019 [41] guideline. Initially, 1

W average input power was applied to the implanted antenna to observe the SAR distributions for 1 g and 10 g contiguous models. The maximum SAR for the 1 g and the 10 g should be less than 1.6 W/kg and 2 W/kg, respectively, as per the standard guidelines [41]. The peak SAR values for the 1 g and 10 g cubical tissues were obtained as 220.26 W/kg and 59.73 W/kg respectively. The maximum input powers for 1 g and 10 g of body tissues were 7 mW and 24 mW respectively, for maintaining the SAR values within the standard SAR limits. Figure 6 (b) and (c) present simulated 3D 1 g and the 10 g SAR distribution for the implanted antenna respectively for a 1 W input power.

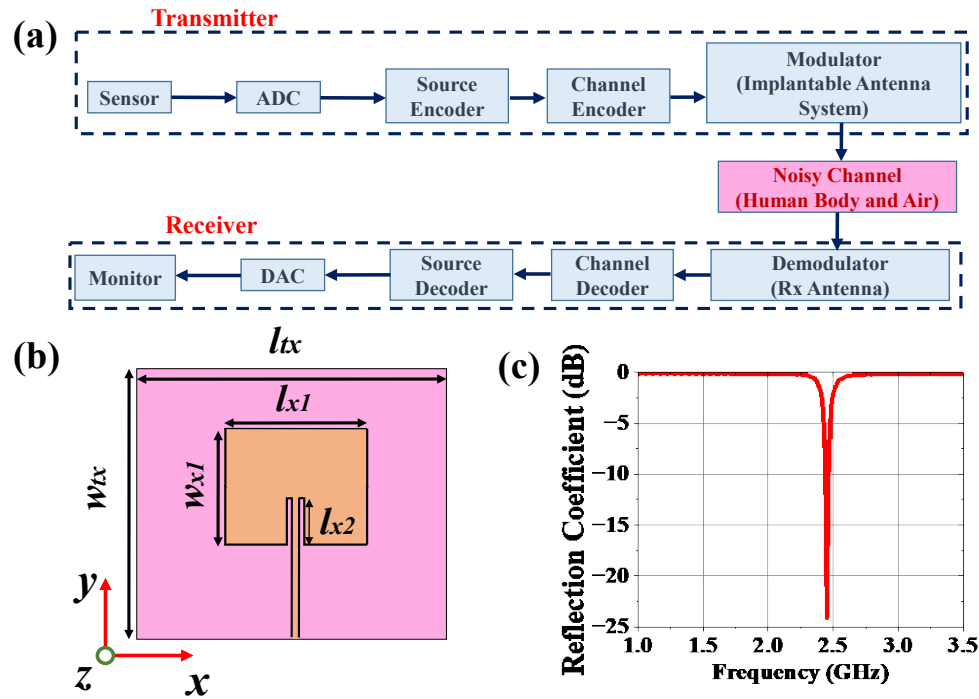


Figure 7. (a) General block diagram of wireless patient monitoring (b) top view of receiving antenna present in external monitoring device where $l_{tx} = 90$ mm, $w_{tx} = 80$ mm, $l_{x1} = 38$ mm, $w_{x1} = 29$ mm and $l_{x2} = 7.5$ mm (c) reflection coefficient plot of Rx antenna.

2.2. Antenna Design for Monitoring Device

The external monitoring device can wirelessly monitor the patient's health condition by collecting sensed data from implantable antenna system tuned to the antenna of the external receiving device as illustrated in Figure 7 (a). Therefore, the receiving antenna of the external monitoring device should be tuned at 2.5 GHz. A patch antenna was designed and placed at 50 mm distance from the top surface of the phantom (refer to Figure 8 (a)). The top view of receiving patch antenna is shown in Figure 7 (b). The antenna has return loss of 24.09 dB at operating frequency 2.49 GHz with realized gain 4.95 dBi.

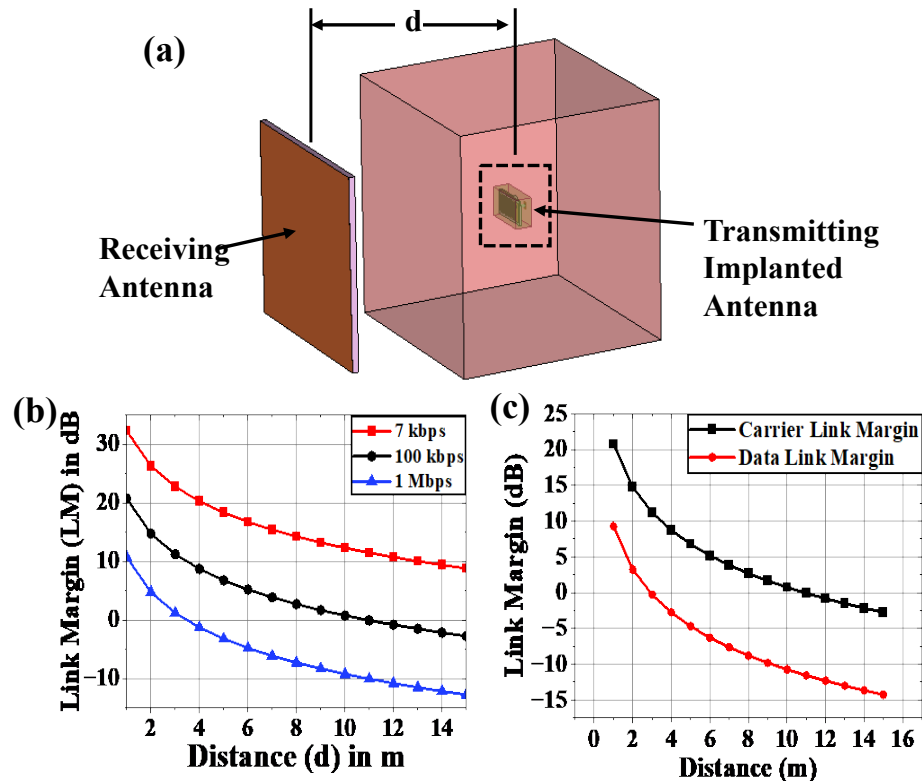


Figure 8. (a) Simulation setup for calculating link margin, (b) generalized link margin vs distance between implanted antenna system and receiving antenna and (c) CLM and DLM vs distance.

2.3. Communication Performance Characterization

For proper establishment of medical communication with external monitoring devices to conduct continuous patient monitoring, the link margin (L) should be calculated using (1). Based on the SAR profile, the input power of the implantable antenna will be $P_{TX} = 7\text{mW} = 8.45\text{dBm}$.

$$L = R_{\text{Link}} (\text{dB}) - R_{\text{req.}} (\text{dB}) \quad (1)$$

$$R_{\text{Link}} = P_{TX} + G_{TX} + G_{RX} - 20 \cdot \log(4\pi d/\lambda) \quad (2)$$

$$R_{\text{req.}} = (E_b/N_0) + 10 \cdot \log(D_r) - G_C + G_D \quad (3)$$

In (2), the expression R_{Link} represents the ratio of the Rx power the patch antenna receives at any distance (d) to the noise power density of the implanted chamfered meander lined antenna. $R_{\text{req.}}$ in (3), denotes the ratio of required carrier power to noise power at the Rx end. Binary Phase Shift Keying (BPSK) modulation with normalized signal-to-noise ratio (E_b/N_0) of 9.6 dB was considered here, and L was calculated using the link budget parameters mentioned in Table 3 for bit rates of 7 kbps, 100 kbps and 1 Mbps. From Figure 8 (b), it was observed that the implantable antenna is able to communicate with the Rx antenna at a distance of more than 700 m for a bit rate of 7 kbps. If the value of D_r is increased to 100 kbps, the transfer range (where $L (\text{dB}) = 0$) is reduced to 200 m. For a further increment of data rate at 1 Mbps, implantable antenna communicates efficiently within 60 m.

2.4. Carrier-Link-Margin and Data-Link-Margin Calculation

Noise temperature is one of the important parameters of any system. Noise temperature is the measurement of equivalent level of available noise power introduced by a component or source. Let us consider the effective noise temperature of the system, which is T_{sys} . Therefore, the modified expression of the generalized link margin is given in (4).

Table 3. Parameters for Link Budget Analysis.

Parameters	Variable	Values
------------	----------	--------

Transmitter	Frequency	f_r	2.47 GHz
	Transmitted Power	P_{TX}	8.45 dBm
	Tx Antenna gain	G_{TX}	-38.42 dBi
	Receiving Antenna gain	G_{RX}	4.95 dBi
	Polarization	P	LP
Receiver	Temperature	T_o	293 K
	Boltzmann Constant	K	1.38×10^{-23}
	Noise Power Density	N_o	199.95 dB/Hz
Signal Quality	Distance	d	1-15m
	Ideal-BPSK	E_b/N_o	9.6 dB
	Coding gain	G_C	0
	Fixing deterioration	G_D	2.5 dB

$$L = P_{TX} + G_{TX} + G_{RX} - 20 \cdot \log(4\pi d/\lambda) - (E_b/N_o) - 10 \cdot \log(D_r) + G_C - G_D - 10 \cdot \log(T_{sys}) \quad (4)$$

To characterize the wireless communication link between the implantable antenna and an external device, carrier link margin (CLM) and data link margin (DLM) were required to learn. CLM is the difference between the achieved carrier-to-noise power and the required carrier-to-noise power in human body communication, and DLM is the difference between the data signal-to-noise power achieved and the data signal-to-noise power required. The CLM and DLM are calculated using (4) for 14 K noise temperature and 100 Kbps data rate and plotted in Figure 8 (c) for variable distance (d) between the receiver and transmitting implanted antenna.

3. Dependence Analysis and Discussion

The human body model's respective mean relative permittivity (ϵ_{eff}) and conductivity (σ_{eff}) are 52.7 and 1.95 S/m as per FCC guidelines at 2.5 GHz. The electrical properties can be varied by around $\pm 20\%$ with respect to reference ϵ_{eff} and σ_{eff} . Therefore, two Gaussian pulses (N_e and N_o) for ϵ_{eff} and σ_{eff} were taken as mentioned in equations (5-6) and sampled into 50 points. Therefore, 2500 scenarios with different combinations of ϵ_{eff} and σ_{eff} were obtained to record the implanted antenna's communication performance and SAR profile. The possible variations in medical communication performance and SAR profile due to both body-electrical properties variations were studied here.

$$N_e = \{1/\sqrt{(2\pi(\Psi_e)^2)} \cdot \exp[(-1/2)\{(\epsilon_{eff}-52.7)^2 / (\Psi_e)^2\}]\} \quad (5)$$

$$N_o = \{1/\sqrt{(2\pi(\Psi_o)^2)} \cdot \exp[(-1/2)\{(\sigma_{eff}-1.95)^2 / (\Psi_o)^2\}]\} \quad (6)$$

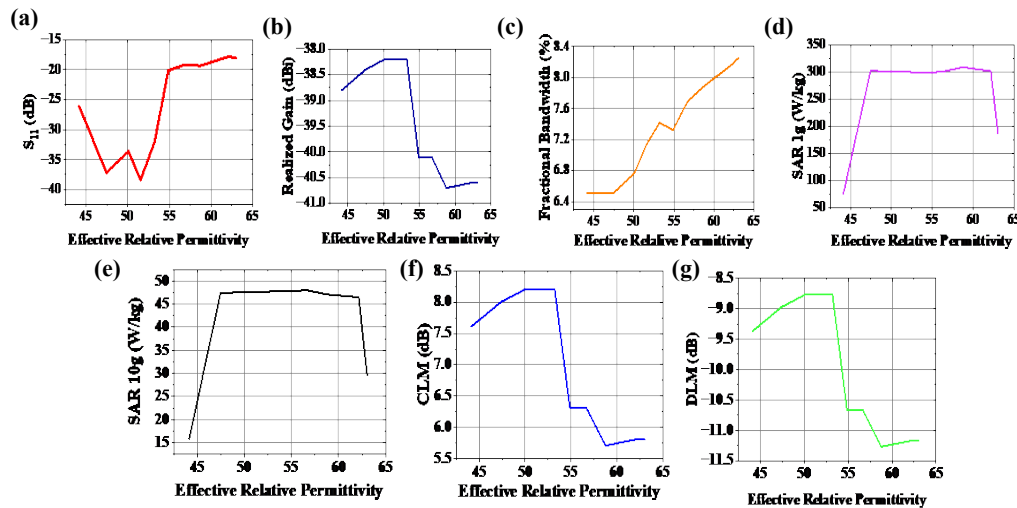


Figure 9. Effect of $\pm 20\%$ variation in effective relative permittivity on (a) S_{11} , (b) realized gain, (c) fractional bandwidth, (d) 1g SAR (1 watt input power) (e) 10g SAR (1 watt input power), (f) CLM (100 kbps data rate at $d = 4$ m) and (g) DLM (100 kbps data rate at $d = 4$ m) of implanted antenna system.

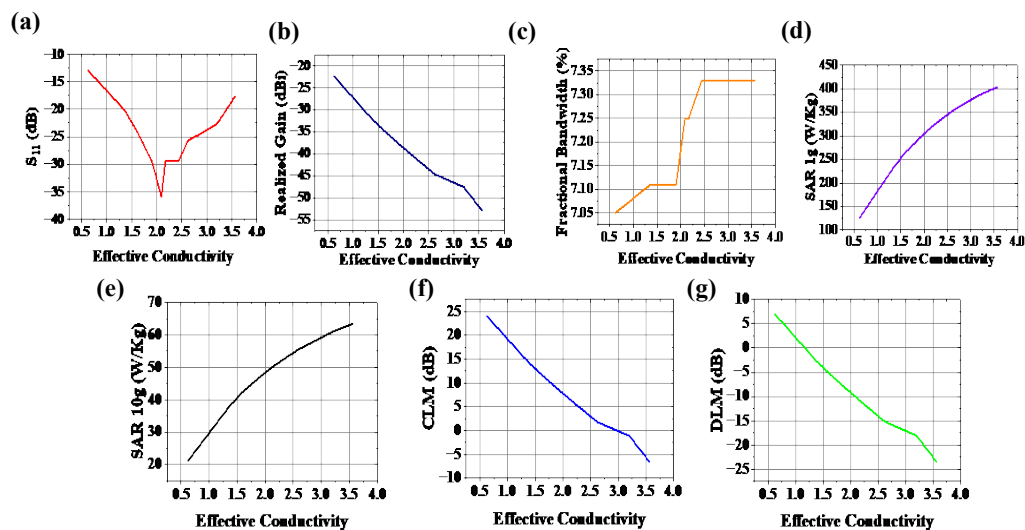


Figure 10. Effect of $\pm 20\%$ variation in effective conductivity on (a) S_{11} , (b) realized gain, (c) fractional bandwidth, (d) 1g SAR (1 watt input power) (e) 10g SAR (1 watt input power), (f) CLM (100 kbps data rate at $d = 4$ m) and (g) DLM (100 kbps data rate at $d = 4$ m) of implanted antenna system.

3.1. Variation of Effective Relative Permittivity

The communication channel characteristics between implantable antenna system and external receiving antenna connected to monitoring device are varied due to variation in electrical property of human tissues. The effect of effective relative permittivity of body model on radiation performance (S_{11} , realized gain, fractional bandwidth), communication performances (CLM, DLM for 100 kbps data rate at 4 m from implantable antenna system) and SAR profile (SAR for 1g and 10g contiguous tissue) was studied at 2.5 GHz keeping effective conductivity of body model constant at 1.95 S/m and plotted in Figure 9. Due to variation in effective relative permittivity of human body, the return loss is improved for $44.12 < \epsilon_{\text{eff}} < 55$ due to increase in loading on antenna system. Beyond this range, the impedance loading is not taking dominant effect on reflection coefficient of the system as obtained from Figure 9(a). For $44.12 < \epsilon_{\text{eff}} < 55$, variation in realized gain (Figure 9(b)) is almost negligible (~ 38.4 dBi). However, it is deteriorated towards -41 dBi which also leads to worsen CLM and DLM (refer to Figure 9 (f, g)). Misinterpretation of patient's data, noisy data acceptance may happen in receiving

end. Therefore, doctor cannot monitor and diagnose patient wirelessly in proper way. From Figure 9(c), fractional bandwidth is improved with increase in effective relative permittivity. SAR values for both 1g and 10g tissue (Figure 9(d) and (e) respectively) are not widely dependent on effective relative permittivity variation between $47.45 < \epsilon_{\text{eff}} < 62.15$.

3.2. Variation of Effective Conductivity

The effect of effective conductivity of body model on system performance was studied at 2.5 GHz keeping effective relative permittivity of body model constant at 52.7 and plotted the effects in Figure 10. The increase in conductivity of the wireless communication channel can increase in noise in terms of loss tangent ($\tan \delta = \sigma_{\text{eff}}/\omega\epsilon_{\text{eff}}$). From Figure 10 (a), S_{11} value is improved when σ_{eff} is between 1.5 and 3 S/m. Realized gain (Figure 10 (b)), CLM (Figure 10 (f)) and DLM (Figure 10 (g)) are deteriorated with increase in conductivity of human body which hamper the communication performance for Wireless Body Area Network. Analyzing the plot of fractional bandwidth vs effective conductivity shown in Figure 10 (c), it is observed that fractional bandwidth has almost linear relationship with effective conductivity with low slope. SAR values for both 1g and 10g tissue (Figures 10 (d, e) respectively) are highly dependent on effective conductivity variation. SAR values increase in large scale with conductivity increment which may hamper patient safety.

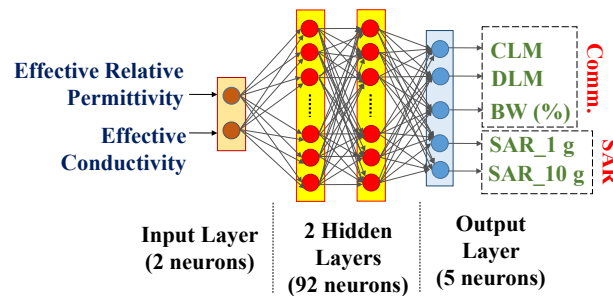


Figure 11. Artificial Neural Network.

3.3. Variations in both Effective Relative Permittivity and Conductivity

Communication characteristics, such as CLM, DLM, include the realized gain and reflection coefficient of implantable antenna system. Therefore only CLM, DLM, SAR for 1g and 10g tissue models and fractional bandwidth are considered for dependence analyses. 2500 scenarios ($\pm 20\%$ variations in reference to effective relative permittivity and conductivity of the human body) were considered here. An artificial neural network (ANN) with two input neurons (ϵ_{eff} and σ_{eff}) two hidden layers (92 neurons), and five output layers (CLM, DLM, BW (%), SAR_1g and SAR_10g) shown in Figure 11, was trained with 80% of the total scenarios and validated by remaining 20% data. Training time was 2 msec/step. 10 random scenarios were simulated in CST, and simulated responses were collected. The responses of similar scenarios predicted by ANN were recorded to observe the efficiency of prediction by designed ANN. The ANN was modeled to predict the antenna system performance parameter values for any random set of (ϵ_{eff} , σ_{eff}) because the set values are different for different patients' bodies.

4. Experimental Setup and Measurement

4.1. Implantable Antenna System

In this section, in-vitro performance analysis of simulated implantable antenna system is described. The physical prototypes of implantable antenna and receiving antenna were fabricated. The fabricated prototype of implantable antenna is shown in Figure 12 (a). Small battery ($\pi \times 3.952 \times 3.6 \text{ mm}^3$), prototype of PCB (Arlon AD 430 covered with copper in both sides), prototypes of sensor and camera (Arlon AD 430) were taken to replicate the simulated antenna system as shown in Figure

12(a). To excite the antenna, 50 Ω coaxial cable was connected using soldering (Figure 12 (b, c)) and other end was connected with one of the two ports of vector network analyzer (VNA) for S-parameter measurement as illustrated in Figure 12 (d). Top and bottom views of implantable antenna system before coating are shown in Figure 12 (b) and (c) respectively.

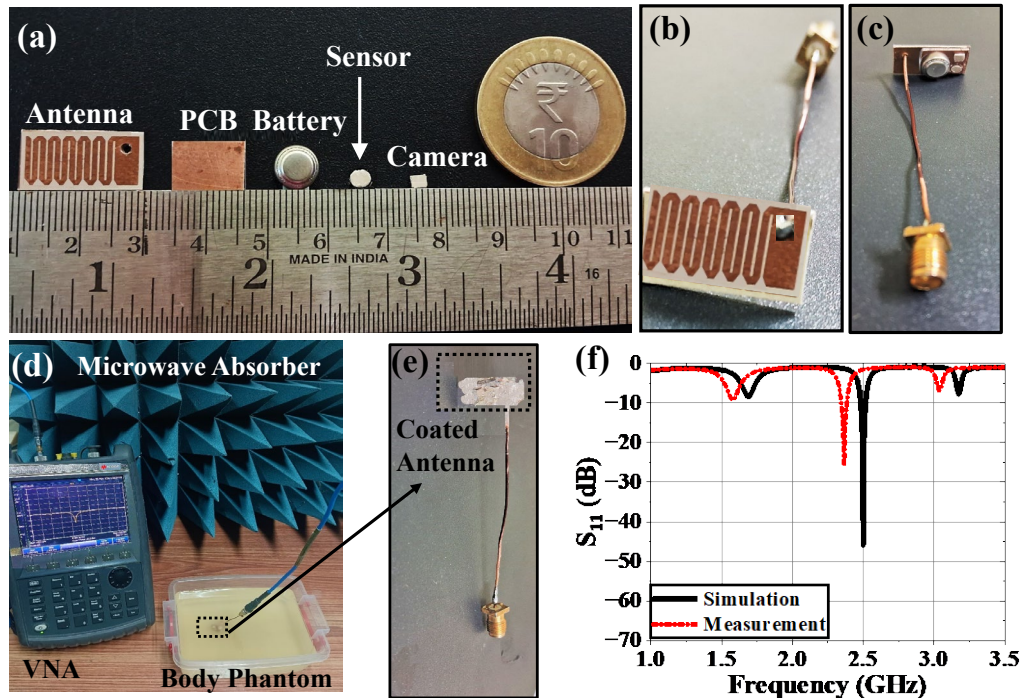


Figure 12. (a) Fabricated prototypes of all components of the implantable antenna system, (b) top and (c) bottom views of implantable antenna system without cover, (d) reflection coefficient measurement setup of implantable antenna, (e) top view of antenna system within gelatin coating and (f) comparison between simulated and measurement.

The whole system was covered with biocompatible gelatin cover made of 15g DI water and 10g gelatin which is depicted in Figure 12 (e). For in-vitro measurement, homogeneous semi-solid body phantom model was developed by 66.3% DI water, 31.6% DGME, 0.4% NaCl and 1.7% Agar agar powder. The dielectric properties in terms of relative permittivity and conductivity of the phantom were measured using Agilent 85070E dielectric kit. The developed phantom had effective relative permittivity and conductivity of 51.75 and 1.91 S/m respectively at 2.5 GHz. The designed antenna system was then implanted within semi-solid human body phantom at 50 mm depth from top surface as shown in Figure 12 (d) to measure the reflection coefficient of the implanted antenna. The comparison between simulated and measured S_{11} responses was plotted in Figure 12 (f). The measured S_{11} was -22.97 dB at 2.43 GHz. The co- and cross-polar E and H plane far field radiation patterns obtained from measurement set up shown in Figure 13 (a-b) are plotted in Figure. 14 (a-d). The antenna system had measured realized gain of -32.68 dBi at its operating frequency.

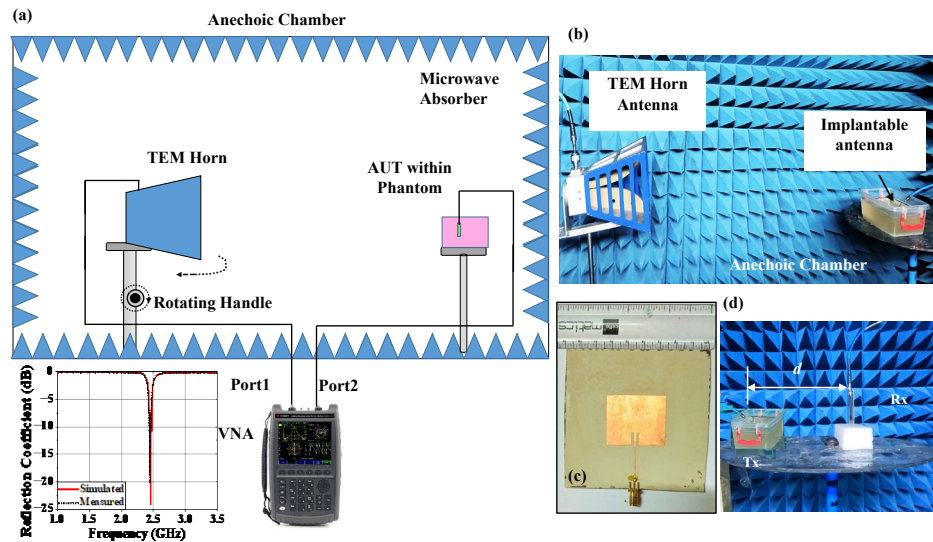


Figure 13. (a) Schematic of far-field radiation pattern measurement setup within anechoic chamber and its required hardware, (b) Far-field radiation pattern measurement of implantable antenna system within phantom using a TEM horn antenna, (c) top view of fabricated receiving antenna and its reflection coefficient plots (comparison between simulation and measurement), (d) communication performance between Tx implantable antenna system and Rx antenna.

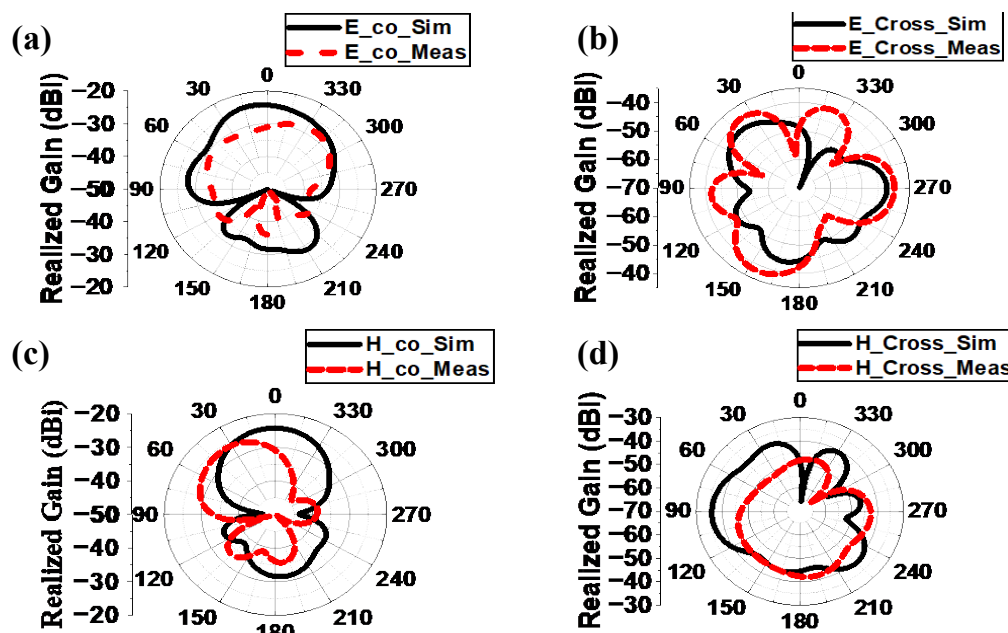


Figure 14. Comparison of radiation patterns between simulated and measured responses at (a) E-plane co-polar, (b) E-plane cross polar, (c) H-plane co-polar and (d) H-plane cross polar at 2.5 GHz.

4.2. Monitoring Antenna

The receiving antenna for monitoring device was fabricated and measured in similar process of reflection coefficient and radiation pattern measurement processes of implantable antenna system. The top view of fabricated Rx antenna along with its comparison plots of reflection coefficient for simulated and measured results is shown in Figure 13 (c). The fabricated antenna had S_{11} and realized gain of -20.18 dB and 4.02 dBi. For communication performance study, Rx antenna was kept at different distances (d) from implantable antenna as shown in Figure 13 (d) and study CLM, DLM and gain from transmission coefficient measurements.

Table 4. Comparison of Estimated Responses of ANN with Simulated and Measured Results.

4.3. Variation Analysis

These scenarios were replicated in a laboratory by varying the amount of DGME with 273 ml DI water and 794 mg NaCl. The practical antenna parameters within 10 prepared phantoms were collected by putting fabricated antenna inside them. Table 4 and 5 show the effective predictions of communication performance and SAR profile by ANN due to the variable human body model, respectively. From Tables 4 and 5, it is observed that the designed antenna could predict the communication performance of the implanted antenna with a respective average accuracy of 99.89% and 99.78% with respect to simulation and measurement for $\pm 20\%$ possible variations in both electrical properties. Respective average accuracies of implantable antenna of 99.01% and 98.27% for 1 g and 10 g SAR profiles were observed. Compared with the reference effective electrical properties of the homogeneous human body model, respective maximum variations of 63%, 41.6%, 17.97%, 26.79% and 5.89% are observed in 1 g and 10 g SAR value, fractional bandwidth, CLM and DLM at 4 m distance for 100 Kbps.

Table 5. Comparison of SAR Profile Predicted By ANN with Simulated Results.

Sample	Effective Properties		Simulation		ANN		% error of prediction w.r.t Simulation	
	ϵ_{eff}	σ_{eff}	1 g	10 g	1 g	10 g	1 g	10 g
1	46.02	0.63	250.15	65.09	247.60	64.98	1.03	0.17
2	46.02	0.92	147.78	43.57	145.98	42.65	1.23	2.16
3	46.02	3.56	302.63	74.26	300.98	75.95	0.55	2.23
4	49.80	1.80	227.38	61.01	227.22	61.42	0.07	0.67
5	51.69	1.51	203.46	56.43	202.65	57.23	0.40	1.40
6	53.59	1.80	225.20	60.72	226.18	60.55	0.43	0.28
7	55.48	2.10	348.30	64.03	345.45	65.22	0.83	1.82
8	57.37	0.63	109.15	33.91	108.45	33.22	0.65	2.08
9	59.26	0.92	127.85	42.47	125.65	42.58	1.75	0.26
10	63.04	2.97	231.16	68.81	235.22	69.18	1.73	0.53

5. Conclusions

In this study, the dependences of communication performance and SAR profile variations of a corner-chamfered meander-line body-implantable antenna at 2.5 GHz on effective relative permittivity and conductivity were numerically analyzed. An ANN with two input variables (ϵ_{eff} , σ_{eff}) and five output variables (SAR_1g, SAR_10g, fractional bandwidth, CLM and DLM) is trained by 80% and tested by 20% of total scenarios for accurate dependence analysis. Compared with the reference effective electrical properties of the homogeneous human body model, respective maximum variations of 63%, 41.6%, 17.97%, 26.79% and 5.89% were observed in 1 g and 10 g SAR value, fractional bandwidth, CLM and DLM at 4 m distance for 100 Kbps. Designed ANN can predict the communication performance of implanted antenna with respective average accuracy of 99.89% and 99.78% with respect to simulation and measurement for $\pm 20\%$ possible variation in both electrical properties. Respective average accuracies of implantable antenna 99.01% and 98.27% for 1 g and 10 g SAR profiles are observed.

Author Contributions: Conceptualization, Soham Ghosh; Formal analysis, Fanuel Elias and Bhaskar Gupta; Funding acquisition, Stephen Alabi; Investigation, Soham Ghosh; Methodology, Soham Ghosh, Sunday Ekpo, Fanuel Elias and Bhaskar Gupta; Software, Soham Ghosh; Supervision, Sunday Ekpo and Bhaskar Gupta; Validation, Soham Ghosh, Sunday Ekpo and Bhaskar Gupta; Writing – original draft, Soham Ghosh; Writing – review & editing, Sunday Ekpo, Fanuel Elias and Stephen Alabi.

Funding: This research received no funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author(s).

Conflicts of Interest: The authors declare no conflicts of interest.

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