

PERFORMANCE CHARACTERISTICS ON PATCH ANTENNA
WITH SAR REDUCTION USING ARTIFICIAL MAGNETIC
CONDUCTOR (AMC) FOR WBAN APPLICATIONS

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Sincerely dedicated to my beloved Mother, father and my Siblings



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ABSTRACT

Great advances have been made in the area of wireless body area networks (WBANs) of improving wireless communication technology since the invention. These advances range in refining, size reduction and shape, gain improvement, more efficiency and combination of the requirements for applications which include health monitoring, military and personal navigation entertainment. Several types of antennas have been developed for WBANs and they have achieved narrow bandwidth, decrease gain, low radiation efficiency, a high specific absorption rate (SAR) value, high front-to-back ratio (FBR) and structural complexity. However, it is necessary to achieve better performance antenna for less impact of frequency detuning, by improving FBR, high radiation efficiency and reduce SAR for WBAN application. Conventional patch antennas are adopted since they can be low weight, low profile and easy to integrate with the device. Having these unique characteristics, patch antenna has shown to have clear advantages for WBAN applications. Since an antenna is placed a close to the human body with its curvatures and complexities, the antenna performance must be taking into account the structural, mismatch, and losses caused by the body, while simultaneously sustaining optimum performance. This work proposes to design, analysis and optimization of low-profile antenna integrated with Artificial Magnetic Conductor (AMC) for WBAN applications. Multilayer model of the adult human body at the frequency band of the proposed antenna is used, which helps to study the effects of the human on the antenna performance. The results showed that the presence of human head affects the antenna performance in terms of radiation pattern, efficiency and S_{11} and SAR values on the body parts. To further improve the performance of the proposed antenna design, several techniques have been developed in reducing SAR value with low complexity using AMC to realize broadside radiation for on /off body communication. AMC structure and miniaturized reflector reduce the back radiation and the impact of frequency detuning due to high losses of human body and the two proposed techniques are mounted on human head phantom. In addition, AMC improved FBR by 15.3 dB with enhanced of gain 7.61 dBi and radiation efficiency

more than 88 %. The AMC have achieved 93.7 % reduction of the initial SAR value while metal reflector achieved a reduction of 77.7 %. Then, the antenna is fabricated and measured to validate the concept. Thus, the proposed antenna with AMC structure was designed and fabricated using two different materials for far-field radiation pattern measurements. The measured and simulated results reveals that proposed antenna with AMC array shows good impedance matching and far-field radiation pattern .Therefore, the proposed antenna is a potential candidate for WBAN.



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ABSTRAK

Kemajuan besar telah dicapai dalam bidang rangkaian kawasan badan tanpa wayar (WBANs) untuk meningkatkan lagi teknologi komunikasi tanpa wayar sejak penciptaannya. Kemajuan ini merangkumi penambahbaikan dari segi pengurangan saiz dan bentuk, peningkatan gandaan, lebin cepak, dan gabungan semua keperluan bagi pelbagai aplikasi termasuk pemantauan kesihatan, tentera dan hiburan navigasi peribadi. Beberapa jenis antena telah dibangunkan untuk WBAN dan telah mencapai lebar jalur yang sempit, penurunan gandaan, kecekapan radiasi yang rendah, nilai kadar penyerapan tertentu (SAR) yang tinggi, nisbah-depan-belakang (FBR) yang tinggi dan pengurangan kerumitan struktur. Walau bagaimanapun, adalah penting bagi mencapai prestasi antena yang lebih baik untuk mengurangkan kesan nyahtala frekuensi, dengan meningkatkan nisbah FBR, meningkatkan kecekapan radiasi serta mengurangkan bacaan SAR yang sesuai untuk aplikasi WBAN. Antena tampalan konvensional diadaptasikan kerana ia bersifat ringan, berprofil rendah dan ianya mudah untuk diintegrasikan dengan peranti. Dengan memiliki ciri-ciri yang unik ini, antena tampalan telah menunjukkan kelebihan yang jelas untuk aplikasi WBAN. Oleh kerana antena sentiasa berhampiran dengan tubuh manusia dan berbentuk lekuk dan rumit, prestasi antena mesti diambil kira berdasarkan kepada struktur, ketidakserasian dan kehilangan yang disebabkan oleh tubuh manusia dalam masa yang sama mengekalkan prestasi yang optimum. Kajian ini memberi tumpuan kepada reka bentuk, analisa dan pengoptimuman antena berprofil rendah yang disambungkan dengan aplikasi Konduktor Magnetik Buatan (AMC) untuk WBAN yang dicadangkan. Model simulasi pelbagai lapisan kepala manusia dewasa pada jalur frekuensi dan antena digunakan, bagi membantu pengkajian tentang kesan manusia terhadap prestasi antena. Hasil kajian yang diperolehi menunjukkan kehadiran kepala manusia berhampiran antena memberi kesan terhadap prestasi antena tersebut terutamanya pada corak radiasi, kecekapan dan S_{11} , ia juga memberi kesan terhadap bacaan SAR dan pengedaran gelombang pada bahagian badan. Untuk mempertingkatkan lagi

prestasi rekabentuk antenna, beberapa teknik telah dilaksanakan dalam mengurangkan bacaan SAR dengan kerumitan yang rendah menggunakan AMC untuk merealisasikan radiasi sisi lebar bagi buka/tutup komunikasi pada badan. Struktur AMC dan reflektor mini mengurangkan radiasi belakang dan impak frekuensi nyahtala disebabkan kehilangan oleh tubuh manusia yang tinggi, dan kedua-dua teknik yang dicadangkan telah dipasang kepada model kepala manusia. Tambahan pula, AMC meningkatkan bacaan FBR sebanyak 15.3 dB dengan peningkatan gandaan sebanyak 7.61 dBi dan kecekapan radiasi lebih daripada 88 %. AMC telah mencapai pengurangan nilai SAR awal sebanyak 93.7 % manakala reflektor logam mencapai 77.7 % pengurangan nilai SAR awal. Untuk mengesahkan konsep yang dicadangkan, antenna menggunakan struktur AMC telah direka dan difabrikasi dengan dua bahan yang berbeza untuk pengukuran corak sinaran medan jauh. Hasil simulasi dan pengukuran antenna menggunakan tatasusun AMC array menunjukkan padanan yang baik dan corak sinaran medan jauh. Oleh itu, antenna ini merupakan calon yang berpotensi untuk WBAN.



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CONTENTS

	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENT	iv
	ABSTRACT	v
	ABSTRAK	vii
	CONTENTS	ix
	LIST OF TABLES	xii
	LIST OF FIGURES	xiv
	LIST OF SYMBOLS AND ABBREVIATIONS	xxi
	LIST OF APPENDICES	xxiii
CHAPTER 1	INTRODUCTION	1
	1.1 Introduction	1
	1.2 Background and Motivation	2
	1.3 Problem Statement	5
	1.4 Objectives	7
	1.5 Scope of Study	7
	1.6 Significant contribution of research	8
	1.7 Thesis organization	8
CHAPTER 2	LITERATURE REVIEW	10
	2.1 Wearable communication technology	10
	2.1.1 Wireless body area network (WBAN)	11
	2.1.2 Specific absorption rate (SAR)	14
	2.1.3 Human head phantoms	15
	2.2 Narrowband antennas for WBAN	21
	2.2.1 Performance changes due to body proximity	24
	2.2.1.1 Effect of human body on resonant frequency	25

2.2.1.2	Changing the radiation of the antenna due to human body	29
2.2.1.3	Power absorption in body tissues	31
2.3	The criteria for optimum performance	34
2.3.1	Improving the antenna performance close to the human body	36
2.3.2	Perfect electric conductor (PEC)	37
2.3.3	EBG structures between the ground plane and antenna	38
2.3.4	Using an antenna with a metamaterial structure	41
2.4	Summary of chapter	49
CHAPTER 3	METHODOLOGY	50
3.1	Research methodology and flow chart	51
3.1.1	Design methodology of the proposed antenna	53
3.1.1.1	Antenna geometry	55
3.1.1.2	Design AMC and reflector structure	61
3.2	Fabrication Process	64
3.2.1	Conventional substrates	64
3.3	Measurement setup	67
3.4	Human head phantom	71
3.4.1	Specific Absorption Rate (SAR)	73
3.5	Summary of chapter	76
CHAPTER 4	RESULTS AND ANALYSIS	77
4.1	Analysis of square ring antenna for different substrates	77
4.1.1	Effect of substrate thickness	78
4.1.2	Effect of tangential loss	81
4.1.3	Effect of different feeding techniques	83
4.1.4	Effects of different substrate materials	85
4.1.5	Effect of ground plane	88
4.2	Integration of conventional antenna with AMC and reflector	96
4.2.1	Design of reflector plane structure	96
4.2.2	Design of proposed AMC structure	100
4.2.3	Integrated antenna with AMC structure	104

4.3	Experiment results and discussion	108
4.3.1	Simulated and measured antenna with full grounded	108
4.3.2	Simulated and measured antenna with DGS	111
4.3.3	Simulated and measured antenna with reflector	113
4.3.4	Simulated and measured antenna with AMC structure	115
4.4	Evaluate the Performance of the proposed antenna in multilayered human head phantom	123
4.4.1	Effects of the ground and the effect of human head phantom	124
4.4.2	Return loss	125
4.4.3	Radiation pattern	127
4.4.4	Specific absorption rate	129
4.4.5	Effects of DGS and the human head on antenna performance	130
4.5	Reduction of SAR on human head with reflector	133
4.5.1	Return loss	134
4.5.2	Radiation pattern	136
4.5.3	Specific absorption rate	139
4.6	Reduction of SAR on human head with AMC	140
4.6.1	Return loss	141
4.6.2	Radiation pattern	143
4.6.3	Specific absorption rate	144
4.7	SAR distribution	144
4.8	Result and discussion	147
4.9	Summary of chapter	150
CHAPTER 5	CONCLUSION AND FUTURE RECOMMENDATION	152
5.1	Conclusion	152
5.2	Future recommendations	154
	REFERENCES	156
	APPENDIX	168
	VITA	181

LIST OF TABLES

1.1	Specific absorption rate (SAR) limits	3
2.1	Dielectric properties of biological tissues used the head model at 5.8GHz[10]	17
2.2	Electrical properties of multilayer phantom at 5.8 GHz [59]	18
2.3	Dielectric properties of the seven-layer human head model [60]	20
2.4	Properties of the tissue equivalent dielectric used for glass shell [60]	21
2.5	Properties of the tissue equivalent dielectric used for tissue equivalent [60]	21
2.6	Simulated and Measured Specific Absorption Rate (SAR)	33
2.7	Performance and characteristics of previous works	45
2.8	Performance comparison of different antenna designs reported for WBAN applications	46
3.1	Optimized design parameters of square slot patch antenna printed FR4 and RT5880 Substrate	61
3.2	Specification design parameters of the selected unit cell	63
3.3	Dielectric properties of tissues used the head models at 5.8GHz [10]	72
4.1	Effect of different substrate thickness on S_{11} and bandwidth	80
4.2	Effect of various tangent loss on S_{11} and bandwidth	82
4.3	Important design parameters of the antenna	86
4.4	Comparison of effect substrate height on antenna performance	88

4.5	Comparison of reference antenna and proposed antenna results	96
4.6	Comparison of directivity and bandwidth while increasing distance for reflector at (FR4)	99
4.7	Comparison of directivity and bandwidth while increasing distance for reflector at (Roger 5880)	100
4.8	Comparison of directivity, S_{11} and bandwidth with and without AMC	107
4.9	Comparison simulated and measured gain with all cases	118
4.10	Dielectric properties of biological tissues used at 5.8 GHz	124
4.11	Comparison SAR Value with and without AMC	146
4.12	Comparison of proposed antenna and the previous works	149



LIST OF FIGURES

1.1	General structure of WBAN system [8]	2
1.2	level of details in human head phantom for SAR distribution (a) human head realistic phantom (b) skull [25]	4
2.1	A general communication architecture of a typical WBAN-based healthcare monitoring system [39].	12
2.2	Classifications and specific applications of BASN and WBAN [44].	13
2.3	List of frequency bands for WBANs [50].	14
2.4	1-g SAR distributions (antenna at the bottom at 1850 MHz, with a phone output power of 1 W) [58].	16
2.5	(Left) Ellipsoid model and (Right) model with anatomical shape [10].	17
2.6	View of human head phantom models: (a) homogeneous phantom (b) multilayer phantom [59].	18
2.7	(a) homogenous, (b) multilayer, (c) gap distance, (d) and (e) antenna at position, (f) SAM phantom, (g) 3D HUGO, (h) top view, (i) side view,(j) front view of the HUGO human head model [60].	19
2.8	Proposed antenna (a) and (b) dielectric parameter measurement	26
2.9	Geometry of the proposed button antenna. (a) Perspective view integrated with clothes; (b) Metal parts on two sides of the substrate; (c) Metal flange; (d) Ground coplanar waveguide (GCPW) feeding. Dimensions (mm) [3]	27
2.10	Geometry and dimensions of the fabricated antenna [2]	28

2.11	Radiation patterns on homogeneous phantom and on hand phantom at (a) lower band; (b) upper band [3]	30
2.12	Radiation pattern of the dipole antenna on human head	31
2.13	(a) On-body case: chest to abdomen; (b) Off-body case: face-to-back [3].	33
2.14	Microstrip patch antenna on human body layers for various substrate	35
2.15	Photographs of the fabricated antennas. (a) Antenna. (b) EBG 1 array. (c) EBG 2 array. (d) EBG 3 array. (e) Antenna measurement setup. (f) Phone cases of different materials and EBG structures.	40
2.16	Reflection phase graph of AMC unit cell with the AMC unit-cell [105].	41
2.17	Models of antenna integrated with MS (a) and (b) antenna positions on the forearm, upper arm, thigh, chest, and back of the model [107].	42
2.18	Antenna positions on the forearm, upper arm, thigh, chest, and back of the model [107].	43
2.19	CST multi-layer tissue model (a) and (b) SAR plot in a three-layer tissue model [108].	44
3.1	Summary of the process of research	50
3.2	Complete flow chart of the research work	52
3.3	Geometry of proposed square patch antenna (a) patch, (b) antenna with reflector, (c) antenna with AMC	54
3.4	Proposed square patch antenna designed using CST (a) patch,	55
3.5	Design layout square slot antenna with different configuration on RT5880 substrate	60
3.6	Design layout square slot antenna with different configuration on FR4 substrate	60
3.7	Layer structure of AMC unit cell (side view)	62
3.8	Unit cell design considerations (a) single slot patch (b) horizontal slot patch and (c) vertical-slot shaped patch	63

3.9	Characteristics of the reflection phase with varying the length of substrate	63
3.10	Fabrication process	64
3.11	Square slot antenna with fabrication using (a) FR-4 (b) Roger RT-5880	66
3.12	Square slot antenna with reflector fabrication using (a) Roger RT-5880 (b) FR-4 substrate	66
3.13	Square slot antenna with AMC fabricated Roger RT-5880	67
3.14	Measurement setup (a) network analyzer calibration kits R&S (b) horn antenna (c) spectrum analyser Rhode & Schwarz FSH20 (d) signal generator	68
3.15	(a) Antenna radiation pattern and (b) gain measurement set up in the anechoic chamber at (UTeM)	69
3.16	(a) Antenna radiation pattern and (b) gain measurement set up in the anechoic chamber at (UTeM)	70
3.17	The proposed human head model developed in CST MWS	72
3.18	Complete flow chart of compute SAR	74
3.19	(a) measurement for the case of presence of human head and (b) measurement for the case of human head with phone case	75
4.1	Simulated S_{11} for various substrate thickness utilizing FR4 substrate	79
4.2	Simulated S_{11} for various substrate thickness utilizing RT-5880 substrate	79
4.3	Simulated S_{11} for various tangent loss utilizing FR4 substrate	81
4.4	Simulated S_{11} for various tangent loss utilizing RT5880 substrate	82
4.5	Comparison of different configuration feeding techniques (a) quarter wave and (b) insert feeding	84
4.6	Simulated S_{11} for two various feeding technique	84

4.7	Geometry of the proposed patch antenna for both (a) FR4 (b) RT5880	86
4.8	Simulated S_{11} Comparison both FR4 and RT5880	87
4.9	Simulated radiation patterns polar plot comparison (a) FR4 and (b) RT5880 substrate	88
4.10	Geometry of the proposed antenna (a) front view (b) back view	90
4.11	Simulated S_{11} without and with DGS using FR4 substrate	91
4.12	Simulated VSWR with and without DGS using FR4 substrate	92
4.13	Simulated radiation patterns polar plot without DGS and with DGS using FR4 substrate	93
4.14	Geometry of proposed antenna design (a) top view (b) bottom view	93
4.15	Simulated S_{11} with and without DGS using RT 5880 substrate	94
4.16	Simulated VSWR with and without DGS using RT 5880 substrate	95
4.17	Simulated radiation patterns polar plot comparison RT5880 substrate	95
4.18	Geometry of the proposal reflector structure at a distance $<\lambda/4$	97
4.19	Effect of simulated S_{11} for square antenna with reflector at a different distance (FR4)	98
4.20	Effect of simulated S_{11} for square antenna with reflector at a different distance (RT 5880)	98
4.21	AMC structure consists of 2 x 3 array of unit cell	101
4.22	Simulated reflection phase with varying the dimensions of the substrate length	102
4.23	Simulated reflection phase with varying the dimensions of the substrate length (Ls)	103
4.24	Simulated reflection phase with varying the dimensions of the substrate length (Ls)	104

4.25	Reflection phase with varying dimensions for the proposed AMC structure	105
4.26	Simulated S_{11} without and with AMC structure	106
4.27	Simulated radiation patterns polar plot comparison (a) DGS (b) Reflector and (c) AMC structure	107
4.28	Simulated and measured S_{11} without using FR4 substrate	109
4.29	Simulated and measured VSWR with DGS using FR4 substrate	109
4.30	Simulated and measured S_{11} without DGS using RT-5880 substrate	110
4.31	Simulated and measured VSWR without DGS using RT-5880 substrate	110
4.32	Simulated and measured S_{11} with DGS using FR4 substrate	112
4.33	Simulated and measured VSWR with DGS using FR4 substrate	112
4.34	Simulated and measured S_{11} with DGS using RT-5880 substrate	113
4.35	Simulated and Measured VSWR with DGS using RT-5880 substrate	113
4.36	Simulated and measured S_{11} with reflector using RT-5880 substrate	114
4.37	Simulated and measured VSWR with reflector RT-5880 substrate	115
4.38	Simulated and measured S_{11} with AMC using RT-5880 substrate	116
4.39	Simulated and measured S_{11} with and without AMC using RT-5880 substrate	117
4.40	Comparison simulated S-parameter of the proposed antenna with RT-5880 substrate material	117
4.41	(a) H- plane and (b) E-plane radiation patterns of a patch antenna without DGS at 5.8 GHz with RT 5880 measurement and simulation	119

4.42	(a) H- plane and (b) E-plane radiation patterns of a patch antenna with DGS at 5.8 GHz with RT 5880 measurement and simulation	120
4.43	(a) H- plane and (b) E-plane radiation patterns of a patch antenna with reflector at 5.8 GHz with RT 5880 measurement and simulation	121
4.44	E- plane and H-plane radiation patterns of a patch antenna with AMC at 5.8 GHz with RT 5880 measurement and simulation	122
4.45	Schematic of the simulation setup on the multilayer tissue model	124
4.46	Simulated S_{11} of free space and multilayer human head phantoms with FR4 substrate.	126
4.47	Simulated S_{11} of free space and multilayer human head phantoms with RT 5880 substrate.	126
4.48	Simulated phantom radiation pattern in (a) free spaces and spherical phantom (b) and (c) cubical phantom	128
4.49	Simulated phantom radiation pattern in (a) free spaces and spherical phantom (b) and (c) cubical phantom	129
4.50	Comparison simulated SAR value of antenna mounted on human head (a) spherical phantom and (b) cubical phantom on FR4	130
4.51	Comparison simulated SAR value of antenna mounted on human head (a) spherical phantom and (b) cubical phantom on RT 5880	130
4.52	Comparison of scattering parameter (S_{11}) of free space and multilayer human head phantom on RT 5880 substrate	131
4.53	Comparison of the simulated on phantom radiation pattern in (a) without DGS (b) With DGS and (c) Phantom	132
4.54	Maximum SAR for 10 g of tissue for 5.8 GHz	133
4.55	Simulated S_{11} of free space and multilayer human head phantom on FR4 substrate	135

4.56	Simulated S_{11} of free space and multilayer human head phantom on RT5880 substrate	136
4.57	Comparison of the simulated on phantom radiation pattern in (a) reflector (b) with spherical phantom (c) cubical phantom	137
4.58	Comparison of the simulated on phantom radiation pattern in (a) reflector (b) with spherical phantom (c) cubical phantom	138
4.59	Comparison simulated SAR value of antenna mounted on human head (a) spherical phantom and (b) cubical phantom on FR4	139
4.60	Comparison simulated SAR value of antenna mounted on human head (a) spherical phantom and (b) cubical phantom on Roger RT5880	140
4.61	Comparison simulated SAR value of antenna mounted on human head (a) spherical phantom and (b) cubical phantom on Roger RT5880	141
4.62	Comparison of scattering parameter (S_{11}) of free space and multilayer human head phantom on RT5880 substrate	142
4.63	Comparison of the simulated on phantom radiation pattern in (a) AMC (b) with spherical phantom (c) cubical phantom	143
4.64	Comparison simulated SAR value of antenna mounted on human head (a) spherical phantom and (b) cubical phantom on Roger RT5880.	144
4.65	Comparison of the vertically orientated antenna locations on SAR.	145

LIST OF SYMBOLS AND ABBREVIATIONS

λ_0	-	Wavelength of radio waves
ϵ_r	-	Dielectric constant
ϵ_{eff}	-	Effective dielectric constant
c	-	Speed of light
Z_0	-	Characteristic impedance
T_x	-	Antenna transmission
R_x	-	Antenna receiving
f_c	-	Resonance frequency
dB	-	Decibel
GHz	-	Gigahertz
BW	-	Bandwidth
S_{11}	-	Reflection coefficient
SMA	-	Surface Mount Adapter
DGS	-	Defected Ground Structure
EBG	-	Electromagnetic Band Gap
S -Parameter	-	Scattering Parameter
CST	-	Computer Simulation Technology
MWS	-	Microwave Studio Environment
PCB	-	Printed Circuit Board
$VSWR$	-	Voltage Standing Wave Ratio
RF	-	Radio Frequency
$WPAN$	-	Wireless Personal Area Network
SAR	-	Specific Absorption Rate
FCC	-	Federal Communication Commission
$(ICNIRP)$	-	International Commission on Non-Ionizing Radiation Protection
EMC	-	Electromagnetic Compatibility Center

<i>ISM</i>	-	Industrial, scientific, and medical radio band
<i>IEEE</i>	-	Institute of Electrical and Electronics Engineers
<i>MRI</i>	-	Magnetic Resonance Imaging
<i>FBR</i>	-	Front-to-Back Ratio
<i>CSF</i>	-	Cerebrospinal Fluid
<i>VNA</i>	-	Vector Network analyzer
<i>SAM</i>	-	Specific Anthropomorphic Mannequin
<i>WBAN</i>	-	Wireless Body Area Network
<i>FDTD</i>	-	Finite-Difference Time-Domain
<i>BCCs</i>	-	Body Coupling Communications.
<i>ERC</i>	-	European Radio Communications Commissions
<i>UBW</i>	-	Ultra-Wideband
<i>MIMO</i>	-	Multiple-Input-Multiple-Output
<i>EM</i>	-	Electromagnetic



LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	List of Publications and Awards	157
B	Mathematical Modeling using Curve Fitting MATLAB	159
C	Equipment for the Measurement Works	165
D	MATLAB Code for Comparative Analysis	168



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CHAPTER 1

INTRODUCTION

1.1 Introduction

Antenna is a significant element for transmitting and receiving signals from the environment and air, as a medium in the radio frequency (RF) system. Without proper antenna design, signals generated by the RF system will not be transmitted and the signal is will not be detected in the receiver. Therefore, antennas have been developed into different categories or shapes and implanted commonly in everyday application, such as personal communication, home electronics, warfare electronics and transportation.

The significance of antennas in wireless associations cannot be neglected and this is obvious in every portable device without a link association. Even though the trend in communication is moving towards wireless, there are users who care about their health, since there are some potential health effects coming from the electromagnetic field radiated by the antenna inside wireless device.

This chapter provides the motivation of the thesis and background of the research work carried out throughout this thesis. Problem statement is defined according to the conventional systems used to verify the purpose of this study. Later, the objectives of the study were discussed to solve the problem. The scope of the research ensures that work and steps are described in detail to achieve the stated objectives. The flow of the thesis is indicated at the end of the section containing a brief introduction to each section of the thesis.

1.2 Background and Motivation

Over the last decade, great research efforts have been made to characterize exposure to radio frequency (RF) below 10 GHz for bands where most radio communications resources operate. The exposure limits proposed by the International Commission on International Protection Indicators (ICNIRP) should not exceed 2 W/kg over 10 g tissue. On the other hand, most studies described the close interactions between biological tissues and antennas that focus on frequency below 3 GHz but were limited to body area network application.

Wireless body area network (WBAN) has attracted greater attention to providing the necessary communication needed for applications such as network applications, health monitoring, military and personal navigation entertainment [1-5]. However, the design of the WBAN antenna faces the biggest challenge in using the particles needed to fully understand the characteristics of the antenna and the loss of propagation in the existence of the human body [6]. For this reason, the importance of a high-efficiency antenna during body proximity becomes a necessity. In particular, the proximity of the body minimizes the efficiency of the antenna and maximizes radiation pattern irregularities and impedance detuning. Additionally, the impact of WBAN radiation on the human body is characterized by a specific absorption rate (SAR), which must be considered to avoid any effect on the human body and the value must be a minimum [7]. Figure 1.1 indicates the general structure of WBAN system.

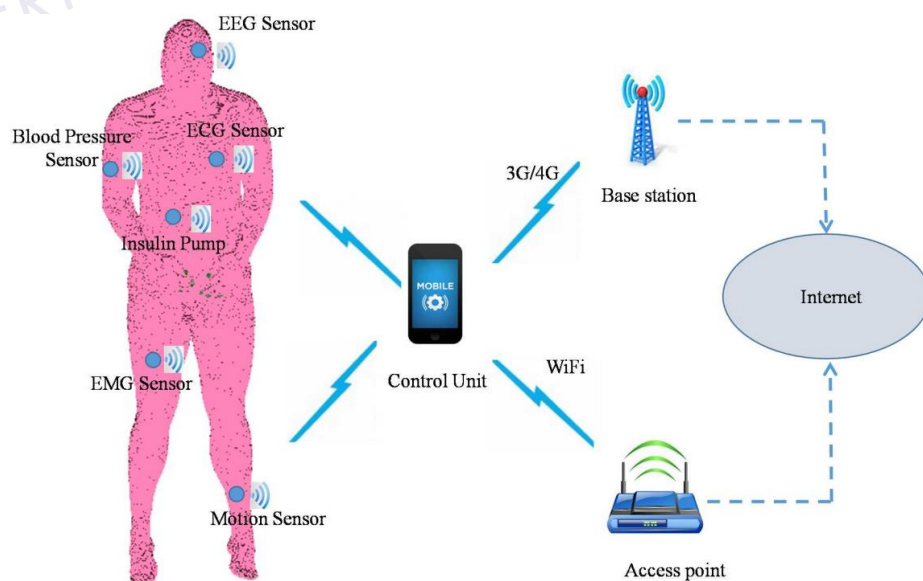


Figure 1.1: General structure of WBAN system [8]

REFERENCES

1. Khan, O. M., Islam, Q. U., Shubair, R. M., & Kiourti, A. Novel multiband Flamenco fractal antenna for wearable WBAN off-body communication applications, in *International Applied Computational Electromagnetics Society Symposium (ACES)*. 2018. 1-2.
2. Tak, J., Woo, S., Kwon, J., & Choi, J. Dual-band dual-mode patch antenna for on-/off-body WBAN communications. *IEEE Antennas and Wireless Propagation Letters*. 2015. 15: 348-351.
3. Zhang, X. Y., Wong, H., Mo, T., & Cao, Y. F. (2017). Dual-band dual-mode button antenna for on-body and off-body communications. *IEEE transactions on biomedical circuits and systems*. 2017. 11(4): 933-941.
4. Tong, X., Liu, C., Liu, X., Guo, H., & Yang, X. Switchable On-/Off-body antenna for 2.45 GHz WBAN applications. *IEEE Transactions on Antennas and Propagation*. 2017. 66(2): 967-971.
5. Kang, S., & Jung, C. W. Wearable fabric reconfigurable beam-steering antenna for on/off-body communication system, in *International Journal of Antennas and Propagation*. 2015.
6. Kumar, A., Utsav, A., & Badhai, R. K. A novel copper-tape wideband wearable textile antenna for WBAN applications. In *2017 IEEE Applied Electromagnetics Conference (AEMC)*. 2017. 1-3.
7. Ashap, A. Y., Abidin, Z. Z., Dahlan, S. H., Majid, H. A., Yee, S. K., Saleh, G., & Malek, N. A. (2017). Flexible wearable antenna on electromagnetic band gap using PDMS substrate. *Telkomnika*. 15(3). 9-12.
8. Ibraheem, A. A.Y. *Implanted antennas and intra-body propagation channel for wireless body area network*. PhD thesis, Virginia Tech; 2014.
9. David, L. M & Kwok W. C. Fields, Radiofrequency Electromagnetic. Evaluating compliance with FCC guidelines for human exposure to radiofrequency electromagnetic fields. *OET bulletin* 65 10. 1997:

10. Razali, N. I. M., Seman, N., & Ishak, N. I. A. Design and Specific Absorption Rate of 2.6 GHz Rectangular-Shaped Planar Inverted-F Antenna. *Indonesian Journal of Electrical Engineering and Computer Science*. 2018. 10(2): 741-747.
11. Björninen, T., & Yang, F. Low-profile head-worn antenna with a monopole-like radiation pattern. *IEEE antennas and wireless propagation letters*. 2015. 15. 794-797.
12. Colombi, D., Thors, B., & Törnevik, C. Implications of EMF exposure limits on output power levels for 5G devices above 6 GHz. *IEEE Antennas and Wireless Propagation Letters*. 2015. 14: 1247-1249.
13. Chahat, N., Zhadobov, M., & Sauleau, R. Antennas for body centric wireless communications at millimeter wave frequencies. In *Progress in compact antennas*. *IntechOpen*. 2014. Doi:10.5772/58816.
14. Samal, P. B., Soh, P. J., & Vandenbosch, G. A. UWB all-textile antenna with full ground plane for off-body WBAN communications. *IEEE transactions on antennas and propagation*, 2013, 62(1), 102-108.
15. Chen, S. J., Kaufmann, T., & Fumeaux, C. (2014, March). Shorting strategies for a wearable L-slot planar inverted-F antenna, in *International Workshop on Antenna Technology: Small Antennas, Novel EM Structures and Materials, and Applications (iWAT)*. 2014. 18-21.
16. Soh, P. J., Vandenbosch, G. A., Ooi, S. L., & Rais, N. H. M. Design of a broadband all-textile slotted PIFA. *IEEE Transactions on Antennas and Propagation*. 2011. 60(1): 379-384.
17. Agneessens, S., Lemey, S., Vervust, T., & Rogier, H. Wearable, small, and robust: The circular quarter-mode textile antenna. *IEEE Antennas and Wireless Propagation Letters*. 2015. 14: 1482-1485.
18. Leduc, C., & Zhadobov, M. Impact of Antenna Topology and Feeding Technique on Coupling with Human Body: Application to 60-GHz Antenna Arrays. *IEEE Transactions on Antennas and Propagation*. 2017. 65(12): 6779-6787.
19. Ashyap, A. Y., Abidin, Z. Z., Dahlan, S. H., Majid, H. A., Shah, S. M., Kamarudin, M. R., & Alomainy, A. Compact and low-profile textile EBG-based antenna for wearable medical applications. *IEEE Antennas and Wireless Propagation Letters*. 2017. 16: 2550-2553.

20. Kamardin, K., Rahim, M. K. A., Hall, P. S., Samsuri, N. A., Latef, T. A., & Ullah, M. H. Planar textile antennas with artificial magnetic conductor for body-centric communications. *Applied Physics A*. 2016. 122(4): 363.
21. Velan, S., Sundarsingh, E. F., Kanagasabai, M., Sarma, A. K., Raviteja, C., Sivasamy, R., & Pakkathillam, J. K. (2014). Dual-band EBG integrated monopole antenna deploying fractal geometry for wearable applications. *IEEE antennas and wireless propagation letters*. 2014. 14: 249-252.
22. Raad, H. R., Abbosh, A. I., Al-Rizzo, H. M., & Rucker, D. G. (2012). Flexible and compact AMC based antenna for telemedicine applications. *IEEE Transactions on antennas and propagation*. 2012. 61(2): 524-531.
23. Abirami, B. S., & Sundarsingh, E. F. EBG-backed flexible printed Yagi–Uda antenna for on-body communication. *IEEE transactions on antennas and propagation*, 2017. 65(7): 3762-3765.
24. Saeed, S. M., Balanis, C. A., Birtcher, C. R., Durgun, A. C., & Shaman, H. N. Wearable flexible reconfigurable antenna integrated with artificial magnetic conductor. *IEEE Antennas and Wireless Propagation Letters*. 2017. 16: 2396-2399.
25. Rashid, T. B. *Analysis of Biological Effects of Cell Phone Radiation on Human Body Using Specific Absorption Rate (SAR) and Thermoregulatory Response*. PhD thesis, University of Colorado Colorado Springs. (2017).
26. Rashid, A. A representation of cylindrical antennas for manpack installation. *IEEE Transactions on Antennas and Propagation*. 1967. 15(5): 699-700.
27. King, H., and J. Wong. Effects of a human body on a dipole antenna at 450 and 900 MHz. *IEEE Transactions on Antennas and Propagation*. 1977. 25(3): 376-379.
28. Krupka, Z. The effect of the human body on radiation properties of small-sized communication systems. *IEEE Transactions on Antennas and Propagation* 1968. 16(2): 154-163.
29. Jensen, Michael A. & Samii. Y.R. The electromagnetic interaction between biological tissue and antennas on a transceiver handset. in *Proceedings of IEEE Antennas and Propagation Society International Symposium and URSI National Radio Science Meeting*. 1994. 1: 367-370.

30. Toftgard, Jorn, Sten N. Hornsleth, and J. Bach Andersen. Effects on portable antennas of the presence of a person. *IEEE Transactions on Antennas and Propagation* 1993. 41(6): 739-746.
31. Chuang, H-R. Human operator coupling effects on radiation characteristics of a portable communication dipole antenna. *IEEE Transactions on Antennas and Propagation*. 1994. 42(4): 556-560.
32. Šarolić, Antonio, Senić, D., Živković,Z., & Zorica.A. Influence of human head and hand on PIFA antenna matching properties and SAR. in *19th International Conference on Software, Telecommunications and Computer Networks*. 2011. 1-5.
33. Zheng, Y.L., , Ding, X.R., Poon,C.C.Y., Lo,B.P.L.L., Zhang, H., Zhou,X.L. Yang,G.Z., Zhao,N. & Zhang.Y.T. Unobtrusive sensing and wearable devices for health informatics. *IEEE Transactions on Biomedical Engineering*. 2014. 61(5): 1538-1554.
34. Movassaghi, S., Abolhasan,M., Lipman,J., Smith,D., & Jamalipour, A. Wireless body area networks: A survey. *IEEE Commun. Surveys Tuts*. 2014. 16(3): 1658–1686.
35. Yoo, H.J. Your heart on your sleeve: Advances in textile-based electronics are weaving computers right into the clothes we wear, *IEEE Solid-State Circuits Mag.*, 2013. 5(1): 59–70.
36. Rabaey, J. M. The Human Intranet--Where Swarms and Humans Meet. *IEEE Pervasive Computing* 2015. 14(1): 78-83.
37. Sam, L., Declercq, F. & Rogier.H. Textile antennas as hybrid energy-harvesting platforms. *Proceedings of the IEEE* 2014. 102(11): 1833-1857.
38. Mäkinen, R. M., & Kellomäki.T. Body effects on thin single-layer slot, self-complementary, and wire antennas. *IEEE Transactions on Antennas and Propagation* 2014. 62(1): 385-392.
39. Zou, S., Xu, Y., Wang, H., Li, Z., Chen, S., & Hu, B. A survey on secure wireless body area networks. *Security and Communication Networks*2017.:1-9.
40. Changrong,L., Guo,Y.X. & Xiao, S., Capacitively loaded circularly polarized implantable patch antenna for ISM band biomedical applications. *IEEE transactions on antennas and propagation* 2014. 62(5): 2407-2417.

41. Changrong, L., Guo, Y.X. & Xiao.S. Compact dual-band antenna for implantable devices. *IEEE Antennas and Wireless Propagation Letters* 2012.11: 1508-1511.
42. Guo, L.Z., & Guo.Y.X. Dual band low profile antenna for body centric communications. *IEEE Transactions on Antennas and Propagation* 2013. 61(4): 2282-2285.
43. Shakib, M. N., Moghavvemi, M. & Mahadi, W.N.L. Design of a tri-band off-body antenna for WBAN communication. *IEEE Antennas and Wireless Propagation Letters*. (2017). 16: 210-213.
44. Alves, T., Poussot,B., & Laheurte. J.M. Analytical propagation modeling of BAN channels based on the creeping-wave theory. *IEEE Transactions on Antennas and Propagation* 2011. 59(4): 1269-1274.
45. Nadeem, A., Hussain,M.A., Owais,O., Salam,A., Iqbal,S. & Ahsan.K. Application specific study, analysis and classification of body area wireless sensor network applications. *Computer Networks* 2015.83: 363-380.
46. Elisabeth, R., Joseph, W., Latré, B., Braem, B., Vermeeren, G., Tanghe, E., Martens,L., Moerman, I., & Blondia. C., Characterization of on-body communication channel and energy efficient topology design for wireless body area networks. *IEEE Transactions on Information Technology in Biomedicine* 2009. 13(6): 933-945.
47. Lim, E. G., Wang, Z., Wang, J.C., Leach, M., Zhou, R., Lei,C.U. & Man. K.L. Wearable Textile Substrate Patch Antennas. *Engineering Letters* 2014. 22(2).
48. Kyeol, K. & Choi. J. Antennas for wireless body area network applications. in *7th European Conference on Antennas and Propagation (EuCAP)*. 2013. 375-379.
49. Lim, E. G., Wang, Z., Leach, M., Zhou,R., Man, K. L. & Zhang, N. Compact size of textile wearable antenna. in *Proceedings of the International MultiConference of Engineers and Computer Scientists*, 2014. 2: 870-873.
50. Tommi Tuovinen. Operation of IR-UWB WBAN Antennas Close to Human Tissues. PhD thesis, University of OULU,OULU. (2014).

51. Samaneh, M., Abolhasan, M., Lipman, J., Smith, D. & Jamalipour, A. Wireless body area networks: A survey. *IEEE Communications Surveys & Tutorials* 2014. 16(3): 1658-1686.
52. Mat, M. H., Malek, M. F., Whittow, W.G. & Bibb, R. Ear prosthesis evaluation: specific absorption rate levels in the head due to different angles and frequencies of electromagnetic exposure. *Journal of Electromagnetic Waves and Applications* 2015. 29(4): 514-524.
53. Ronald, S. H., Malek, M. F. B. A., Hassan, S. I. S., Cheng, E. M., Mat, M. H., Zulkefli, M. S., & Binti Maharimi, S. F. Designing asian-sized hand model for SAR determination at GSM900/1800: Simulation part. *Progress In Electromagnetics Research*, 2012. 129. 439-467.
54. Yelkenci, T., & Paker, S. SAR changes in a human head model for plane wave exposure (500–2500 MHz) and a comparison with IEEE 2005 safety limits. *Journal of Microwave Power and Electromagnetic Energy*. 2007. 42(2): 64-68.
55. IEEE Standards Coordinating Committee, 28. *IEEE standard for safety levels with respect to human exposure to radio frequency electromagnetic fields, 3kHz to 300GHz*. IEEE C95. 1-1991 (1992).
56. Al-Sehemi, A., Al-Ghamdi, A., Dishovsky, N., Atanasov, N., & Atanasova, G. On-body investigation of a compact planar antenna on multilayer polymer composite for body-centric wireless communications. *AEU-International Journal of Electronics and Communications*, 2017. 82: 20-29.
57. Hazarika, B., Basu, B., & Kumar, J. A multi-layered dual-band on-body conformal integrated antenna for WBAN communication. *AEU-International Journal of Electronics and Communications*, 2018. 95: 226-235.
58. Lee, A. K., Hong, S. E., Kwon, J. H., & Choi, H. D. SAR comparison of SAM phantom and anatomical head models for a typical bar-type phone model. *IEEE Transactions on Electromagnetic Compatibility*, 2015. 57(5): 1281-1284.
59. Wardhani, S. W. K., Zulkifli, F. Y., & Rahardjo, E. T. Effect of human head phantom models on the performance of dipole antenna at 5.8 GHz. in *International Conference on Quality in Research (QiR)* 2015. 12-15.
60. Belrhiti, L., Riouch, F., Tribak, A., Terhzaz, J., & Sanchez, A. M. Investigation of dosimetry in four human head models for planar monopole antenna with a coupling feed for LTE/WWAN/WLAN internal mobile phone. *Journal of*

- Microwaves, Optoelectronics and Electromagnetic Applications*, 2017. 16(2), 494-513.
61. Italian National Research Council, Dielectric Properties of Body Tissues, Institute for Application Physics, [Online]. Available <http://niremf.ifac.cnr.it/tissprop/htmlclie/htmlclie.htm>.
 62. Sultana, S., Miran, M. M., Uddin, S. M. A., Naby, M. M., & Haque, M. Performance analysis of a modified implantable PIFA operates at MICS band for human head phantom model. *3rd International Conference on Electrical Information and Communication Technology (EICT) 2017*. 1-5.
 63. Ali, I. H., Hamd, H. I., & Abdalla, A. I. Design and comparison of two types of antennas for SAR calculation in wireless applications. *Advances in Science and Engineering Technology International Conferences (ASET) 2018*. 1-5.
 64. Wang, J., Zhao, L., Chen, G., Wang, Y., & Yu, W. Ground plane effects on SAR for human head model exposed to a dual-band PIFA. *IEEE MTT-S 2015 International Microwave Workshop Series on RF and Wireless Technologies for Biomedical and Healthcare Applications (IMWS-BIO) 2015*. 161-162.
 65. Kumar, G. P., Agarwal, N., Kranthi, P., & Babu, S. S. Design considerations to calculate SAR in multiband MIMO antenna for mobile handsets. In *2016 International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET) 2016*. 2434-2438.
 66. Tharakan, A., Deepthi, J., Gopika, J., & Krishna, D. D. Specific absorption rate reduced (SAR) mobile phone antenna designs. *Fifth International Conference on Advances in Computing and Communications (ICACC) 2015*. 250-253.
 67. Chowdhury, T., Farhin, R., Hassan, R. R., Bhuiyan, M. S. A., & Raihan, R. Design of a patch antenna operating at ISM band for brain tumor detection. *4th International Conference on Advances in Electrical Engineering (ICAEE) 2017*. 94-98.
 68. Iftikhar, A., Masud, M. M., Rafiq, M. N., Asif, S., Braaten, B. D., & Khan, M. S. Radiation performance and Specific Absorption Rate (SAR) analysis of a compact dual band balanced antenna. In *2015 IEEE International Conference on Electro/Information Technology (EIT) 2015*. 672-675.
 69. Raihan, R., Bhuiyan, M. S. A., Hasan, R. R., Chowdhury, T., & Farhin, R. A wearable microstrip patch antenna for detecting brain cancer. In *2017 IEEE*

- 2nd International Conference on Signal and Image Processing (ICSIP) 2017*. 432-436).
70. Karimian, R., Pourahmadazar, J., Nedil, M., & Denidni, T. A. On the design of low SAR CPW antenna with magneto dielectric AMC based ground plane. *10th European Conference on Antennas and Propagation (EuCAP) 2016*. 1-5.
 71. Riaz, A., Shereen, M. K., Ullah, S., Shahjehan, W., & Rashid, A. Design and SAR Analysis of a Compact Multiband Handset Antenna for UMTS/HSPA+ 2100 MHz and 2.4 GHz ISM-Band standards for Cellular Applications. In *2018 5th International Multi-Topic ICT Conference (IMTIC) 2018*. 1-8.
 72. Afrin, F., Yenisey, W. A., & Syed, M. A. A. A. Miniaturized planar Inverted-F antenna for Off-body wireless body area network (WBAN) application. In *TENCON 2017-2017 IEEE Region 10 Conference 2017*. 2654-2657.
 73. Sultana, S., & Basak, R. Numerical Investigations of Implan Meander Line Antenna of Three-Dimensional Human Head Phantom for Brain Machine Interference. *International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST) 2019*. 324-328.
 74. Tian, J., Lagore, R. L., & Vaughan, J. T. Design considerations for dipole for head MRI at 10.5 T. *IEEE MTT-S International Microwave Workshop Series on RF and Wireless Technologies for Biomedical and Healthcare Applications (IMWS-BIO)*. 2015. 99-100.
 75. Manoufali, M., Abbosh, A., & Bialkowski, K. Design of a miniaturized circular implantable antenna. *Asia-Pacific Microwave Conference (APMC)*. 2016. 1-4.
 76. Messaoudi, H., & Aguil, T. Use of a Split Ring Resonators with Dipole and PIFA Antenna to Reduce the SAR in a Spherical Multilayered Head Model. *6th International Conference on Multimedia Computing and Systems (ICMCS) 2018*. 1-6.
 77. Uddin, M. N., Hasan, R. R., Rahman, M. A., Nath, S. K., & Sarkar, P. Bio-implantable Antenna at Human Head Model. *International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST) 2019*. 522-526.
 78. Stanley, M., Huang, Y., Wang, H., Zhou, H., Tian, Z., & Xu, Q. A novel reconfigurable metal rim integrated open slot antenna for octa-band smartphone applications. *IEEE Transactions on Antennas and Propagation*, 2017. 65(7), 3352-3363.

79. Faruque, M. R. I., Hossain, M. I., & Islam, M. T. (2015). Low specific absorption rate microstrip patch antenna for cellular phone applications. *IET Microwaves, Antennas & Propagation*, 2015. 9(14): 1540-1546.
80. Haydar, W., AlSayah, S., & Sarkis, R. *Design and analysis of conformal antennas for smart glasses*. IET Digital Library. 2018.
81. Wardhani, S. W. K. Tissue-Mimicking Model for Bioelectromagnetics Study in Microwave Frequency. *4th International Conference on Nano Electronics Research and Education (ICNERE)* 2018. 1-4.
82. Singh, R., Seth, D., Rawat, S., & Ray, K. Performance Investigations of Multi-resonance Microstrip Patch Antenna for Wearable Applications. *Soft Computing: Theories and Applications* 2019. 159-169.
83. Masood, R., Person, C., & Sauleau, R. A dual-mode, dual-port pattern diversity antenna for 2.45-GHz WBAN. *IEEE Antennas and Wireless Propagation Letters*, 2017. 16, 1064-1067.
84. Hong, Y., Tak, J., & Choi, J. Dual-band dual-mode patch antenna for on–on–off WBAN applications. *Electronics Letters*, 2014. 50(25): 1895-1896.
85. Simorangkir, R. B., Yang, Y., Matekovits, L., & Esselle, K. P. Dual-band dual-mode textile antenna on PDMS substrate for body-centric communications. *IEEE Antennas and Wireless Propagation Letters*. 2017. 16: 677-680.
86. Bhattachajee, S., Teja, S., Chaudhuri, S. B., & Mitra, M. Wearable triangular patch antenna for ON/OFF body communication. *IEEE Applied Electromagnetics Conference (AEMC)* 2017. 1-2.
87. Hussain, S., & Munir, W. UWB BAN antennas: Recent trend and developments. *International Conference on Communication, Computing and Digital Systems (C-CODE)*. 2017.86-89.
88. Mendes, C., & Peixeiro, C. A dual-mode single-band wearable microstrip antenna for body area networks. *IEEE Antennas and Wireless Propagation Letters*, 2017. 16, 3055-3058.
89. Zhu, X. Q., Guo, Y. X., & Wu, W. (2016). Miniaturized dual-band and dual-polarized antenna for MBAN applications. *IEEE Transactions on Antennas and Propagation*, 2016. 64(7), 2805-2814.
90. Guha, D., & Antar, Y. M. *Microstrip and printed antennas: new trends, techniques and applications*. John Wiley & Sons. 2011.

91. Amani, N., Dehghanian, V., & Nielsen, J. User-induced antenna variation and its impact on the performance of RSS-based indoor positioning. In *2016 IEEE Canadian Conference on Electrical and Computer Engineering (CCECE) 2016*. 1-5.
92. Rahmat-Samii, Y., & Kim, K. W. Antennas and human in personal communications: applications of modern EM computational techniques. *12th International Conference on Microwaves and Radar. MIKON-98. Conference Proceedings (IEEE Cat. No. 98EX195) 1998* 4: 36-55.
93. Yan, S., Soh, P. J., & Vandenbosch, G. A. Wearable dual-band magneto-electric dipole antenna for WBAN/WLAN applications. *IEEE Transactions on antennas and propagation*, 2015. 63(9): 4165-4169.
94. Simorangkir, R. B., Yang, Y., Matekovits, L., & Esselle, K. P. (2016). Dual-band dual-mode textile antenna on PDMS substrate for body-centric communications. *IEEE Antennas and Wireless Propagation Letters*, 2016. 16: 677-680.
95. Dey, S., Dipto, N. A., Rafin, M. A. R., Mojumder, S., & Shahrin, M. (2013). Design of wearable antenna system on different materials & their performance analysis at the off and on body environment in terms of impedance matching and radiation characteristics. *American Academic & Scholarly Research Journal*, 2013. 5(5): 181.
96. Liu, L., Wang, X. & Zhang, P. Performance Analysis of Linear Polarization Antenna in 2.45 GHz on Body Communications. *International Journal of Applied Engineering Research* ,2017. 12(17): 6405-6413
97. Tayar, K., & Werfelli, H. Study of the effects of human tissue on performance of a loop antenna. *Journal of Electrical and Electronics Engineering* 2016. 11(4)
98. Boyes, S. J., Soh, P. J., Huang, Y., Vandenbosch, G. A., & Khiabani, N. Measurement and performance of textile antenna efficiency on a human body in a reverberation chamber. *IEEE Transactions on Antennas and Propagation*, 2012. 61(2): 871-881.
99. Dutta, P. K., Jayasree, P. V. Y., & Baba, V. S. S. N. S. SAR reduction in the modelled human head for the mobile phone using different material shields. *Human-centric Computing and Information Sciences*, 2016. 6(1): 3.

100. Islam, M. T., Faruque, M. R. I., & Misran, N. Design analysis of ferrite sheet attachment for SAR reduction in human head. *Progress In Electromagnetics Research*, 2009. 98, 191-205.
101. Hariharan, V., Maheshwaran, S., Selvam, S., & Gunavathi, N. (2015, December). Comparison of electromagnetic band gap (EBG) structures for specific absorption rate (SAR) reduction. In *2015 Annual IEEE India Conference (INDICON) 2015*. 1-4.
102. Inum, R., Rana, M. M., & Quader, M. A. Modeling of an efficient microstrip patch antenna for microwave brain imaging system. In *2016 3rd International Conference on Electrical Engineering and Information Communication Technology (ICEEICT) 2016*. 1-6.
103. Tharakan, A., Deepthi, J., Gopika, J., & Krishna, D. D. Specific absorption rate reduced (SAR) mobile phone antenna designs. *Fifth International Conference on Advances in Computing and Communications (ICACC) 2015*. 250-253.
104. Das, R., & Yoo, H. Application of a Compact Electromagnetic Bandgap Array in a Phone Case for Suppression of Mobile Phone Radiation Exposure. *IEEE Transactions on Microwave Theory and Techniques*, 2018, 66(5): 2363-2372.
105. Agarwal, K., Guo, Y. X., & Salam, B. Wearable AMC backed near-endfire antenna for on-body communications on latex substrate. *IEEE Transactions on components, packaging and manufacturing technology*, 2016. 6(3): 346-358.
106. Mahmud, M., Islam, M., Misran, N., Singh, M., & Mat, K. (2017). A negative index metamaterial to enhance the performance of miniaturized UWB antenna for microwave imaging applications. *Applied Sciences*, 7(11), 1149.
107. Wang, M., Yang, Z., Wu, J., Bao, J., Liu, J., Cai, L., ... & Li, E. (2018). Investigation of SAR reduction using flexible antenna with metamaterial structure in wireless body area network. *IEEE Transactions on Antennas and Propagation*, 66(6), 3076-3086.
108. Bhattacharjee, S., Maity, S., Chaudhuri, S. R. B., & Mitra, M. (2018). Metamaterial-inspired wideband biocompatible antenna for implantable applications. *IET Microwaves, Antennas & Propagation*, 12(11), 1799-1805.
109. CST Microwave Studio®. [Online: www.cst.com/products/cstmws2015].
110. Balanis, C. A. *Antenna theory: analysis and design*. 3rd edition. John Wiley & sons. 2016.

111. Ndujiuba, C. U., Ilesanmi, O. A., & Agboje, O. E. (2017). Bandwidth Enhancement of An Inset-Fed Rectangular Patch Antenna using Partial Ground with Edge-cut Method. *International Journal of Electromagnetics and Applications*, 7(1), 9-16.

