

# **MILLIMETER WAVE ANTENNAS FOR BODY AREA NETWORK**

**SHAKTI SINGH CHAUHAN**



**CENTRE FOR APPLIED RESEARCH IN ELECTRONICS  
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**OCTOBER 2022**

**© Indian Institute of Technology Delhi (IITD), New Delhi, 2022**

# **MILLIMETER WAVE ANTENNAS FOR BODY AREA NETWORK**

by

**SHAKTI SINGH CHAUHAN**

*Centre for Applied Research in Electronics*

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**OCTOBER 2022**

**DEDICATED**  
**To**  
**My Teachers, Family And Friends**

## **CERTIFICATE**

This is to certify that the work reported in this thesis entitled “**Millimeter Wave Antennas For Body Area Network**” being submitted by **Mr. Shakti Singh Chauhan** for the award of the degree of **Doctor of Philosophy** to the Indian Institute of Technology Delhi, New Delhi, India, is a record of original bonafide research work carried out by him under our guidance and supervision. The results contained in this thesis have not been submitted in part or full, to any other university or institute for the award of any degree or diploma.

We certify that he has pursued the prescribed course of research.

**Prof. Mahesh P. Abegaonkar**

Associate Professor

Centre for Applied Research

in Electronics (CARE)

Indian Institute of Technology Delhi,

New Delhi – 110016, India.

**Prof. Ananjan Basu**

Professor

Centre for Applied Research

in Electronics (CARE)

Indian Institute of Technology Delhi,

New Delhi – 110016, India.

## ACKNOWLEDGEMENTS

First, I would like to thank my supervisors **Prof. Mahesh P. Abegaonkar** and **Prof. Ananjan Basu** for letting me be a part of the RF and Microwave Group, Centre for Applied Research in Electronics (CARE) IIT Delhi, and for giving me this opportunity to endeavour my research in the field of Millimeter Wave Antennas for Body Area Network. I would like to express my sincere thankfulness to my supervisors for their continuous support and guidance. I am thankful to them for contributing their valuable time and efforts to my personal and professional growth. Their wisdom and experience inspired me to traverse beyond my technical realisation.

I would also like to thank **Prof. Shibhan K. Koul** for being part of my research committee and providing his valuable technical input which help me to improve my work.

I also thank **Prof. Shouri Chatterjee** for his suggestions that have aided in my research development. I am grateful to **Prof. Arun Kumar** for chairing my research committee.

I would also like to thank **Prof. Kirti Dhvaj** for giving me his support as a part of CARE fraternity.

I would also like to thank **Prof. Djuradj Budimir** from the University of Westminster, London, UK to provide me an opportunity as an Visiting Student in his lab.

I am thankful to my colleagues here in the RF and Microwave group who have been a part of my Ph.D. journey. I would like to thank, **Dr. Sukomal Dey**, **Dr. Srujana Kagita**,

**Dr. Ankita Malhotra, Dr. Robin Kalyan, Dr. Saurabh Pegwal, Dr. Rajesh Kumar Singh, Dr. Anushruti Jaiswal, Dr. Deepika Sipal, Dr. Karthikeyan, Dr. Amit Kumar Singh, Dr. Harikesh, Santosh Kumar Bhagat, Rakhi, Sriparna, Priyansha Kaurav, Somia Sharma, Ratul, Shilpi, and Drishti** for their support and making this journey memorable. I would like to thank **Mr. Ashoke Pramanik** for their help in fabrication.

I would like to special thanks to **Nitesh Thapa, Dr. Zamir Wani, Dr. Ayushi Barthwal, Deepak Maikhuri, Pranav Kumar Shrivastava, and Ruchi Shrivastava** for their never-ending support during my entire journey.

I am also grateful to **Dr. Veerendra Dhyani, Dr. Vaibhav, Dr. Pratiksha, Akhil, John, Prabal, Sumit, and Pragay** for their technical and non-technical discussions over a cup of tea.

I am grateful to all the teaching and office staff members from CARE, IIT Delhi for improving me throughout my Ph.D journey and keep me motivating in different ways for finishing my dissertation.

Finally, I would like to thank my parents, whose unconditional support and patience towards me motivate me throughout my life. I would also want to show my gratitude towards my brother **Satbeer** for his firm support. I will be forever grateful to them.

**Shakti Singh Chauhan**

## ABSTRACT

The research work presented in this thesis is focused on the design and development of Millimeter Wave Antennas that can be used for Body Area Networks. And based on the requirements to set up a link between nodes used in Body Area Networks, different antenna configurations are presented.

First, a 3D printed lens antenna is proposed to be used for the off-body scenario. A lens is used in switched beam configuration in which three patches are used beneath the lens of diameter  $3\lambda_0$ . The lens integrated structure increases the gain of the patch antenna and the beam switching configuration helps in increasing the angular coverage of narrow beam radiation characteristics of the lens integrated patch. The beam direction of the presented structure will change with the change in patch excitation. Three beam directions that are  $0^\circ$  (center patch),  $+17^\circ$  (left patch), and  $-21^\circ$  (right patch) are achieved. The measured 10 dB overlapping bandwidth is from 57.27 GHz to 60 GHz and isolation better than 25 dB is achieved. The measured gain for the center patch is around 15.28 dBi. A flat skin phantom is used to estimate the effects of the change in antenna performance when placed in proximity of the human body. It is seen that the broadside antennas are not much affected by the flat skin phantom in terms of s-parameters, and its radiation characteristics. A single input waveguide-fed multi-beam antenna is also designed to be used in external nodes. The antenna radiates in three orthogonal directions and the gain of the antenna is increased by using the

3D printed lens. The measured impedance bandwidth is 1.7 GHz. The measured beam directions of the structure are  $0^\circ$ ,  $87^\circ$ , and  $270^\circ$  at 57 GHz.

Two switched beam antenna configuration for on-body communication is also presented. In the first configuration, the main beam direction is tilted with the rotation of the dipole arm. The second radiating element is also used to incorporate the beam switching configuration. The tilted dipole arm (termed as common arm) of the structure is common to both of the radiating elements. The isolation between two elements is improved by increasing the width of the common arm and by etching out a semicircular shape in the common arm. The overlapping bandwidth for the structure is from 55 GHz to 64.1 GHz with the isolation better than 30 dB below 63.13 GHz. The directors are also used to enhance the gain for both radiators. The antenna will be able to communicate with two devices in two different directions. In the second configuration, pair of off-center directors are used to enhance the gain of the dipole structure. Three antenna elements are placed orthogonally sharing the common ground plane. The antenna will cover the directions  $8^\circ$ ,  $278^\circ$ , and  $87^\circ$ . The overlapping bandwidth for all three elements is from 55 GHz to 60 GHz. The effect on antenna parameters in the proximity of the flat skin phantom is studied at a gap of 5 mm between the antenna and the skin phantom. It can be seen that the radiation characteristics are mainly affected due to the reflections from the phantom.

A dual-mode antenna that can be used for both on-/off-body scenarios is designed. The higher-order mode microstrip ring is used for on-body mode and the coaxially located patch antenna is used for off-body mode. The overlapping bandwidth for both modes is 57

to 58.9 GHz with isolation of better than 30 dB for the entire range. Dual-beam characteristics are achieved for on-body mode with a beam direction of  $30^\circ$  and  $339^\circ$  at 58 GHz. The gain achieved in on-body mode is 9.5 dBi and for off-body mode is 6.7 dBi. When the antenna is placed over the flat skin phantom, the main beam direction changes in on-body mode due to the reflection from the flat skin phantom.

A vertically polarized antenna is presented for on-body propagation. The antenna uses a  $TM_{21}$  mode circular patch which is transformed into an end-fire radiating element. The circular patch is cut to quarter size and printed on both sides of the substrate. An electric wall is made at the edges of both the quarter patches with the conducting Vias while the curved edges are kept open to radiate in the end-fire way with E-field direction perpendicular with reference with the human body. The antenna is further loaded with a loop-like structure to improve the gain of the proposed structure. The measured impedance bandwidth of the antenna is from 56.84 GHz to 62.13 GHz. The end-fire radiation is achieved with vertical polarization for on-body applications. Antenna performance is also estimated using the flat skin phantom.

## सार

इस थीसिस में प्रस्तुत शोध कार्य मिलीमीटर वेव एन्टेनास के डिजाइन और विकास पर केंद्रित है जिसका उपयोग बॉडी एरिया नेटवर्क के लिए किया जा सकता है। और बॉडी एरिया नेटवर्क में उपयोग किए जाने वाले नोड्स के बीच एक लिंक स्थापित करने की आवश्यकताओं के आधार पर, विभिन्न एंटीना कॉन्फिगरेशन प्रस्तुत किए गये हैं।

सबसे पहले, ऑफ-बॉडी परिदृश्य के लिए एक 3डी प्रिंटेड लेंस एंटीना का उपयोग करने का प्रस्ताव है। स्विचड बीम कॉन्फिगरेशन में एक लेंस का उपयोग किया गया है जिसमें  $3\lambda_0$  व्यास के लेंस के नीचे तीन पैच का उपयोग किया गया है। लेंस एकीकृत संरचना पैच एंटीना के गेन को बढ़ाती है और बीम स्विचिंग कॉन्फिगरेशन लेंस एकीकृत पैच की संकीर्ण बीम विकिरण विशेषताओं के कोणीय कवरेज को बढ़ाने में मदद करता है। प्रस्तुत संरचना की बीम दिशा पैच उत्तेजना में परिवर्तन के साथ बदल जाएगी। तीन बीम दिशाएँ जो  $0^\circ$  (केंद्र पैच),  $+17^\circ$  (बाएँ पैच), और  $-21^\circ$  (दायाँ पैच) हैं, प्राप्त की गयी हैं। मापा गया 10 डीबी ओवरलैपिंग बैंडविड्थ 57.27 गीगाहर्ट्ज़ से 60 गीगाहर्ट्ज़ तक है और 25 डीबी से बेहतर अलगाव हासिल किया गया है। केंद्र पैच के लिए मापा गेन लगभग 15.28 dBi है।

मानव शरीर की निकटता में रखे जाने पर एंटीना के प्रदर्शन में परिवर्तन के प्रभावों का अनुमान लगाने के लिए एक सपाट स्किन फैंटम का उपयोग किया गया है। यह देखा गया है कि ब्रॉडसाइड एंटेना एस-पैरामीटर और इसकी विकिरण विशेषताओं के संदर्भ में फ्लैट स्किन फैंटम से ज्यादा प्रभावित नहीं होते हैं। एक एकल इनपुट वेवगाइड-फेड मल्टी-बीम एंटीना को बाहरी नोइस में उपयोग करने के लिए भी डिज़ाइन किया गया है। एंटीना तीन ओर्थोगोनल दिशाओं में विकिरण करता है और 3 डी प्रिंटेड लेंस का उपयोग करके एंटीना का गेन बढ़ाया गया है। मापा इम्पीडेंस बैंडविड्थ 1.7 गीगाहर्ट्ज़ है। 57 गीगाहर्ट्ज़ पर संरचना के मापा बीम दिशाएं 0 डिग्री, 87 डिग्री और 270 डिग्री हैं।

ऑन-बॉडी संचार के लिए दो स्विचड बीम एंटीना कॉन्फिगरेशन भी प्रस्तुत किया गया है। पहले विन्यास में, मुख्य बीम दिशा डाई-पोल भुजा के घूर्णन के साथ घूम जाती है। दूसरे विकिरण तत्व का उपयोग बीम स्विचिंग कॉन्फिगरेशन को शामिल करने के लिए भी किया गया है। संरचना की घूमी हुई डाई-पोल भुजा (सामान्य भुजा कहलाती है) दोनों विकिरण तत्वों के लिए समान है। सामान्य भुजा की चौड़ाई बढ़ाकर और सामान्य भुजा में अर्धवृत्ताकार आकृति बनाकर दो तत्वों के बीच अलगाव में सुधार किया गया है। संरचना के लिए ओवरलैपिंग बैंडविड्थ 55 गीगाहर्ट्ज़ से 64.1 गीगाहर्ट्ज़ तक है और आइसोलेशन 63.13 गीगाहर्ट्ज़ से नीचे, 30 डीबी से बेहतर है। दोनों रेडिएटर्स के गेन को बढ़ाने के लिए डायरेक्टर्स का भी उपयोग किया गया है। एंटीना दो अलग-अलग दिशाओं में दो उपकरणों के

साथ संचार करने में सक्षम है। दूसरे विन्यास में, डाई-पोल संरचना के गेन को बढ़ाने के लिए ऑफ-सेंटर डायरेक्टर्स की जोड़ी का उपयोग किया गया है। तीन एंटेना तत्वों को कॉमन ग्राउंड प्लेन को साझा करते हुए ओर्थोगोनली रखा गया है। एंटीना  $8^\circ$ ,  $278^\circ$  और  $87^\circ$  दिशाओं को कवर करेगा। तीनों तत्वों के लिए ओवरलैपिंग बैंडविड्थ 55 गीगाहर्ट्ज़ से 60 गीगाहर्ट्ज़ तक है। फ्लैट स्किन फैंटम की निकटता में एंटीना मापदंडों पर प्रभाव का अध्ययन एंटीना और स्किन फैंटम के बीच 5 मिमी के अंतराल पर किया गया है। यह देखा जा सकता है कि फैंटम से परावर्तन के कारण विकिरण विशेषताएँ मुख्य रूप से प्रभावित होती हैं।

एक ड्यूल-मोड एंटेना जिसे ऑन/ऑफ-बॉडी परिदृश्य दोनों के लिए उपयोग किया जा सकता है, डिज़ाइन किया गया है। उच्च-क्रम मोड माइक्रोस्ट्रिप रिंग का उपयोग ऑन-बॉडी मोड के लिए किया गया है और समाक्षीय रूप से स्थित पैच एंटीना का उपयोग ऑफ-बॉडी मोड के लिए किया गया है। दोनों मोड के लिए ओवरलैपिंग बैंडविड्थ 57 से 58.9 गीगाहर्ट्ज़ है और पूरी रेंज के लिए 30 डीबी से बेहतर आइसोलेशन है। 58 गीगाहर्ट्ज़ पर  $30^\circ$  और  $339^\circ$  की बीम दिशा के साथ ऑन-बॉडी मोड के लिए ड्यूल बीम विशेषताओं को प्राप्त किया गया है। ऑन-बॉडी मोड में प्राप्त गेन 9.5 dBi है और ऑफ-बॉडी मोड के लिए 6.7 डी बी आई है। जब एंटेना को फ्लैट स्किन फैंटम के ऊपर रखा जाता है, तो फ्लैट स्किन फैंटम से परावर्तन के कारण ऑन-बॉडी मोड में मुख्य बीम दिशा बदल जाती है।

शरीर पर प्रसार के लिए एक वर्तिकल पोलोरिसेड एंटीना प्रस्तुत किया गया है। एंटीना  $TM_{21}$  मोड सर्कुलर पैच का उपयोग करता है, जो एक एन्ड-फायर विकिरण एलिमेंट में बदल दिया गया है। गोलाकार पैच को चौथाई आकार में काटा गया है और सबस्ट्रेट के दोनों साइड्स पर प्रिंट किया गया है। कंडक्टिंग वायस के साथ दोनों क्वार्टर पैच के किनारों पर एक इलेक्ट्रिक वाल बनाई गयी है, जबकि घुमावदार किनारों को मानव शरीर के संदर्भ में ई-फील्ड दिशा लंबवत के साथ एन्ड-फायर तरीके से विकिरण के लिए खुला रखा गया है। प्रस्तावित संरचना के गेन को बेहतर बनाने के लिए एंटीना को आगे लूप जैसी संरचना के साथ लोड किया गया है। एंटीना की मापित इम्पीडेन्स बैंडविड्थ 56.84 गीगाहर्ट्ज़ से 62.13 गीगाहर्ट्ज़ तक है। एन्ड-फायर विकिरण ऑन-बॉडी अनुप्रयोगों के लिए वर्तिकल ध्रुवीकरण के साथ प्राप्त किया गया है। फ्लैट त्वचा फैंटम का उपयोग करके एंटीना के प्रदर्शन का भी अनुमान लगाया गया है।

## TABLE OF CONTENT

|                                                                            |     |
|----------------------------------------------------------------------------|-----|
| CERTIFICATE .....                                                          | I   |
| ACKNOWLEDGEMENTS .....                                                     | III |
| ABSTRACT.....                                                              | V   |
| TABLE OF CONTENT .....                                                     | XII |
| LIST OF FIGURES .....                                                      | XV  |
| LIST OF TABLES.....                                                        | XIX |
| LIST OF ABBREVIATIONS.....                                                 | XX  |
| Chapter One: INTRODUCTION .....                                            | 1   |
| 1.1 Background .....                                                       | 1   |
| 1.2 Overview of BAN Applications.....                                      | 4   |
| 1.3 Requirements of BAN.....                                               | 6   |
| 1.4 60 GHz Communication.....                                              | 6   |
| 1.4.1 Overview .....                                                       | 7   |
| 1.4.2 Advantages of 60 GHz Communication.....                              | 8   |
| 1.5 Antennas for BAN at 60 GHz .....                                       | 9   |
| 1.6 Scope and Objective of Work .....                                      | 16  |
| 1.7 Thesis Organization.....                                               | 18  |
| Chapter Two: LENS-INTEGRATED BROADSIDE ANTENNAS FOR OFF-BODY<br>LINKS..... | 21  |
| 2.1 Introduction .....                                                     | 21  |
| 2.2 Microstrip Patch Antenna.....                                          | 22  |
| 2.2.1 Microstrip Patch Geometry .....                                      | 22  |
| 2.2.2 Design Equations .....                                               | 23  |
| 2.2.3 Patch Simulation.....                                                | 24  |
| 2.3 3D Printed Lens Antennas .....                                         | 28  |

|                                                                                      |    |
|--------------------------------------------------------------------------------------|----|
| 2.3.1 Reduced Size Extended Hemispherical Lens .....                                 | 28 |
| 2.3.2 Single Element.....                                                            | 31 |
| 2.3.3 Beam Switching.....                                                            | 34 |
| 2.3.4 Three Element Configuration .....                                              | 37 |
| 2.3.5 Antenna prototype and Measurement Results .....                                | 39 |
| 2.4 On Phantom Simulations.....                                                      | 44 |
| 2.5 Single Fed Multi-Beam Antenna for External Nodes for Off-Body Links.....         | 47 |
| 2.5.1 Antenna Design .....                                                           | 48 |
| 2.5.2 Prototype and Results .....                                                    | 50 |
| 2.6 Conclusion.....                                                                  | 56 |
| Chapter Three: END-FIRE ANTENNAS FOR ON-BODY LINKS.....                              | 57 |
| 3.1 Introduction .....                                                               | 57 |
| 3.2 Printed Dipole Antenna.....                                                      | 58 |
| 3.3 Modified Yagi Antenna with Beam Tilt (First configuration).....                  | 61 |
| 3.3.1 Single Element: Beam Tilt .....                                                | 61 |
| 3.3.2 Single Element:Gain Enhancement .....                                          | 63 |
| 3.3.3 Switched Beam Configuration.....                                               | 66 |
| 3.3.4 On Phantom Simulations .....                                                   | 69 |
| 3.3.5 Prototype and Results .....                                                    | 71 |
| 3.4 Printed Yagi Antenna with Off-Center Director Pairs (Second configuration) ..... | 75 |
| 3.4.1 Single Element.....                                                            | 75 |
| 3.4.2 Switched Beam Configuration: Prototype and Results .....                       | 79 |
| 3.4.3 On Phantom Simulations .....                                                   | 84 |
| 3.5 Conclusion.....                                                                  | 86 |
| Chapter Four: DUAL-MODE ANTENNA FOR ON/OFF-BODY LINKS .....                          | 87 |
| 4.1 Introduction .....                                                               | 87 |
| 4.2 Antenna Design .....                                                             | 87 |
| 4.2.1 Antenna Design for On-body Propagation .....                                   | 88 |
| 4.2.2 Antenna Design for Off-body Propagation .....                                  | 94 |
| 4.2.3 Final Dual-Mode Antenna .....                                                  | 98 |

|                                                                    |     |
|--------------------------------------------------------------------|-----|
| 4.3 On Phantom Simulations.....                                    | 99  |
| 4.4 Prototype and Results.....                                     | 103 |
| 4.5 Conclusion.....                                                | 108 |
| Chapter Five: VERTICALLY POLARIZED ANTENNAS FOR ON-BODY LINKS..... | 109 |
| 5.1 Introduction .....                                             | 109 |
| 5.2 Vertically Polarised End-Fire Antenna .....                    | 111 |
| 5.2.1 Antenna Design .....                                         | 111 |
| 5.2.2 Enhancement in the Gain with Loading a Loop .....            | 116 |
| 5.2.3 On Phantom Simulations .....                                 | 123 |
| 5.3 Prototype and Experimental Results .....                       | 127 |
| 5.4 Conclusion.....                                                | 132 |
| Chapter Six: CONCLUSION AND FUTURE SCOPE .....                     | 133 |
| 6.1 Conclusion.....                                                | 133 |
| 6.2 Future Scope.....                                              | 136 |
| References.....                                                    | 137 |
| PUBLICATIONS.....                                                  | 145 |
| BRIEF BIO .....                                                    | 146 |

## LIST OF FIGURES

|                                                                                                                                                                                                                                                                                                       |    |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| <b>Fig. 1.1.</b> Four element antenna array mounted on a phantom [69].                                                                                                                                                                                                                                | 11 |
| <b>Fig. 1.2.</b> Semi-solid Phantom of an arm and hand [71].                                                                                                                                                                                                                                          | 12 |
| <b>Fig.1.3.</b> Pictorial representation of Yagi Uda Array [76] for on-body applications at 60 GHz.                                                                                                                                                                                                   | 14 |
| <b>Fig.1.4.</b> SIW integrated Yagi antenna operating in 60 GHz range [78] for on-body propagation. ..                                                                                                                                                                                                | 14 |
| <b>Fig.1. 5.</b> Textile antenna for Body Area Networks at 60GHz (a) Yagi Uda [80]; (b) Patch antenna Array [81].                                                                                                                                                                                     | 15 |
| <b>Fig.2.1.</b> Geometry of rectangular microstrip patch antenna (a) Extended patch length with fringing into considerations; (b) Patch showing fringing fields. ....                                                                                                                                 | 24 |
| <b>Fig.2.2.</b> (a) Simulated structure in CST (b) Reflection parameters of simulated microstrip patch antenna structure. (wp=1.98 mm; Lp=1.58 mm; wg= 30 mm ; Lg= 35 mm).....                                                                                                                        | 25 |
| <b>Fig.2.3.</b> The radiation Characteristics of the microstrip patch antenna at 60 GHz (a) 3D radiation pattern; (b) 2D H-plane pattern; (c) 2D E-plane pattern. ....                                                                                                                                | 27 |
| <b>Fig.2.4.</b> (a) Parametric view of reduced size extended lens with an elliptical profile; (b) Simulated structure of modified lens; (c) 3D printed Lens structure. ....                                                                                                                           | 30 |
| <b>Fig.2.5.</b> Electric field distribution at 59 GHz in H-plane (a) Patch without lens; (b) Patch with lens integration. ....                                                                                                                                                                        | 31 |
| <b>Fig.2.6.</b> Simulated antenna characteristics of a lens integrated patch (a) Reflection parameters; (b)3D radiation pattern at 60 GHz; (c) 2D H-plane pattern at 60 GHz; (d) 2D E-plane pattern at 60 GHz. ....                                                                                   | 34 |
| <b>Fig.2.7.</b> The variation of antenna parameters with a displacement of the patch from the central axis of the lens at 59 GHz (a) Pictorial representation of displacement; (b) Main beam direction; (c) Sidelobe level; (d) Gain. ....                                                            | 37 |
| <b>Fig.2.8.</b> (a) Geometry showing three element configuration for beam switching; (b) E-field distribution in H-plane for left excitation at 59 GHz; (c) E-field distribution in H-plane for center excitation at 59 GHz; (d) E-field distribution in H-plane for right excitation at 59 GHz. .... | 38 |
| <b>Fig.2.9.</b> Fabricated structure for beam switching (a) Without 3D printed lens; (b) With 3D printed lens. ....                                                                                                                                                                                   | 39 |
| <b>Fig.2.10.</b> S-parameters of the designed prototype antenna (a) Reflection parameters; (b) Isolation parameters (in terms of S-parameters: $ S_{21} $ and $ S_{32} $ ). ....                                                                                                                      | 40 |
| <b>Fig.2.11.</b> The simulated and measured radiation patterns of the 3D printed lens integrated over a patch (a) at 56 GHz; (b) at 58 GHz; (c) at 60 GHz; (d) Simulated Cross-pol at 60 GHz. ....                                                                                                    | 43 |
| <b>Fig.2.12.</b> The comparison of the measured gains of the antenna with a simulated gain of the designed structure in the frequency range from 56 GHz to 60 GHz. ....                                                                                                                               | 44 |
| <b>Fig.2.13.</b> (a) Antenna in close proximity of flat skin phantom; (b) Dispersive properties of the flat skin used in simulations. ....                                                                                                                                                            | 45 |
| <b>Fig.2.14.</b> Antenna characteristics in close proximity of flat skin (a) S-parameters; (b) 2D Normalized radiation pattern in H-plane at 60 GHz. ....                                                                                                                                             | 47 |

|                                                                                                                                                                                                                                                                                                                                                             |    |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| <b>Fig.2.15.</b> (a) E-field distribution of the cylindrical cavity in eigenmode; (b) 2D-Pictorial representation of Metallic Cylindrical structure; (c) E-field distribution of the antenna structure with a metallic post at 61 GHz; (d) Dimensional view of the 3D printed lens structure; (e) 3D view of the 3D printed lens with Air Cavity.....       | 50 |
| <b>Fig.2.16.</b> Dimensional view of the structure (a) Top view of the bottom piece; (b) Top view of the top piece.....                                                                                                                                                                                                                                     | 51 |
| <b>Fig.2.17.</b> 3D view of the top and bottom pieces of the antenna structure.....                                                                                                                                                                                                                                                                         | 51 |
| <b>Fig.2.18.</b> Fabricated final antenna structure with lens integration.....                                                                                                                                                                                                                                                                              | 52 |
| <b>Fig.2.19.</b> Simulated reflection coefficients of Antenna (a) Without lens integration; (b) After lens integration with a parametric variation of the length of an air pocket in the lens.....                                                                                                                                                          | 53 |
| <b>Fig.2.20.</b> Comparison between the simulated and measured results of the final fabricated antenna structure (a) Reflection coefficients; (b) E-field distribution at 57GHz; (c) 2D normalized XoY-plane (H-plane) pattern at 57 GHz.....                                                                                                               | 55 |
| <b>Fig.3.1.</b> The geometry of the printed dipole structure. ....                                                                                                                                                                                                                                                                                          | 59 |
| <b>Fig.3.2.</b> Designed antenna dipole antenna (a) Top and bottom view of the designed structure; (b) Reflection Parameters of the designed structure; (c) 2D normalized pattern at 58 GHz in XoY plane.....                                                                                                                                               | 60 |
| <b>Fig.3.3.</b> (a) Pictorial representation of the angular variation of second dipole arm; (b) Variation of main beam direction with an angle of second dipole arm.....                                                                                                                                                                                    | 62 |
| <b>Fig.3.4.</b> Pictorial representation of the modified structure. ....                                                                                                                                                                                                                                                                                    | 63 |
| <b>Fig.3.5.</b> (a) Reflection parameters of the designed structure; (b) 2D normalized radiation pattern in XoY-plane at 60 GHz. ....                                                                                                                                                                                                                       | 64 |
| <b>Fig.3.6.</b> Power flow distribution of antenna at 60 GHz (a) Dipole; (b) Tilted antenna configuration. ....                                                                                                                                                                                                                                             | 65 |
| <b>Fig.3.7.</b> The change in $S_{21}$ (dB) with the change in width of the common arm between two radiators. ....                                                                                                                                                                                                                                          | 66 |
| <b>Fig.3.8.</b> Pictorial representation of structure (a) Without a semi-circular patch; (b) With semi-circular patch cut in common arm.....                                                                                                                                                                                                                | 67 |
| <b>Fig.3.9.</b> Electric Field distribution at 56 GHz (a) Without a cut; (b) With semicircular cut in the common arm; (c) $S_{21}$ (dB) with and without a semi-circular cut in the common arm.....                                                                                                                                                         | 68 |
| <b>Fig.3.10.</b> On Phantom Simulations (a) S-parameters; (b) 2D normalized pattern in H-plane at 60 GHz ( $\phi=301^\circ$ , port1 excitation); (c) 2D normalized pattern in XoY plane at 60 GHz (port1 excitation). ....                                                                                                                                  | 70 |
| <b>Fig.3.11.</b> Fabricated structure of the designed antenna (a) Top view;(b) Bottom view. ....                                                                                                                                                                                                                                                            | 71 |
| <b>Fig.3.12.</b> Measured results of the fabricated structure (a) S-parameters; 2D normalized radiation pattern in XoY plane: (b) at 56 GHz (port1); (c) at 56 GHz (port2); (d) at 60 GHz (port1); (e) at 60 GHz (port2); (f) at 64 GHz (port1); (g) at 64 GHz (port2). ....                                                                                | 73 |
| <b>Fig.3.13.</b> Measured gain of the fabricated structure for port1. ....                                                                                                                                                                                                                                                                                  | 74 |
| <b>Fig.3.14.</b> (a) Pictorial representation of the modified structure; (b) Top View; (c) Back View.....                                                                                                                                                                                                                                                   | 76 |
| <b>Fig.3.15.</b> Simulated results of the dipole antenna with off-center director pairs (a) E-field distribution without off-center director pair; (b)E- field distribution with off-center director pairs; (c) Reflection parameter of the proposed structure; (d) Normalized pattern at 58 GHz (E-plane); (e) Normalized pattern at 58 GHz (H-plane)..... | 78 |

|                                                                                                                                                                                                                                                                                                                                                                                                |     |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>Fig.3.16.</b> Switched beam configuration of designed antenna structure (a) Top view; (b) Bottom View; (c) Fabricated structure.....                                                                                                                                                                                                                                                        | 80  |
| <b>Fig.3.17.</b> Switched beam antenna configuration (a) Reflection parameters; (b) Isolation parameters (in terms of S-parameters); (c) E-field distribution when the center port is excited at 60 GHz; (d) E-field distribution when the left port is excited at 60 GHz. ....                                                                                                                | 82  |
| <b>Fig.3.18.</b> Normalized radiation pattern in XoY-plane for all three excitations at 58 GHz. ....                                                                                                                                                                                                                                                                                           | 83  |
| <b>Fig.3.19.</b> Measured gain of the fabricated structure for the center and the right element. ....                                                                                                                                                                                                                                                                                          | 83  |
| <b>Fig.3.20.</b> On Phantom Simulations (a) S-parameters; (b) 2D normalized pattern in H-plane at 58 GHz ( $\phi=0^\circ$ , port1 excitation); (c) 2D normalized pattern in H-plane at 58 GHz ( $\phi=276^\circ$ , port2 excitation). ....                                                                                                                                                     | 85  |
| <b>Fig.4.1.</b> (a) The geometry of the partial ground microstrip ring antenna structure; (b) Top view of simulated structure; (c) Back view of simulated structure. ....                                                                                                                                                                                                                      | 89  |
| <b>Fig.4.2.</b> Antenna characteristics of the proposed structure (a) Reflection parameters; (b) 2D normalized pattern in XoY plane ( $\phi$ component) at 59 GHz. ....                                                                                                                                                                                                                        | 90  |
| <b>Fig.4.3.</b> (a) The geometry of the partial ground microstrip ring antenna structure with triangular patches; (b) Top view of simulated structure; (c) Back view of simulated structure. ....                                                                                                                                                                                              | 92  |
| <b>Fig.4.4.</b> Electric field distribution(maximum) at 59 GHz (a) without triangular patches; (b) with triangular patches. ....                                                                                                                                                                                                                                                               | 92  |
| <b>Fig.4.5.</b> Antenna characteristics of the proposed structure (a) 2D Gain pattern in XoY-plane ( $\phi$ component) at 59 GHz; (b) Reflection parameters. ....                                                                                                                                                                                                                              | 94  |
| <b>Fig.4.6.</b> Geometry of the aperture coupled patch (a) Top view; (b) Side view. ....                                                                                                                                                                                                                                                                                                       | 95  |
| <b>Fig.4.7.</b> A 3D graphic view of the aperture coupled patch antenna showing three copper layers and two dielectric layers of thickness 10 mil and 5 mil. ....                                                                                                                                                                                                                              | 96  |
| <b>Fig.4.8.</b> Antenna characteristics of the proposed structure (a) Reflection parameters; (b) 2D normalized pattern at 60 GHz in E-plane at 60 GHz; (c) 2D normalized pattern in H-plane at 60 GHz. ....                                                                                                                                                                                    | 97  |
| <b>Fig.4.9.</b> Final antenna Geometry (a) Top copper layer; (b) Mid copper layer; (c) Bottom copper layer ( black region indicates copper printed on the substrate). ....                                                                                                                                                                                                                     | 98  |
| <b>Fig.4.10.</b> 3D view of the proposed antenna design with gray color indicating metal part brown color to the dielectric substrate. ....                                                                                                                                                                                                                                                    | 99  |
| <b>Fig.4.11.</b> The comparison between the antenna s-parameters for two excitation modes (port1 for on-body mode; port2 for off-body mode) in free space and antenna over the flat skin phantom. ....                                                                                                                                                                                         | 100 |
| <b>Fig.4.12.</b> 2D normalized radiation pattern in different cut planes (a) Beam 1 (cut plane at $25^\circ$ ;port1 excitation; at 59 GHz); (b) Beam 2 (cut plane at $335^\circ$ ;port1 excitation; at 59 GHz); (c) XoY-plane (port1 excitation; 59 GHz); (d) H-plane with reference of patch (port2 excitation; 60 GHz); (e) E-plane with reference of patch (port2 excitation; 60 GHz). .... | 102 |
| <b>Fig.4.13.</b> Final fabricated structure (a) Top view; (b) Mid ground Layer; (c) Bottom view (Feed line). ....                                                                                                                                                                                                                                                                              | 104 |
| <b>Fig.4.14.</b> Measured s-parameters of the fabricated structure (a) Reflection parameters; (b) Isolation parameters(in terms of S-parameters). ....                                                                                                                                                                                                                                         | 106 |
| <b>Fig.4.15.</b> The simulated 3D radiation pattern for on-body/ off-body mode operation at 58 GHz. .                                                                                                                                                                                                                                                                                          | 107 |
| <b>Fig.4.16.</b> Measured 2D normalized radiation pattern (a) at 55 GHz (XoY-plane, port1 excitation); (b) at 58 GHz (XoY-plane, port1 excitation); (c) at 58 GHz (H-plane, port2 excitation). ....                                                                                                                                                                                            | 108 |

|                                                                                                                                                                                                                                                             |     |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>Fig.5.1.</b> Power absorption and reflection for vertical and horizontal polarised antenna[111].                                                                                                                                                         | 110 |
| <b>Fig.5.2.</b> Design steps of the proposed antenna (a) Circular-shaped patch; (b) Quarter Patch with shorting vias at two adjacent edges; (c) Two-quarter patches are joined using shorting vias to realize a final structure.                            | 112 |
| <b>Fig.5.3.</b> Electric Field Distribution of a proposed patch (Fig. 5.2(c)).                                                                                                                                                                              | 112 |
| <b>Fig.5.4.</b> The proposed end-fire antenna structure (a) Top view; (b) Back view; (c) Feeding line ; (d) 3D View elaborating microstrip feed line and its connection with top patch using PTH.                                                           | 114 |
| <b>Fig.5.5.</b> The reflection coefficient of the proposed end-fire antenna.                                                                                                                                                                                | 115 |
| <b>Fig.5.6.</b> Normalized radiation pattern of the proposed antenna at 60 GHz (a) H-plane pattern; (b) E-plane pattern.                                                                                                                                    | 115 |
| <b>Fig.5.7.</b> The proposed antenna structure with the loading of a loop-like structure to enhance gain.                                                                                                                                                   | 116 |
| <b>Fig.5.8.</b> E-field distribution of the proposed antenna for H-plane (a) without loading of a loop-like structure; (b) with the loading of a loop-like structure.                                                                                       | 117 |
| <b>Fig.5.9.</b> Magnitude plots of electric field (a) Along x-axis (dashed blue line), $z = -1$ mm, $y = 1.5$ mm; (b) Along y-axis (dashed red line), $x = 12.5$ mm and $z = -1$ mm; (c) Pictorial representation for 1D E-field plot along x- and y- axis. | 118 |
| <b>Fig.5.10.</b> Reflection coefficients at different values of gap ( $G_p$ ) between the radiator and loop-like structure.                                                                                                                                 | 119 |
| <b>Fig.5.11.</b> (a) Electric field plot along the y-axis (red dashed line) at $z = -1$ mm; (a) Pictorial representation for 1D E-field plot along y- axis.                                                                                                 | 121 |
| <b>Fig.5.12.</b> Comparison of the reflection coefficients of the antenna with and without loading of the loop-like structure.                                                                                                                              | 122 |
| <b>Fig.5.13.</b> Comparison of normalised gain pattern with and without loading of loop-like structure in an angular variation of $180^\circ$ (a) H-plane; (b) E-plane.                                                                                     | 123 |
| <b>Fig.5.14.</b> The effect on reflection coefficient by placing the proposed antenna on flat skin phantom.                                                                                                                                                 | 124 |
| <b>Fig.5.15.</b> Normalized radiation pattern in an angular variation of $180^\circ$ (a) E-plane pattern; (b) XoY-plane pattern.                                                                                                                            | 125 |
| <b>Fig.5.16.</b> (a)Antenna over Curved surface; (b) S-parameter comparison over flat skin and curved surface.                                                                                                                                              | 126 |
| <b>Fig.5.17.</b> (a) End launch connector used to excite the proposed antenna; (b) Top view of the fabricated structure; (c) Back view of the fabricated structure.                                                                                         | 128 |
| <b>Fig.5.18.</b> The measured reflection parameter of the fabricated prototype in comparison with simulated parameters.                                                                                                                                     | 129 |
| <b>Fig.5.19.</b> (a) Simulated pattern at 60 GHz with and without end-launch connector; (b) Measured pattern at 60 GHz; (c) Measured pattern at 62 GHz.                                                                                                     | 131 |
| <b>Fig.5.20.</b> The comparison between the simulated gain and the measured gain of the prototype.                                                                                                                                                          | 131 |

## LIST OF TABLES

|                                                                                                  |     |
|--------------------------------------------------------------------------------------------------|-----|
| <b>Table 1. 1.</b> Different propagation links and their frequency band [9].                     | 3   |
| <b>Table 1. 2.</b> Frequency range for 60 GHz based on different countries [1],[51].             | 7   |
| <b>Table 1. 3.</b> Comparison of antenna parameters with and without phantom [69].               | 11  |
| <b>Table 3. 1.</b> Dimensions of the proposed dipole antenna structure.                          | 59  |
| <b>Table 3. 2.</b> Tabulated values of measured 2D radiation characteristics in the XoY-plane.   | 75  |
| <b>Table 3. 3.</b> Dimensions of the proposed antenna structure.                                 | 77  |
| <b>Table 4. 1.</b> Radiation characteristics in XoY-plane at 59 GHz.                             | 91  |
| <b>Table 4. 2.</b> Tabulated values of radiation characteristics at 59 GHz for port1 excitation. | 101 |

## LIST OF ABBREVIATIONS

| Abbreviations | Definitions                                       |
|---------------|---------------------------------------------------|
| BCCs          | Body Centric Communications                       |
| IoT           | Internet of Things                                |
| AR            | Augmented Reality                                 |
| BAN           | Body Area Network                                 |
| RF            | Radio Frequency                                   |
| VR            | Virtual Reality                                   |
| WBAN          | Wireless Body Area Network                        |
| IEEE          | Institute of Electrical and Electronics Engineers |
| FSPL          | Free Space Path Loss                              |
| PIFA          | Planar Inverted F Antenna                         |
| UWB           | Ultra-Wideband antennas                           |
| PCB           | Printed Circuit Board                             |
| PLA           | Poly Lactic Acid                                  |

|      |                                |
|------|--------------------------------|
| FDM  | Fused Deposition Modelling     |
| SLL  | Sidelobe Level                 |
| PNA  | Performance Vector Analyzer    |
| TM   | Transverse Magnetic            |
| SIW  | Substrate Integrated Waveguide |
| PTH  | Plated Through Holes           |
| ECAL | Electronic Calibration         |