Rajeev Kumar Kanth

Analysis and Life Cycle Assessment of Printed Antennas for Sustainable Wireless Systems

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Analysis and Life Cycle Assessment of Printed Antennas for Sustainable Wireless Systems

Rajeev Kumar Kanth

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University of Turku
Department of Information Technology
Joukahaisenkatu 3-5 B, Turku-20520, Finland

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Supervisors

Professor Hannu Tenhunen
Department of Information Technology
University of Turku
Joukahaisenkatu 3-5 B, Turku-20520
Finland

Adjunct Professor Pasi Liljeberg
Department of Information Technology
University of Turku
Joukahaisenkatu 3-5 B, Turku-20520
Finland

Reviewers

Professor Leena Ukkonen
Department of Electronics and Computer Engineering
Tampere University of Technology
Korkeakoulunkatu 10, FI-33720 Tampere
Finland

Professor Johan Sidén
Department of Electronics
Mid Sweden University
S-Building, Holmgatan 10, 852 30 Sundsvall
Sweden

Opponent

Professor Shaofang Gong
Department of Science and Technology
Linkoping University
601 74 Norrkoping
Sweden

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An idea is brilliant, If it's realization seems almost impossible.
-A. Einstein

Abstract

In recent years, green design approaches and environment friendly ICT systems have become one of the major driving forces in ICT industry and academia. Along with the expansion of functional capability, design for low emissive manufacturing, reliability and adaptability emerge as critical concerns for ICT researchers. The goal of this research work is to design low profile, single and multiple band microstrip and fractal antennas, and to carry out an extensive study on their sustainability and life cycle assessment. This innovatively incorporates the issues such as wireless communication design paradigms, concept of conventional and modern printing methods, and environmentally friendly approaches during design and development. ICT for environmental sustainability is a vague field of scientific research. In this research work, we have carried out design, analysis and life cycle assessment of printed antennas.

This work has accomplished an integrated platform to create a concrete RF simulation, design and development of microstrip, fractal antenna and RFID tag based applications along with their environmental sustainability and life cycle analysis. The environmentally friendly design would be the prime objectives for each component of RF systems. An attempt has been made to demonstrate a quantitative picture of environmental emissions particularly emissions to air, fresh water, sea water and industrial soil in manufacturing process of ICT based applications. The core focus is to analyze the comparative environmental emissions between polymer and paper substrate printed antennas' production processes and also to carry out an extensive investigation on the life cycle stages including raw material preparation, production and end-of-life stage. This research work also includes a study on resources utilization for each antenna systems.

Specifically, effort has been made to resolve the following research questions through this work. What are the green and sustainable design methodologies for manufacturing microstrip, fractal and RFID based applications? What are the quantitative emissions in each life cycle stages of printed antennas? How severe are the impacts of environmental emissions? Based on this research experience, we have made an effort to formulate a course curriculum for "Green ICT" as one of the courses in engineering education.

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The success and final outcome of this PhD thesis required a lot of guidance and assistance from many people. I am extremely fortunate to have got this guidance along the way of my four year research works at department of Information Technology, University of Turku Finland.

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I would like to express my deepest gratitude to my parents for all the assistance from the beginning of my life and during my academic career. I am specially grateful to my father whose values to education and knowledge have been crucial in shaping my life. All the support they have provided me over the years was the greatest gift anyone has even given me. My brothers also deserve thanks for their encouragement through out the years.

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Turku, December 2013

Rajeev Kumar Kanth

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List of Abbreviations

AOX Adsorbable Organic Halogens

BOD Bio-logical Oxygen Demand

CFC Chloro Fluoro Carbon

COD Chemical Oxygen Demand

dB Decibel

dBi Decibel Isotropic

DCB Di-Chlro Benzene

DNG Double Negative: Negative Epsilon Negative Mu

DPI Dots Per Inch

EBG Electromagnetic Band Gap

ECTS European Credit Transfer System

EM Electromagnetic

EOL End-of-Life

EOS End of Sale

EPD Environmental Product Declaration

EPM Electronics Product Manufacturing

ETMSA Equilateral Triangle Micro Strip Antenna

FR Flame Retardant

GHG Green House Gas

GHz Giga Hertz

GICT Green Information and Communication Technology

GSM Global System for Mobile communications

GWP Global Warming Potential

ICT Information Communication Technology

IEEE Institute of Electrical and Electronics Engineers

ISO International Standardization Organization

ISM Industrial Scientific and Medicine radio bands

ITU International Telecommunication Union

KHz Kilo Hertz

LCA Life Cycle Assessment

LCD Liquid Crystal Display

LCI Life Cycle Inventory

LCIA Life Cycle Inventory Analysis

LHCP Left Hand Circular Polarization

MHz Mega Hertz

MSA Microstrip Antenna

NFPA National Fire Protection Association

PCB Printed Circuit Board

PCI Peripheral Component Interconnect

PIFAS Planer Inverted F Antennas

PVC Poly Vinyl Chloride

RF Radio Frequency

RL Return Loss

RFID Radio Frequency Identification

RHCP Right Hand Circular Polarization

RoHS Restriction of Hazardous Substances and Services

RNSS Regional Navigation Satellite System

ROM Read Only Memory

SMA Sub Miniature version A connectors

SSD Solid State Devices

TM Transverse Magnetic

UHF Ultra High Frequency

UMTS Universal Mobile Telecommunications System

VNA Vector Network Analyzer

WLAN Wireless Local Area Network

Contents

Chapter 1

Introduction

The present state of the art research in the direction of embedded systems demonstrate that analysis of life-cycle, sustainability and environmental assessment have not been a core focus for the ICT researchers. The greatest bottleneck of ICT designers today is the difficulty in achieving eco-friendly designs. To reinforce researcher's contribution in developing environmentally friendly products, devising green manufacturing processes, there is a strong need to enhance life-cycle awareness and sustainability understanding among system researchers, so that the next generation of engineers will be able to realize the goal of sustainable life-cycle of the products.

The concept of making the wireless communication greener is currently one of the popular research topics all over the world, as it tends to be a practical way for more efficient exploitation of natural resources in the global scale. As the ICT industry consumes around 2% [1] of the total used energy worldwide, and huge part of it falls on the wireless communication and particularly base stations including wireless instruments and antennas, it is rational to put strong effort on reduction of energy consumption in that sector of economy. Such an approach leads not only to better environmental protection but also reduces the cost of network management. Moreover, in the advent of internet-of-things and smart cities, where billions of devices are foreseen to communicate over the network, the need of efficient energy utilization is one of the key research aspects.

The present trends in RF design demonstrate that vital shortcomings in design procedure are evading the green approach, avoiding to quantify the environmental impacts assessment, insufficient study of product life cycle and ignoring environmental sustainability analysis. The study of life cycle and environmental impacts assessment are left for other community of researcher without any hindrance. This is an important fact that an RF designer should be responsible for not only exploring the design considerations as per the specifications but also investigating the issues related with environmental sustainability at the same time. Moreover, we can say that the design of a product and its environmental sustainability investigation are the two faces of the same coin. Both faces are very important and critically challenging. This thesis presents design methodology, exploring radio frequency based designs for several models, analysis of environmental impacts and life cycle assessment of printed antennas. This thesis also aims to fulfill the gaps between traditional RF design and environmental sustainability solutions through intensive study and design procedure analysis of the printed antennas.

1.1 Era of Environmentally Friendly RF Design

The Information and Communication Technology plays a significant role in creating a low carbon society and enabling environmental sustainability. It has delivered innovative products and services that are integral to everyday life and increased productivity and supported economic growth. Radio frequency engineering is a part of communication technology that deals with devices that are designed to operate in the radio frequency spectrum. The normal operating range for the radio frequency spectrum is 3 KHz to 300 GHz. There are tremendous amount of devices that operate on this frequency range and the production of these devices are growing rapidly with the advancement of information communication technologies.

There is a need for the ICT domain to drive energy and resources efficiency in its products and services to reduce the direct impact of ICT on the environment in areas such as material usage, manufacturing processes, supply chains, product usage efficiency and end-of-life considerations.

1.2 Thesis Navigation

Fig. 1.1 shows the thesis navigation. This figure contains core technical areas, chapters, results, and publications together. Though organization of the thesis is explained in section 1.6, this navigation page will help to understand the brief research work in this thesis pictorially. The core technical areas can be found on leftmost side of the picture while list of chapters, proposed schemes and model designs are situated to the center of the thesis navigational drawing. At the rightmost areas, the published papers linked with the core technical ideas are shown. The numbering system of the publications are followed as per the list of original publications shown in section 1.7.

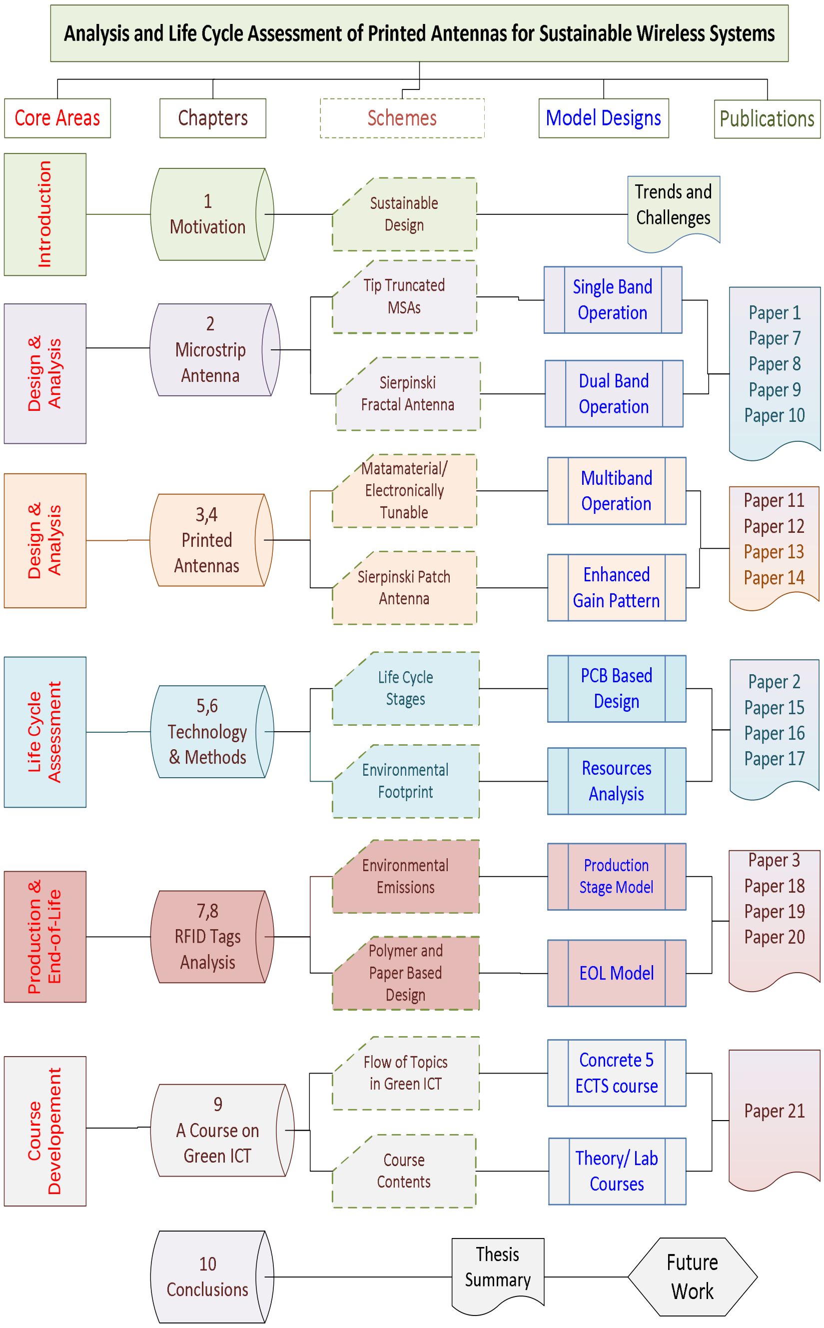

Figure 1.1: Navigation of the Dissertation

1.3 Design Challenges

The world today is increasingly turning towards wireless technology for communication purpose, which is evidenced by the widespread use of mobile phones, wi-fi, blue-tooth, and myriad behind the scenes network backbone technologies. The need for improved performance, low profile, compact and lower price has become critical as we continue to push the boundaries of bandwidth, cost, and power savings especially with the application of wireless technology to mobile and battery powered platforms. At the one side, the performance of an RF device turns to be a critical concern for the designer while at the other side environmental sustainability, and life cycle assessment emerge as the counter challenges.

1.3.1 Microstrip Antenna Design

A wireless link comprises a transmitter with an antenna, a transmission path and a receiver with an antenna. The choice of a certain design of a microstrip antenna for a particular application is left to the decision of an individual. In selecting a design, certain factors like portability, ruggedness, compactness, signal gain versus size, weight, wind loading and availability of materials must be taken into account to realize an optimum performance for constructing a particular antenna. With the increasing requirements of personal and mobile communication, the demand for smaller and low profile antennas has brought microstrip antenna (MSA) to forefront.There are several configurations of MSA patches. Square, circular, triangular, semicircular, annular ring and square ring are few popular configurations [2]-[6]. This research work adds contribution The advantages and disadvantages of MSA are briefly explained below:
Advantages:

- They are light wight, have a relatively smaller volume and a low-profile planer configuration.
- They can be made conformal to the host surface.
- Their ease of mass production using printed circuit technology leads to a low fabrication cost.
- They are easier to integrate with other microwave integrate circuits on the same substrate.
- They allow both linear and circular polarization.
- They can be made compact for use in personal mobile communication.
- They allow for dual and multiband frequency operations.

Disadvantages:

- Narrow bandwidth
- Lower gain
- Low power handling capability

The advantages of MSAs are exploited in numerous wireless communication applications. The telemetry and communication antennas on missiles need to be thin and conformal, so MSAs are primary candidates for such applications. Radars use small arrays of microstrip radiators and aircraft related applications employ MSAs for telephone and satellite communications. Microstrip arrays have been used for satellite imaging systems. Smart weapon systems use MSAs because of their thin profile. Global system for mobile communication and global positioning system are major users of MSAs.

1.3.2 Environmental Impacts Analysis

With the growing demand of printed electronics products and emerging wireless communication technology worldwide, analysis of environmental impacts turns out to be a global challenge for each and everyone living in this world. At least one should know the quantity of impacts in terms of emissions to air, fresh water, sea water, industrial soil and agricultural soil in the process of development of a product, service or a wireless network. The quantification of the carbon footprint of the printed electronics product is becoming essential in day-to-day life.

1.4 Thesis Objectives

In recent years, green design approach and environment friendly ICT systems have become one of the major driving forces in ICT industries and academia. Along with the expansion of functional capability, design for low emissive manufacturing, reliability and adaptability emerge as critical concerns for ICT researchers. The goal of this research work is to design low profile, single and multiple band microstrip and fractal antennas, and to carry out an extensive study on their sustainability and life cycle assessment. This will innovatively incorporates the issues such as wireless communication design paradigm, concept of conventional and modern printing methods, and environmentally friendly approach during design and development. ICT for environmental sustainability is a vague field of scientific research. In this research work, we have carried out design, analysis and life cycle assessment of printed antennas. These printed antennas are widely used in wireless communication and RFID based applications.

This work will accomplish an integrated platform to create a concrete RF simulation, design and development of microstrip, fractal antenna and RFID tag based applications along with their environmental sustainability and life cycle analysis. The environmentally friendly design would be the prime objectives for each component of RF systems. A set of experiments using several simulation tools have been carried out to demonstrate a quantitative picture of environmental emissions particularly emissions to air, fresh water, sea water and industrial soil in manufacturing process of ICT based applications. The core focus is to analyze the comparative environmental emissions between polymer and paper substrate printed antennas' production processes and also to carry out an extensive investigation on the life cycle stages including raw material preparation, production and end-of-life. This research work also includes an analytical study on resources utilization for each antennas system.

Specifically, we have tried to resolve the following research questions through this work. What are the efficient design methodologies for manufacturing microstrip, fractal and RFID based antennas? What are the quantitative emissions in each life cycle stages of printed microstrip and RFID antennas? How severe are the impacts of environmental emissions?

1.5 Thesis Contribution

In this starting period of this research work, main concentration has been given on the literature study, initial theoretical and quantitative modeling and experiments of the design paradigm. This work has continued the research based on design of single and multiband microstrip and fractal antennas; explore the sustainability issues and end-user applications. These are the following contributions at the early stage of this research work:

- The basic antenna theory has been employed to design two single bands (1.176 GHz and 2.487 GHz) and a dual band fractal antenna for the applications in mobile and hand-held terminals.

- Many experimental simulations have been performed to achieve the required specifications of the antenna in terms of bandwidth and gain radiation pattern for the resonant frequencies 1.176GHz and 2.487GHz.

- Based on the required specifications, two separate L-band and S-band antennas have been fabricated in collaboration with Royal Institute of Technology (KTH), Sweden

- The general performances of the fabricated antenna have been measured with Vector Network Analyzer and gain radiation pattern in anechoic chamber. The measured results have been analyzed and compared with the simulated results.

- Metamaterials based antenna, which can operate on dual UMTS and ISM bands simultaneously, is designed. The simulation results offer an excellent performance in terms of bandwidth and gain radiation pattern.

- Varactor diode coupling mechanism is successfully employed to create an electronically tunable circular patch antenna, that gives an excellent electromagnetic characteristics.

- A Sierpinski grid fractal patch antenna in stacked configuration has been developed.

In the mid stage of this four year PhD research, in-depth study and modeling of several environmentally friendly ICT designs, including printed circuit board, polymer based printed RFID antenna and paper based RFID antennas have been carried out. In this stage, effort has been made to investigate and evaluate the life cycle assessment and the environmental impacts of printed electronics products, i.e. the antennas. The contributions are as follows:

- Comprehensive theoretical modeling, in particular detailed models of each components of printed electronic resources such as printed antenna.

- More analytic description in several life cycle stages including raw material preparation, production processing.

- Life Cycle Inventory analysis to quantify total systems' inputs and outputs that are relevant to environmental impact especially emissions to air, fresh water, sea water and industrial soil.

- Complete case study of quantitative environmental emission analysis of paper and polymer based RFID antennas.

At last stage of the research work, full system simulation, end-of-life technologies and issues related to energy and material resources utilization have been thoroughly studied. The following tasks were successfully performed:

- Study, modeling and simulation of end-of-life technologies related to incineration and land filling.

- Focus on massive amount of parameters that need to consider during LCA process and analysis of their significances.

- Optimization of technology.
- Consider the recyclability issues and to achieve the complete cradle to grave life cycle assessment.

1.6 Organization of Thesis

This thesis is divided into ten chapters covering different design aspects of printed antennas. The thesis also aims to detail various MSA configurations along with environmental footprint, sustainability analysis and life cycle assessment. An attempt has been made to make the text self-contained so that the readers would quickly grasp the ideas contained within. This thesis has been composed using the experimental results obtained from several published articles in referred journals and peer reviewed conference proceedings. The language of the text is kept as simple without losing technical objectivity. A summary is given at the end of each chapter to highlight the important points given in the chapter.

Chapter 1 contains the introductory part of my thesis. This mainly includes the thesis contribution and the specific objectives.

Following introduction, chapter 2 introduces the printed antennas, their scopes, substrate materials and frequency spectrum. This chapter includes the design and analysis of triangular printed antenna, multi-band fractal structures, their layouts, and simulated and measured results.

Chapter 3 accomplishes an extensive study on electromagnetic band gap behavior of metamaterials and electronically tuned circular polarized printed antennas. This chapter will discuss parametric studies of meta material based antenna and performance analysis of varactor diode used electronically tunable antennas.

Chapter 4 carries out an in-depth study to design a planar Sierpinski fractal antenna with stacked configuration for multiband applications. Sierpinski fractal geometries and its multiband electromagnetic behavior has been described in this chapter.

Chapter 5 address life cycle assessment of printed antenna. Firstly chapter 5 will discuss the definition of LCA, its variants and then overview generic LCA methodology. The main part of this chapter proposes a model for printed antenna and examine the life cycle analysis including procedural flow diagram, life cycle stages and environmental impacts assessment.

In Chapter 6, study and analysis of sustainability and quantitative environmental footprint in the manufacturing process of the printed antennas are carried out. This chapter presents a cradle to gate life cycle impact assessment of the epoxy resin printed antenna. The global warming potential, acidification, eutrophication, ozone layer depletion and human toxicity potentials have also been analyzed.

Chapter 7 and 8 describes different aspects of RFID tags such as toxic potential indicators, comparative study of polymer and paper substrate printed antennas and end-of-life management. In these two chapters, the author would like to aware the readers about the number of antennas considered during the impact analysis. These two numbers are 6.3 million and one million. This is because of our published articles based on these two quantities.

Chapter 9 gives an overview for building a concrete 5 ECTS course unit named as “Green ICT” which includes the several entities that are relevant to green computing, environmental impact assessment, sustainable ICT design. Concluding remarks have been covered in the last chapter i.e. chapter 10.

This thesis also contain an appendix. The appendix shows the output data which includes flows, amount of resources and environmental impacts in terms of emissions to air in the production of 6.3 million paper based RFID antennas.

1.7 Research Publications

During the course of conducting research presented in this thesis, the following papers have been published in international journals and proceedings of conferences.

Referred Journal Publications (JNL):

1. **Rajeev Kumar Kanth**, Pasi Liljeberg, Hannu Tenhunen, Qiang Chen, Lirong Zheng, Haris Kumar, *Study on Glass Epoxy Based Low Cost and Compact Tip-Truncated Triangular Printed Antenna*, International Journal of Antennas and Propagation 2012 (2012)(184537), PP: 1-8, 2012. Hindawi Publication, DOI:10.1155/2012/18453

2. **Rajeev Kumar Kanth**, Qiansu Wan, Harish Kuamr, Pasi Liljeberg, Qiang Chen, Lirong Zheng, Hannu Tenhunen, *Evaluating Sustainability, Environment Assessment and Toxic Emissions in Life Cycle Stages of Printed Antenna*, Elsevier Publication, Procedia Engineering 30(1), PP: 508-513, 2012

3. **Rajeev Kumar Kanth**, Pasi Liljeberg, Yasar Amin, Qiang Chen, Lirong Zheng, Hannu Tenhunen, *Comparative End-of-Life Study of Polymer and Paper Based Radio Frequency Devices*, International Journal of Environmental Protection Vol: 2, Issue:8, PP: 23-27, 2012. Online ISSN: 2224-7777, Print ISSN: 2226-6437

4. Yasar Amin, **Rajeev Kumar Kanth**, Pasi Liljeberg, Qiang Chen, Lirong Zheng, Hannu Tenhunen, *Green Wideband RFID Tag Antenna*

for Supply Chain Applications, IEICE ELECTRONICS EXPRESS Vol: 9, Issue: 24, PP: 18611866, DOI: 10.1587/elex.9.1861, 2012

5. Liang Guang, **Rajeev Kumar Kanth**, Juha Plosila, Hannu Tenhunen, *Hierarchical Monitoring in Smart House: Design Scalability, Dependability and Energy-Efficiency*, A International Journal of Communications in Information Science and Management Engineering (CISME) Vol: 2, Issue: 5, PP: 46-51, ISSN: 2222-1859 (Print), ISSN: 2224-7785 (Online) 2012

6. Yasar Amin, **Rajeev Kumar Kanth**, Pasi Liljeberg, Q. Chen, L.-R. Zheng, and Hannu Tenhunen, *Performance-Optimized Printed Wide band RFID Antenna and Environmental Impact Analysis*, Submitted for publication at ETRI Journal (p-ISSN 1225-6463, e-ISSN 2233-7326), 2012

Peer-Reviewed Conference Publications (CNF):

7. **Rajeev Kumar Kanth**, Waqar Ahmad, Yasar Amin, Lirong Zheng, Pasi Liljeberg, Hannu Tenhunen, Analysis, *Design and Development of Novel, Low Profile 2.487 GHz Microstrip Antenna*, In: Conference Proceedings of 14th International Symposium on Antennas Technology and Applied Electromagnetics and The American Electromagnetic Conference (ANTEM/AMEREM) 2010, PP: 1-4, IEEE, 2010

8. **Rajeev Kumar Kanth**, Waqar Ahmad, Subarna Shakya, Pasi Liljeberg, Lirong Zheng, Hannu Tenhunen, *Autonomous Use of Fractal Structure in Low Cost, Multiband and Compact Navigational Antenna*, In: Proceedings of 10th Mediterranean Microwave Symosium MMS 2010, PP: 135-138, IEEE, 2010

9. **Rajeev Kumar Kanth**, Alok Kumar Singhal, Pasi Liljeberg, Hannu Tenhunen, *Design of Multiband Fractal Antenna for Mobile and Handheld Terminals*, In: First IEEE Asian Himalyan International Conferecne on Internet Conference Proceedings, PP: 1-4, IEEE, 2009

10. **Rajeev Kumar Kanth**, Alok Kumar Singhal, Pasi Liljeberg, Hannu Tenhunen, *Analysis, Design and Development of Novel, Low Profile Microstrip Antenna for Satellite Navigation*, In: NORCHIP 2009 IEEE Conference Proceedings, PP: 1-4, IEEE, 2009

11. Harish Kumar, **Rajeev Kumar Kanth**, Pasi Liljeberg, Hannu Tenhunen, *Metamaterial Based Slotted Patch Antenna*, In: B. Milovanovi

(Ed.), Conference Proceedings of Jubilee 10th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Services - TELSIKS 2011 , Vol. 1, PP: 43-46, IEEE, 2011

12. Harish Kumar, M.d. Upadhyay, **Rajeev Kumar Kanth**, Pasi Liljeberg, *Study of Electronically Tunable Circular Patch Antenna*, In: B. Milovanovi (Ed.), Proceedings of 10th International Conference on Telecommunication in Modern Satellite Cable and Broadcasting Services (TELSIKS 2011), Vol. 2, PP: 536-539, IEEE, 2011

13. Harish Kumar, Manish Kumar, Mohit Kumar, Abhijeet Kumar, **Rajeev Kumar Kanth**, *Study on Band Gap Behaviour of Electromagnetic Band-Gap(EBG) Structure With Microstrip Antenna*, In: Seang-Tae Kim (Ed.), 14th International Conference on Advanced Communication Technology, PP: 356-359, ISSN : 1738-9445, Print ISBN: 978-1-4673-0150-3 IEEE, 2012

14. **Rajeev Kumar Kanth**, Pasi Liljeberg, Hannu Tenhunen, Qiang Chen, Axel Janstch, Lirong Zheng, Harish Kumar, Leena Varshney, *Design of Sierpinski Grid Patch Antenna for Multiband Application*, Progress In Electromagnetics Research Symposium , PP: 577-582, Proceedings of PIERS, 2013

15. **Rajeev Kumar Kanth**, Qiansu Wan, Harish Kumar, Pasi Liljeberg, Lirong Zheng, Hannu Tenhunen, *Life Cycle Assessment of Printed Antenna: Comparative Analysis and Environmental Impacts Evaluation*, In: Matthew Eckelman (Ed.), Conference Proceedings of IEEE International Symposium on Sustainable Systems and Technology (ISSST), Vol. 1, PP: 1, IEEE, 2011

16. **Rajeev Kumar Kanth**, Pasi Liljeberg, Hannu Tenhunen, Harish Kumar, Yasar Amin, Qiang Chen, Lirong Zheng, *Quantifying the Environmental Footprint of Rigid Substrate Printed Antenna*, In: Michael Arnold (Ed.), IEEE International conference on Technology and Society in Aisa 2012, PP: 1-5, DOI: 10.1109/TSAsia.2012.6397973, IEE-Explore, 2012

17. **Rajeev Kumar Kanth**, Qiansu Wan, Pasi Liljeberg, Aulis Tuominen, Lirong Zheng, Hannu Tenhunen, *Investigation and Evaluation of Life Cycle Assessment of Printed Electronics and its Environmental Impacts Analysis*, In: Proceedings of NEXT 2010 Conference, PP: 52-67, NEXT Conference, 2010

18. **Rajeev Kumar Kanth**, Pasi Liljeberg, Hannu Tenhunen, Wan Qiansu, Yasar Amin, Botao Shao, Qiang Chen, Lirong Zheng, Harish Kumar,

Evaluating Sustainability, Environmental Assessment and Toxic Emissions during Manufacturing Process of RFID Based Systems, In: Jinjun Chen (Ed.), 2011 IEEE Ninth International Conference on Dependable, Autonomic and Secure Computing (DASC), PP: 1066-1071, DOI: 10.1109/DASC.2011.175, IEEE Computer Society, 2012

19. **Rajeev Kumar Kanth**, Pasi Liljeberg, Hannu Tenhunen, Qiang Chen, Lirong Zheng, Harish Kumar, *Comparative Toxic Emission Analysis in Production Process of Polymer and Paper Based RFID Tags*, In: M. Caciotta, Zbigniew Leonowicz (Eds.), 11th International Conference on Environment and Electrical Engineering, PP: 184187, DOI: 10.1109/ EEEIC.2012.6221570 IEEE, 2012

20. **Rajeev Kumar Kanth**, Qiansu Wan, Pasi Liljeberg, Lirong Zheng, Hannu Tenhunen, *Insight into Quantitative Environmental Emission Analysis of Printed Circuit Board*, In: Zbigniew Leonowicz (Ed.), Conference Proceedings of International Conference on Environment and Electrical Engineering (EEEIC.EU) 2011, PP: 1-4, IEEE, 2011

21. **Rajeev Kumar Kanth**, Harish Kumar, Pasi Liljeberg, Qiang Chen, Lirong Zheng, Hannu Tenhunen, *Exploring Course Development for Green ICT in Engineering Education: A Preliminary Study*, In: Mathew Arackal (Ed.), International conference on Engineering Education: Innovative Practices and Future Trends (AICERA 2012), PP: 1-5, DOI: 10.1109/AICERA.2012.6306685, IEEE Explore, 2012

22. Yasar Amin, **Rajeev Kumar Kanth**, Pasi Liljeberg, Adeel Akram, Qiang Chen, Li-Rong Zheng, Hannu Tenhunen, *Printable RFID Antenna with Embedded Sensor and Calibration Functions*, In: He Sailing (Ed.), Progress In Electromagnetics Research Symposium , PP: 567-570, Proceedings of PIERS, 2013

23. Liang Guang, **Rajeev Kanth**, Juha Plosila, Hannu Tenhunen, *Hierarchical Monitoring in Smart House: Design Scalability, Dependability and Energy-Efficiency*, In: Yi Pan (Ed.), Proc. of the 3rd International Conference on Information Science and Engineering (ICISE2011) , PP: 291-296, IEEE, 2011

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25. **Rajeev Kumar Kanth**, Pasi Liljeberg, Hannu Tenhunen, Qiansu Wan, Waqar Ahmad, Lirong Zheng, Harish Kumar, *Insight into the*

Requirements of Self-aware, Adaptive and Reliable Embedded Subsystems of Satellite Spacecraft, In: Juha Plosila (Ed.), Conference Proceedings of International Conference on Pervasive and Embedded Computing and Communication Systems, PP: 603-608, Science and Technology Publications Lda (SCiTePress), 2011

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27. Waqar Ahmad, **Rajeev Kumar Kanth**, Qiang Chen, Lirong Zheng, Hannu Tenhunen, *Power Distribution TSVs Induced Core Switching Noise*, In: Conference Proceedings of Electrical Design of Advanced Packaging & Systems Symposium (EDAPS), 2010 IEEE , Vol. 1, PP: 1-4, Electrical Design of Advanced Packaging & Systems Symposium (EDAPS), 2010 IEEE , 2010

Technical Report (TR):

28. **Rajeev Kumar Kanth**, Qiansu Wan, Lirong Zheng, Pasi Liljeberg, Hannu Tenhunen, *Comparative Study for Environmental Assessment of Printed and PCB Technologies*, TUCS Technical Reports 990, Turku Centre for Computer Science, University of Turku 2010

Chapter 2

Design and Performance Analysis of Printed Antennas

This chapter begins with an introduction to printed antennas, their scopes, substrate materials and frequency spectrum. This study includes the design and analysis of triangular printed antenna, multi-band fractal structures, their layouts, and simulated and measured results.

The rapid progress in telecommunication systems needs to address a great variety of communication systems, like cellular network, global positioning, and satellite communications, each of these systems operate at several frequency bands. To provide an efficient and seamless services to the users, each of these systems must have an antenna that has to operate in the allocated frequency band. Dielectric material plays an important role to characterize the performance of a microstrip antenna [7]-[10]. Usually it is difficult to configure and optimize the parameters of an antenna with known value of dielectric constant. A glass epoxy resin, that is widely available and low cost dielectric material, is proposed for design and fabrication of the antennas. Glass epoxy dielectric material has several advantages such as rigid, low cost, uniform permittivity, fine dielectric loss tangent characteristics over other substrates. A glass epoxy substrate, which is extensively used in printed circuit board to realize analog and digital circuits, can also be used in low cost printed electronic applications. The relative dielectric constant (ε_r) of the substrate varies typically from 3.8 to 4.7 and tangent loss varies from 0.01 to 0.03 in the microwave frequency band.

Another major constraint is the frequency spectrum in which the antenna is suppose to operate. International Telecommunication Union Radio Communication Sector (ITU-R) has assigned two frequencies 1.176 GHz and 2.487 GHz for Regional Navigation Satellite System (RNSS) for the purpose of satellite navigational aids. One of the specific objectives of this work is to design and develop two separate antennas resonating at those specific frequencies accomplishing the required bandwidths, axial ratios and gain radiation patterns.

The antenna is a device which transforms guided electromagnetic signals into electromagnetic waves propagating in free space. It can be used for reception and transmission. A microstrip printed antenna consists of a very thin radiating patch on one side of a dielectric substrate and a conducting ground plane on the other side. The patch and the ground plane are separated by a dielectric. The antenna tracing material, copper, is considered as a radiating patch conductor and it can have any regular geometry. The patches are normally photo etched on the dielectric substrate and the substrate is usually non-magnetic. The relative permittivity of the substrate is an important parameter to consider because it will affect the fringing fields that accounts for radiation. To achieve the design specification for these separate 1.176 GHz and 2.487 GHz antennas, substrate is considered as glass epoxy whose relative dielectric constant (ε_r) is 4.4 and dimensions of the antenna is set up by the empirical relationship [11] as illustrated in equations (2.1), (2.2), (2.3) and (2.4) for equilateral triangle microstrip antenna. MathCAD tool is used to find the exact dimensions of both the antennas.

$$f_{mn} = \frac{2c(m^2 + mn + n^2)^{\frac{1}{2}}}{3S_e\sqrt{\varepsilon_e}} \tag{2.1}$$

$$S_e = S + \frac{4h}{\varepsilon_e} \tag{2.2}$$

$$\varepsilon_e = \frac{(\varepsilon_r + 1)}{2} + \frac{(\varepsilon_r - 1)}{2}\left[1 + \frac{20h}{S}\right]^{\frac{-1}{2}} \tag{2.3}$$

$$y = \sqrt{S^2 - \left(\frac{S}{2}\right)^2} \tag{2.4}$$

The characteristics and performance of the low profile microstrip antennas are explored in the published literature [12]-[17]. In recent years several micro-strip patch geometries have been introduced for antenna applications with varying degrees of success in improving antenna characteristics [18]-[24]. Some of these geometries have been particularly useful in reducing the size of the antenna. However the proposed models are appropriate for the specified frequencies respectively in L and S band having the gain of -4 dBi up to ±50° and can be employed in the space application of satellite navigation.

This chapter is organized as follows. The next two sections provide the description about triangular printed antenna and multi-band fractal structure design. Related theory, specifications of the antennas, design layout, physical dimensions and probe positions, fabrication and measurement of the proposed antennas are included as the sub-sections. These two sections also include the outcomes obtained and their analysis in each antenna configuration.

2.1 Triangular Printed Antenna

In this part, design and fabrication of triangular printed antenna made on glass epoxy substrate is discussed. On the basis of required specifications and assigned frequencies, tip truncated triangular printed antennas are designed, analyzed, and fabricated. The performances of the antennas are measured in terms of return loss, frequency of operation, bandwidth and radiation pattern. Copper as active radiating patch and glass epoxy as dielectric substrate are skimmed off in the configuration of triangular microstrip antenna to achieve the essential characteristics and satisfying desired low cost antenna. The method of moment analyzing techniques are employed to attain the required specific properties while optimized tip truncation technique and varying feed point location give rise to suitable LHCP or RHCP configuration of the printed antenna. The coaxial probe signal feed arrangement have been considered for this work. The proposed printed antennas are suitable for establishing communication links between ships or buoys and satellites especially for navigation purpose.

2.1.1 Related Theory

Related antenna theory has been discussed in this section. The aim of this section is to clarify the readers about mathematical background of specified parameters during antenna design. Fig. 2.1 characterize the dominant mode of ETMSA, TM_{10} and TM_{01} are required to configure circular polarization and this figure also elucidates voltage distribution and field vector representation around ETMSA. The notations TM stands for transversal magnetic field distribution. The set of four equations shown in (2.1) to (2.4) help to determine the dimensions of both the antennas.

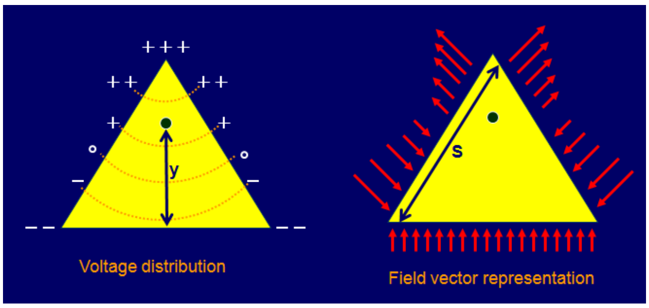

Figure 2.1: ETMSA Voltage Distribution and its Vector Representation

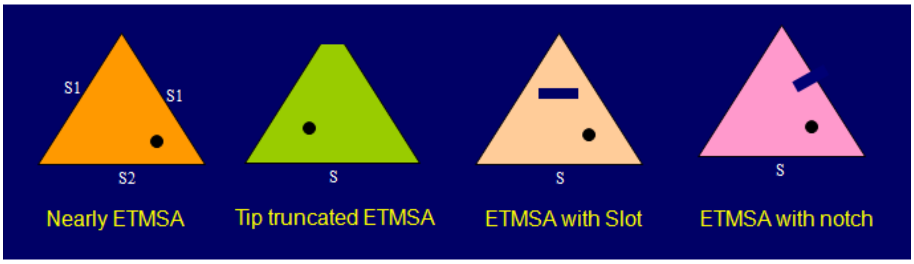

Figure 2.2: Methods Obtaining Circular Polarization

The resonant frequency (f_{mn}) can be expressed in terms of effective side length (S_e), mode of triangular patch antenna (m=1, n=0), speed of light (c) and the effective dielectric constant (ε_e). Similarly the effective side length can be estimated with equation (2.2) where effective dielectric constant (ε_e) can be obtained in equation (2.3) with the use of associated parameters like relative dielectric constant (ε_r), height or thickness of the ground plane to patch (h) and side of equilateral triangle (S). The empirical mathematical statements shown in equations (2.1), (2.2), (2.3) and (2.4) assist to compute the dimensions of the active patches. MathCAD tool has been employed to achieve the optimized parameters.

Modified triangular MSA configuration with a single feed generates circular polarization. Some of the well known techniques for generating circular polarization in ETMSA are nearly ETMSA (isosceles triangle with S1/S2=1.01 to 1.1), tip truncated ETMSA, ETMSA with a rectangular slot and notched ETMSA as shown in Fig. 2.2. LHCP or RHCP can be obtained by variation of feed point location and dimensions of the antenna. For the sake of convenience and easy realization, tip truncated ETMSA has been employed for these designs. For these developed antennas, coaxial probe feeding technique has been exploited. The coaxial feed or probe feed is a very common technique used for feeding microstrip patch antennas. In this technique, inner conductor of the coaxial connector extends through the dielectric and is soldered to the radiating patch, while the outer conductor is connected to the ground plane. For the present design the substrate chosen is glass epoxy and the reasons for selection of glass epoxy are low cost, compact size and easily available for mass production.

2.1.2 Specifications

A specification is an explicit set of requirements to be satisfied by the antenna. The technical specifications for both antennas are shown in Table 2.1. Based on communication link between associated application and the satellite, this technical specification came in to the picture. It is evident from Table 2.1 that antennas bandwidth must be large enough such that

Table 2.1: Specifications of 1.176 GHz and 2.487 GHz Antennas

S.N.	Parameters	1.176 GHz Antenna	2.487 GHz Antenna	Unit
1.	Frequency Band	1.16-1.19	2.46-2.50	GHz
2.	Gain	-4(Minimum)	-4(Minimum)	dBi up to $\pm 50°$
3.	Axial Ratio	3	3	dB
4.	Polarization	LHCP	LHCP	
5.	3 dB Beam width	$\pm 50°$	$\pm 50°$	

frequency of operation can be included within the band. The numerical values of the bandwidths are 30 MHz and 40 MHz respectively for both antennas respectively. Apart from bandwidth consideration, the gain must exceed -4 dBi and feed point must be set up such that left hand circular polarization (LHCP) is obtained.

2.1.3 Design Layout

The design criteria regarding physical dimensions as well as probe position will be discussed. The layout of the 1.176 GHz microstrip antenna is shown in Fig. 2.3. In this layout, tip truncated ETMSA has been devised to get the circular polarization. Truncated portion creates two dominant modes with equal amplitude and 90° phase difference. Both modes are applied on orthogonal plane to generate circular polarization. This method is employed because of good axial ratio and bandwidth. The sides of the patch have been optimized as 72.43 mm, 78.55 mm and 72.45 mm respectively for three sides of the triangle. These lengths of the patch side offer the required specification of the antenna operating at 1.176 GHz. The Probe Position plays a significant role in designing the patch antenna. Several iterations have been performed to achieve the exact impedance matching. At the same time the resonant frequency is controlled by changes in dimensions of the patch. For the design of 1.176 GHz patch it has been noticed that port P of coordinate (1.9, 35.4) in Fig. 2.3 is required position of the probe for maximum impedance matching where the lower vertex of the antenna is assumed at the position (0, 0).

The layout of the 2.487 GHz microstrip antenna is also similar to Fig. 2.3. As shown in Fig. 2.3, the sides of the patch have been optimized as 31.1 mm, 36.5 mm and 31.1 mm respectively for three sides of the triangle. These lengths of the patch sides offer the required specification of the antenna operating at 2.487 GHz. For the design of 2.487 GHz patch it has been noticed that port P of coordinate (0.78, 15) in Fig. 2.3 is required position of the probe for maximum impedance matching where the lower vertex of the antenna is assumed at the position (0, 0).

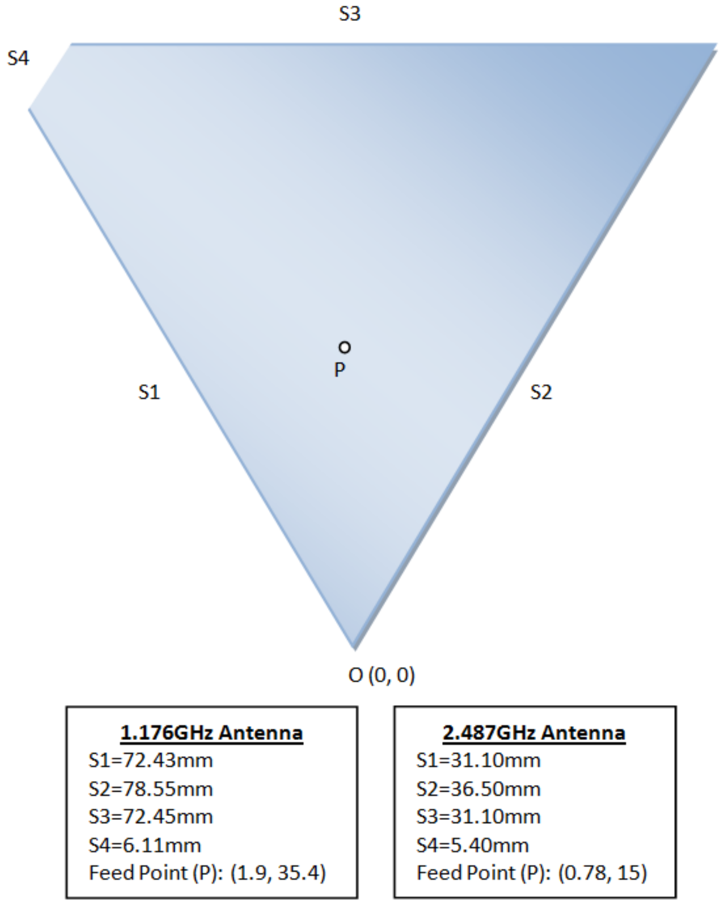

Figure 2.3: Layout of 1.176 GHz and 2.487 GHz Antennas

2.1.4 Simulated and Measured Results of 1.176 GHz Antenna

This section discusses simulated and measured results. It has been attempted to analyze the specific design parameters shown in Table 2.1 for 1.176 GHz antenna. An electromagnetic modeling tool, Ansoft Designer has been employed to simulate the required specifications of the antenna. The following segment of texts deal with the results in terms of return loss, bandwidth, smith plot, axial ratio and gain radiation pattern.

(A) ***Outcomes***

The Fig. 2.4 is return loss diagram analyzed using Ansoft designer version-2 software tool. It points out that the antenna is resonating at 1.176 GHz frequency and providing a large enough bandwidth of 30 MHz ranging from 1.17 GHz to 1.20 GHz at the level of 10 dB return loss. This value of bandwidth has been achieved after several iterations optimizing several parameters in the design. The measured return loss curves are also presented in the Fig. 2.4. The desired frequency of operation has been attained on 4.8 mm thickness of the substrate. As glass epoxy substrate sheet was available with 1.6 mm thickness, and the required thickness of the substrate was 4.8 mm (according to design) therefore three layers of the substrate were stacked together to get the desired thickness for the specific design. These three layers have been stacked by two ways; firstly, they have been stacked with air gapping and secondly, they have been stacked using the adhesive. In both the cases measurements have been carried out. Simulated and measured impedance matching plots have been performed using Ansoft tool and Vector Network Analyzer (VNA) respectively. The reflection coefficient and impedance matching were found exactly as desired. Gain radiation pattern and axial ratio diagrams are shown in Fig. 2.5 and Fig. 2.6 respectively.

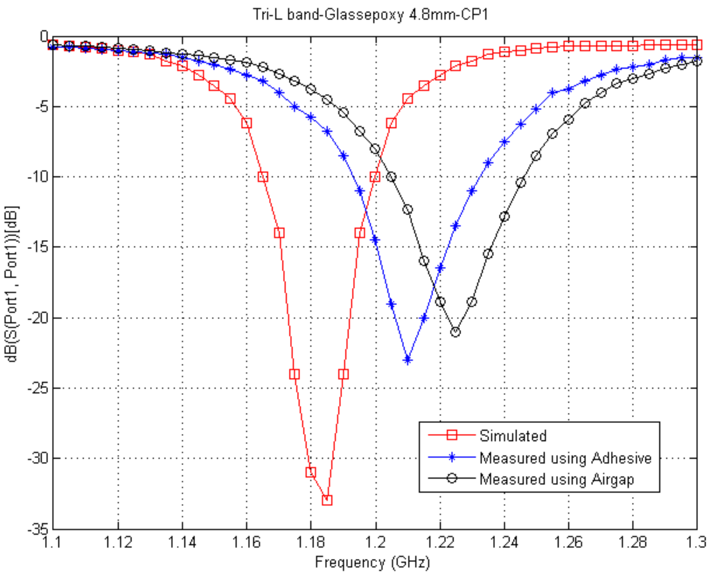

Figure 2.4: Return Loss Diagram

(B) ***Results Analysis***

For 1.176 GHz antenna, Fig. 2.4 is showing that the antenna is resonating at 1.176 GHz corresponding to lower data cursor in simulated labeled return loss curve. This depicts that at 10 dB S_{11}, bandwidth of 30 MHz is achieved ranging from 1.17 GHz to 1.20 GHz. The measured return loss with adhesive and air gap have been shown with correspond-

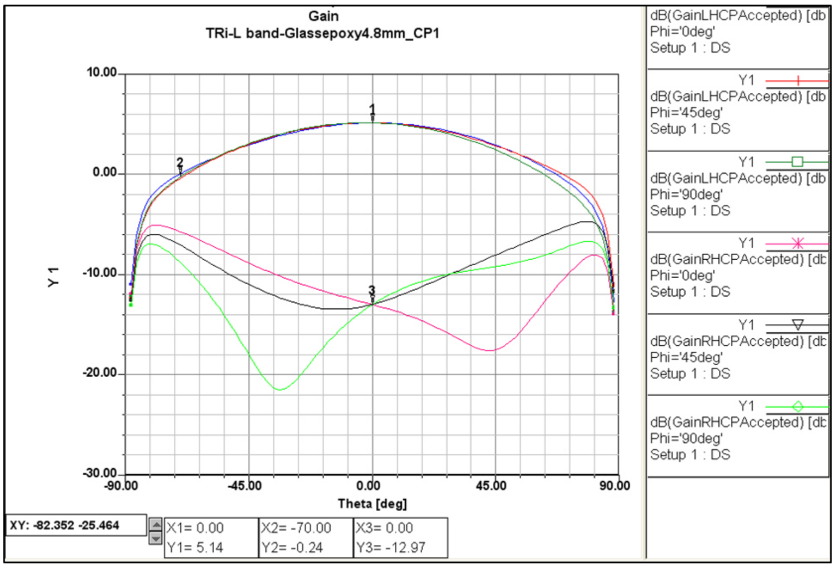

Figure 2.5: Gain Radiation Pattern

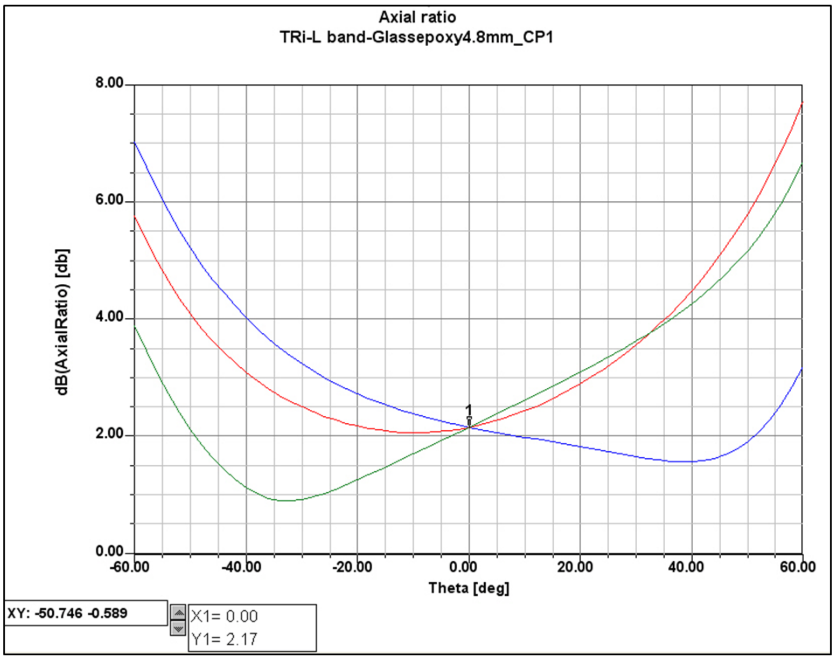

Figure 2.6: Axial Ratio

ing lower cursor points in the same Fig. 2.4. In this design the center frequency is 1.176 GHz but the measured center frequency using Vector Network Analyzer (VNA) becomes 1.226 GHz in case of air gap and

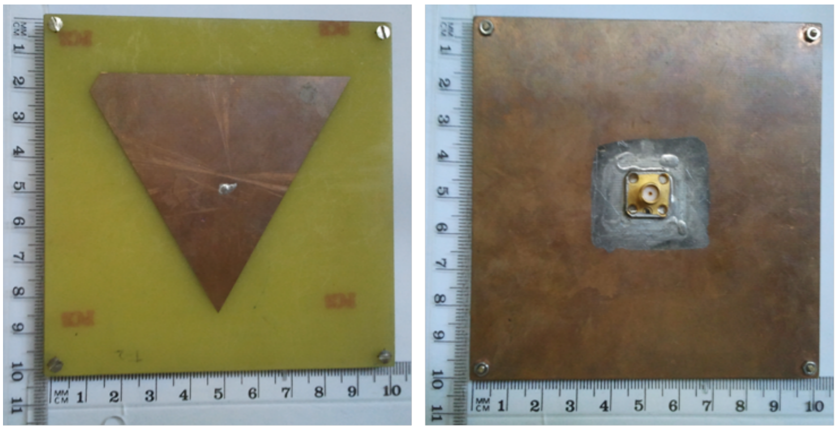

Figure 2.7: Developed 1.176 GHz Antenna: Left-Radiation face, Right-Ground face with 3mm via

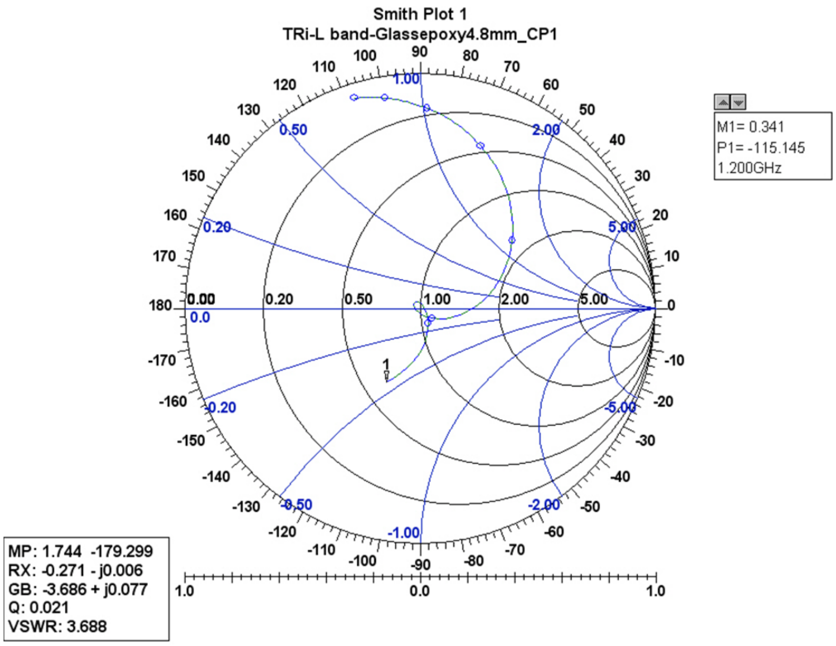

Figure 2.8: Simulated Impedance Plot of 1.176 GHz Antenna

1.221 GHz in case of adhesive, both of them are shifted toward the right. The possible reasons for center frequency shift and bandwidth are as follows.

- It has been considered that the solo thickness of the dielectric material should be 4.8 mm, but this desired thickness was not available. The substrate thickness available in the market was

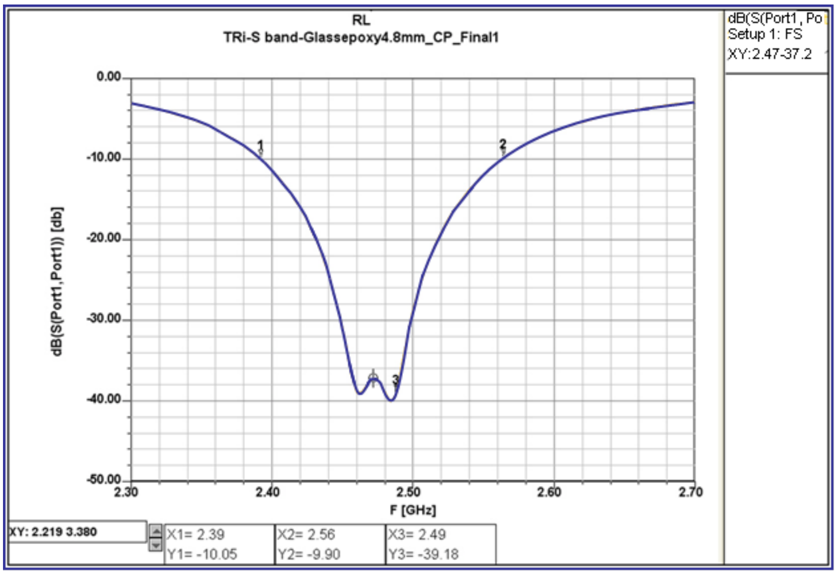

Figure 2.9: Simulated Return Loss

with 1.6 mm. Therefore three 1.6 mm sheets of glass epoxy are stacked together to get the desired specification.

- Another reason for frequency shift is that the effective dielectric constant must decrease due to insertion of some gaps among these three layers of glass epoxy.

In a similar way the return loss of the antenna is measured with the air gap in between the sheets of the glass epoxy, which is also shifted due to the change in the effective dielectric material of the antenna.

The simulated impedance plot, in Fig. 2.8 shows that there is a loop formation near 1.0, which explains that antenna is accurately matched, and inductive reactance is created by a change in thickness of actual hardware. The resonant frequency, i.e. 1.176 GHz, is at the nearest point in the loop that shows the usual behavior of the patch antenna. The measurement of smith plot for both adhesive and air gap instances 1.176 GHz antenna have been performed. The measured and simulated impedance plots are very close to each other.

From gain radiation pattern, shown in Fig. 2.5, it can be stated that the gain along the bore sight is around 5.14 dBi. The radiation pattern has been constructed for three different angles of Φ i.e. $0°$, $45°$ and $90°$, which gives the pattern appropriate to the specification. For the angle theta (θ) of $\pm 70°$ the gain pattern is reasonable. The axial ratio for the specified patch antenna is shown in Fig. 2.6. It has been shown that the

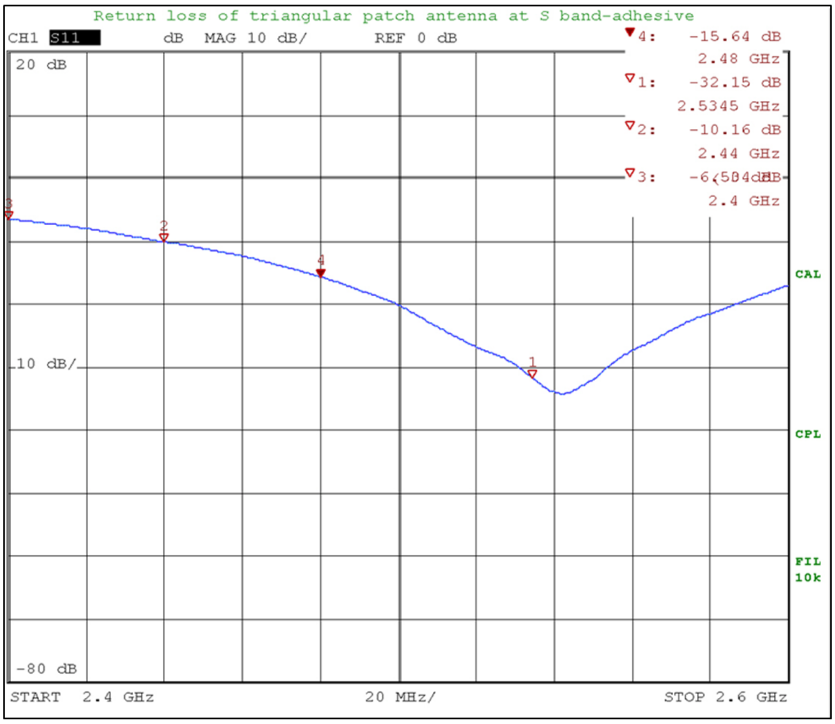

Figure 2.10: Measured Retun Loss using Adhesive

axial ratio is 2.17 dB and in practical case it should be less than 3 dB. Hence this also fulfills the requirement of the design. The actual 1.176 GHz antenna developed fulfilling the required specification showing its patch side where as the other side of the antenna has a coaxial probe, soldered with the patch through 3 mm via is shown in Fig. 2.7.

2.1.5 Simulated and Measured Results of 2.487 GHz Antenna

This section discusses simulated and measured results for 2.487 GHz antenna. As similar to 1.176 GHz antenna, it has been attempted to analyze the appropriate design parameters for this s-band antenna. Ansoft Designer has been employed to simulate the required specifications of the antenna. The following sections of the texts deal with the results in terms of return loss, bandwidth, smith plot, axial ratio and gain radiation pattern for this antenna.

(A) ***Outcomes***

Simulated return loss diagram is presented in Fig. 2.9 using RF design tool. This diagram shows that the antenna is resonating at 2.487 GHz

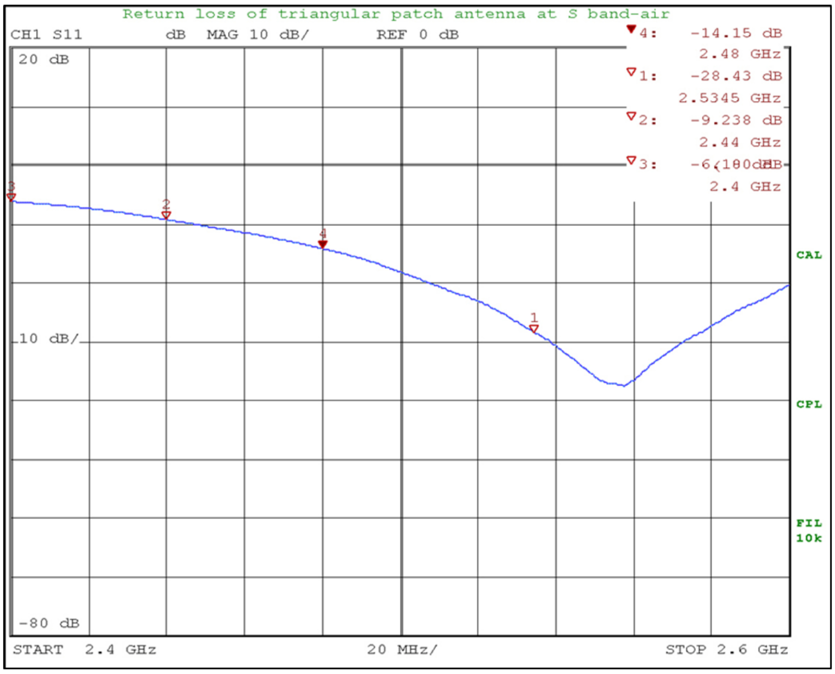

Figure 2.11: Measured Retun Loss using Air-Gap

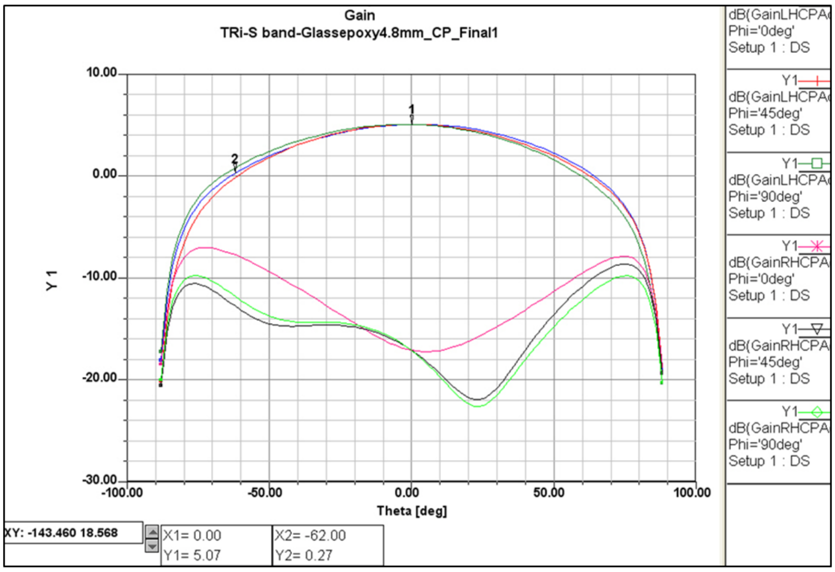

Figure 2.12: Gain Radiation Pattern

frequency and providing the suitable bandwidth of 170 MHz ranging from 2.39 GHz to 2.56 GHz at the level of 10 dB return loss. This

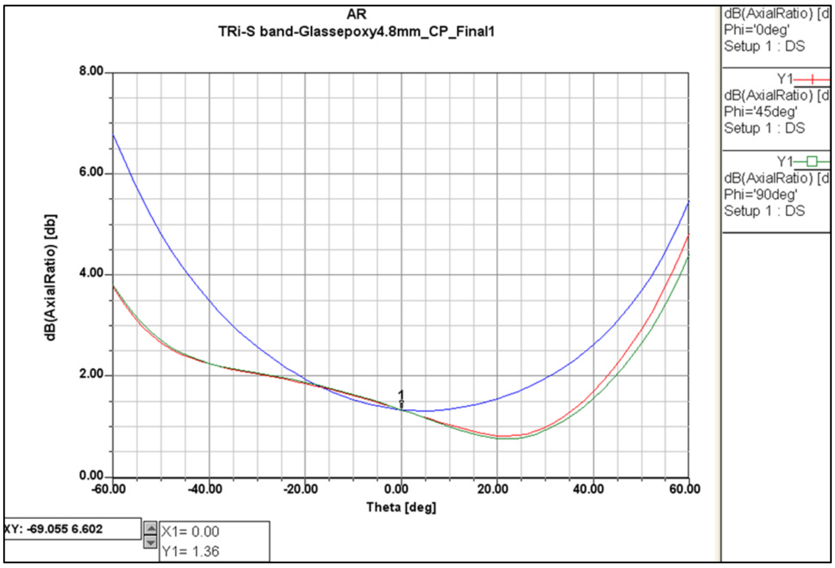

Figure 2.13: Axial Ratio

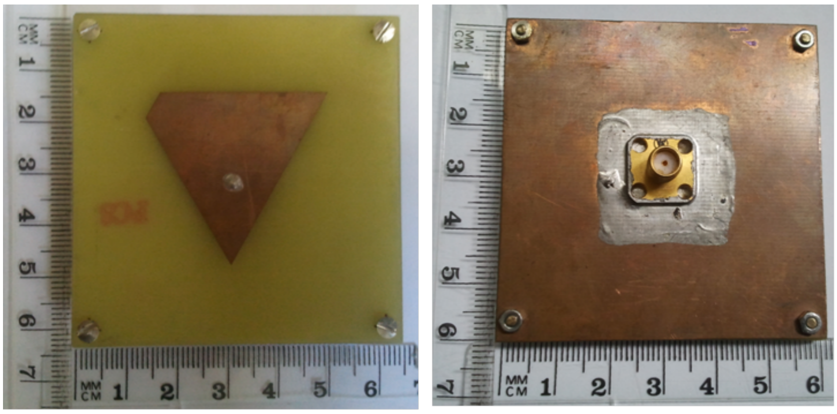

Figure 2.14: Developed 2.487 GHz Antenna: Left-Radiation face, Right-Ground face with 3 mm via

value of bandwidth is obtained after several iterations with optimized parameters in design. The measured return loss diagrams are shown in Fig. 2.10 and Fig. 2.11 in presence of adhesive and the air gap respectively. Again there is same problem for stacking the sheets of glass epoxy due to unavailability of 4.8 mm single sheet. This problem has been sorted out by stacking three sheets of 1.6 mm together using adhesive and using air gap in between the sheets. In both instances, the measurements have been carried out.

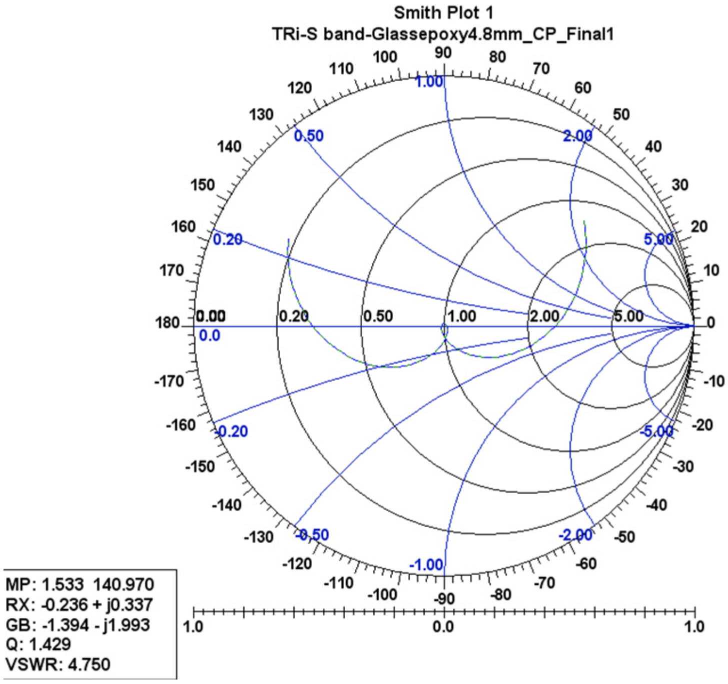

Figure 2.15: Simulated Impedance Plot of 2.487 GHz Antenna

(B) ***Results Analysis***

For 2.487 GHz antenna, Fig. 2.9 is showing that the antenna is resonating at 2.487 GHz corresponding to data cursor 3 where as data cursor 1 and 2 at the level of 10 dB providing a good bandwidth of approximately 170 MHz ranging from 2.39 GHz to 2.56 GHz. The measured return loss with adhesive and air gap has been shown in Fig. 2.10 and Fig. 2.11 respectively. In this design, the simulated center frequency is 2.487 GHz but the measured center frequency using Vector Network Analyzer is 2.5345 GHz, which is shifted toward the right. The possible reasons for center frequency shift and bandwidth are the same as in the case of 1.176 GHz antenna. Similarly the return loss of the antenna is measured with the air gap in between the sheets of the glass epoxy, which is also shifted due to the change in the effective dielectric material of the antenna.

The impedance plot for this antenna, in Fig. 2.15 show that there was a loop formation near 1.0, which explains that antenna is perfectly matched, and inductive reactance is created by a change in thickness of actual hardware. The resonant frequency, i.e. 2.487 GHz, is at the nearest point in the loop that shows the perfect behavior of the patch antenna. The measuring smith chart for both adhesive and air gap

2.487 GHz antenna have been performed. Here also the measured and simulated smith plots are nearly similar.

From gain radiation pattern, shown in Fig. 2.12, it can be stated that the gain along the bore sight is around 5.07 dBi. The radiation pattern has been manipulated for three different angles of Φ i.e. $0°$, $45°$ and $90°$, which gives the pattern appropriate to the specification. For the angle theta (θ) of $\pm 62°$ the gain pattern is reasonable. The axial ratio for the specified patch antenna is shown in Fig. 2.13. It has been shown that the axial ratio is 1.36 dB and in practical case it should be less than 3 dB. Hence this also fulfills the requirement of the design. Fig. 2.14 is the actual 2.487 GHz antenna developed fulfilling the required specification showing its patch side where as the other side of the antenna has a coaxial probe, soldered with the patch through 3 mm via.

2.1.6 Fabrication Process

The antenna artwork has been composed using a software tool, AutoCAD 2010. Here, the whole fabrication process flow is presented briefly. The photo-etching process utilizes the final schematic constructed in AutoCAD 2010. Following steps have been carried to perform the etching process.

- Cutting and lamination as per antenna layout
- Scanning and making film for desired pattern of the layout on the laminate.
- Etching process where the scanned laminate use chemical liquid to wipe off the unwanted copper area.

The fabrication process begins with the final layout of 1.176 GHz triangular patch and 2.487 GHz triangular patch designed using simulation software tool. This layout is exported to the AutoCAD in dxf format, as this format of layout can easily be readable by film making machine. This machine changes the dxf format into the gbx (gerbar) format and the resolution of the machine was set to 10000 dpi. The machine is capable of producing the film up to 20000 dpi and it utilizes the transparent photo plotter film of size 24 inch by 28 inch. The machine is capable of printing copper patch on the glass epoxy substrate using subtractive printing methodology. Presently several additive printing technology and equipments are available in market.

Then the film was sent to fabrication where etching, rinsing, scrapping and drying processes were carried out. The 50 ohm SMA is the soldered at the feeding point of the fabricated antenna. The complete fabrication process is shown in Fig. 2.16.

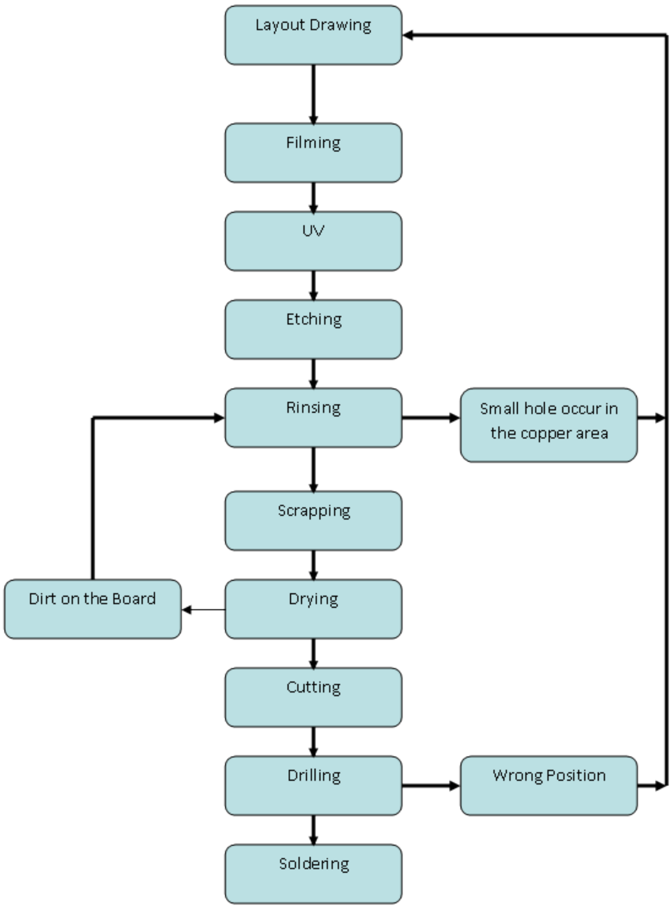

Figure 2.16: Fabrication Process

2.1.7 Measurement

The testing and evaluation of the antenna parameters are performed. The measurement refers to the testing of the printed antennas is to ensure that their parameters meets the specifications. Typical parameters of antennas are gain, radiation pattern, beam width, polarization, and impedance. The measured parameters and their values for both 1.176 GHz and 2.487 GHz antennas are shown in Table 2.2 and Table 2.3 respectively. The cause of shifting the resonant frequencies in both the antennas are explained in the sections 2.1.4 and 2.1.5.

Table 2.2: Measurement of 1.176 GHz Antenna

S.N.	Parameters	Value	unit
1.	Measured Center Frequency	1.21	GHz
2.	Retun Loss (Adhesive)	Better than 10 dB	
3.	Return Loss at 1.176	3.3	dB

Table 2.3: Measurement of 2.487 GHz Antenna

S.N.	Parameters	Value	unit
1.	Measured Center Frequency	2.53	GHz
2.	Retun Loss (Adhesive)	Better than 10 dB	
3.	Return Loss at 2.487	3.1	dB

2.2 Multi-band Fractal Antenna Design

A recent trend shows that there is a need for a multi-band antenna to diminish the space usage and cost instead of using one antenna for each specific system. Modern telecommunication system requires antennas having multi-band characteristics, wider bandwidths and smaller dimensions than conventionally possible. This has initiated antenna research in several directions, one of which is using fractal structure in antenna elements. In recent years several fractal geometries have been introduced for antenna applications with varying degree of success in improving the antenna characteristics such as reducing size of the antenna, capable of resonating at multiple frequencies.

2.2.1 Generations of Fractal Structures

At the outset, it is important to define fractal structure in context of this work. A fractal structure is a curve or a geometric figure, each part of which is self-similar to the whole. This part of work introduces the method of generating classical fractals such as Koch Curve, Sierpinski Carpet and Sierpinski Gasket with extensive use MATLAB code and its versatile engineering and graphical features. These fractal structures are generated normally on basis of number of iteration cycles. As number of iterations increases, size of the structural details become tiny compared to resolution of the screen. The structures of Koch Curve, Sierpinski Carpet and Sierpinski Gasket made with four iterations are shown in Fig. 2.17 (a), (b) and (c) respectively.

The Sierpinski gasket structure is chosen among all other classical structures due to its resemblance with equilateral triangle microstrip antenna

(ETMSA). The method of generating this structure is to develop the equilateral triangle with the specified length and another inverted equilateral triangle is made by the joining the mid points of the sides of the former triangle and being subtracted from the earlier one.

Besides the fractal geometry itself, the parasitic elements play an important role in fractal antenna design. The parasitic elements act as resonators and couple electromagnetically with the driven element, and serve to modify the radiation pattern of the antenna, directing the radio waves in one direction, increasing the gain of the fractal antennas.

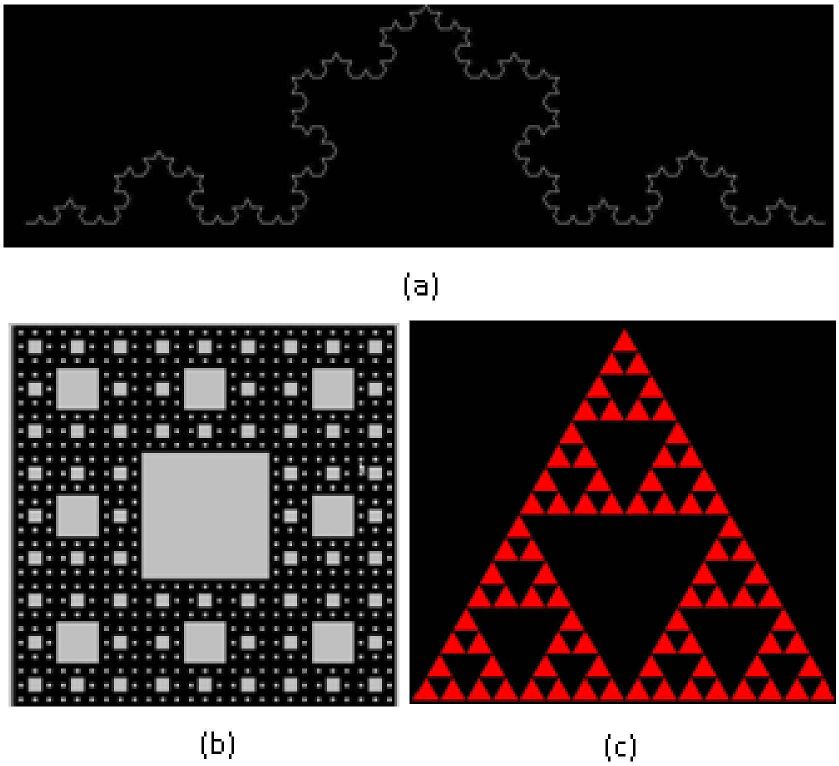

Figure 2.17: (a) Koch Curve (b) Sierpinski Carpet (c) Sierpinski Gasket

2.2.2 Design of Dual Band Fractal Antenna

The specifications of the dual band fractal antenna are shown in Table 2.4. The parameters in the table are as per communication link between the transmitter and receiver. The design of dual band sierpinski fractal antenna consists of three different steps: dimension determination, planer EM design and setting the probe position. The dimensions of the parasitic layers are determined using equations (2.1), (2.2) and (2.3)[12]-[14]. To achieve the

Table 2.4: Specifications of Dual Band Fractal Antenna

S.N.	Parameters	Values
1.	Frequency Bands (L and S band)	1.16-1.19 GHz and 2.46-2.50 GHz
2.	Gain	-4 dBi up to ±50°
3.	Axial Ratio	3 dB
4.	Polarization	LHCP
5.	Return Loss	Minimum -10 dB
6.	3 dB Beam width	±50°

design specification, the glass epoxy and rogers RO3003 have been used as substrates whose relative dielectric constants (ε_r) are 4.4 and 3.0 respectively.

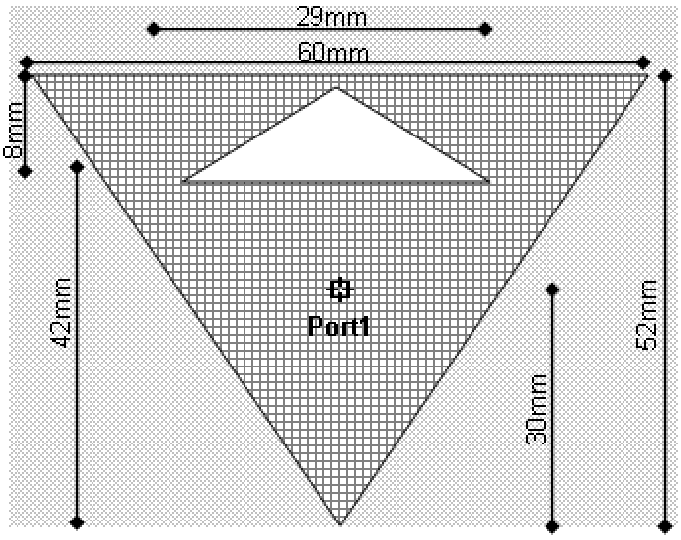

Figure 2.18: Active Patch Layout of Fractal Antenna

(A) ***Dimension Determination***

The dimensions of layers of the fractal antenna are determined using equations (2.1)-(2.3). Several optimizations have been carried out to obtain the specified characteristics of the fractal antenna. The dual frequency behavior is obtained through the perturbation of the classical Sierpinski via a reduction of the fractal iteration and a modification of the scale properties. The inner triangular slot controls the frequency ratio and maximum coupling is achieved by proper dimensioning of the lower patch. Fig. 2.18 illustrates bottom layer while Fig. 2.19 (a) and (b) show the dimensions of the middle layer and the upper parasitic layer patches respectively.

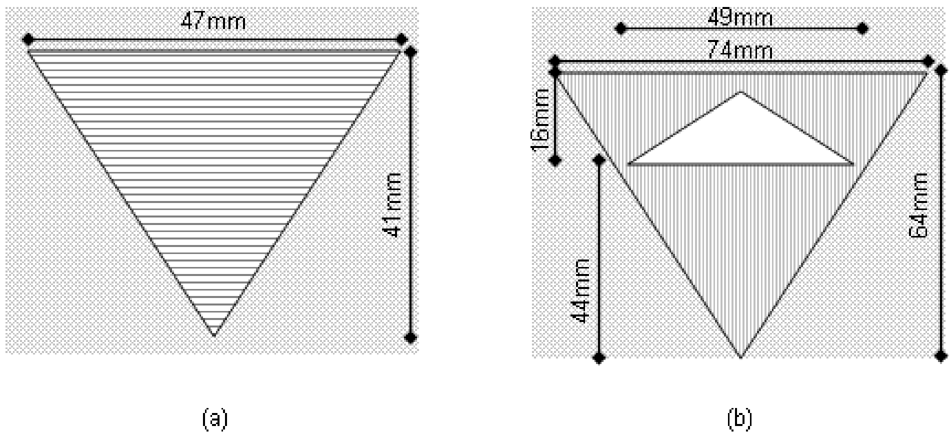

Figure 2.19: (a) Lower Parasitic Patch (b) Upper Parasitic Patch

Table 2.5: Layers of the Fractal Antenna

S.N.	Layers	Type	Material	thickness (mm)	Lower Elevation (mm)	Upper Elevation (mm)
1.	Parasitic patch 2	Signal	Copper	0	16.62	16.62
2.	Substrate 5	Dielectric	Glass Epoxy	0.8	11.32	16.62
3.	Substrate 4	Dielectric	Air (foam)	4	11.32	15.82
4.	Parasitic patch 1	Signal	Copper	0	11.32	11.32
5.	Substrate 3	Dielectric	Glass Epoxy	0.8	10.52	11.32
6.	Substrate 2	Dielectric	Air (foam)	10	1.52	10.52
7.	Active patch 2	Signal	Copper	0	1.52	1.52
8.	Substrate 1	Dielectric	Rogers RO3003	1.52	0	1.52
9.	Ground	Metalized Signal	Copper	0	0	0

(B) ***Planer EM Design***
The planer EM design elaborates each cumulative layers beginning from ground to parasitic patch 2. The layers of the fractal antenna and their width are illustrated in Table 2.5. The planer EM design specifies how several layers are stacked to each other.

(C) ***Probe Position***
The probe position is set to co-ordinate (0, 33) to get the desired specification. Port 1 is the probe position shown in Fig. 2.18. During several optimization cycles it is found that this probe position gives the suitable characteristics impedance and matching with the input impedance of the antenna.

2.2.3 Simulated and Measured Results

Fig. 2.20 presents return loss diagram analyzed using Ansoft designer tool. It shows that the antenna is simultaneously resonating at 1.76 GHz and 2.85

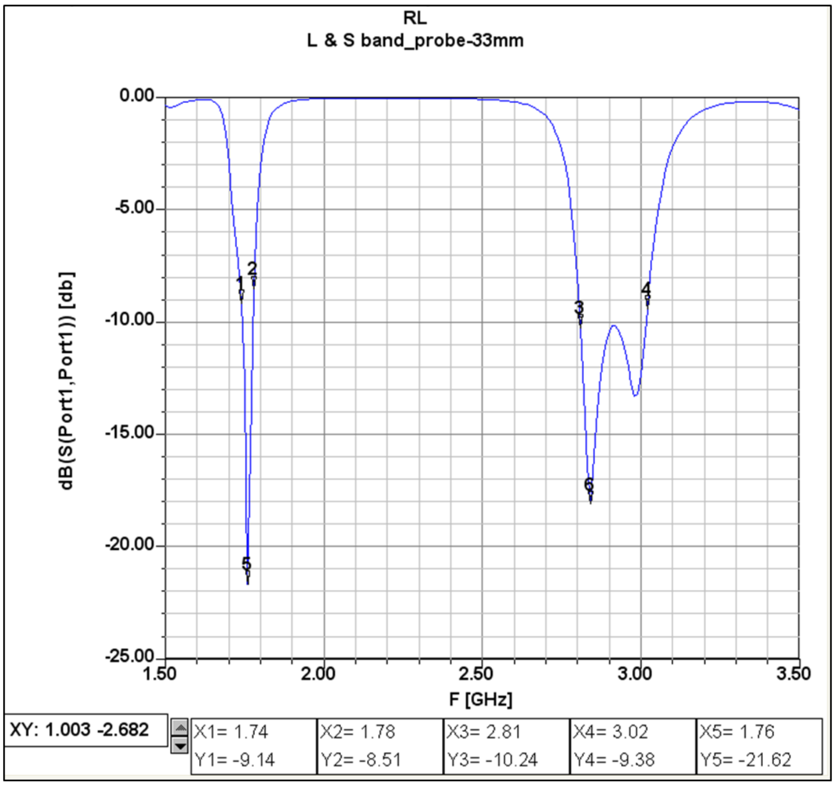

Figure 2.20: Simulated Return Loss of Dual Band Fractal Antenna

GHz. Moreover, it provides an appropriate bandwidth of 40 MHz ranging from 1.74 GHz to 1.78 GHz and 210 MHz ranging from 2.81 GHz to 3.02 GHz respectively in L and S band. These values of bandwidths are obtained after several iterations by optimizing the parameters in the design. The measured return loss diagram is shown in Fig. 2.21. One can notice that the developed antenna is resonating at 1.73 GHz and 2.94 GHz generating a significant bandwidth in both the bands. This result has been measured with vector network analyzer. Simulated and measured Impedance plots and gain radiation patterns in L and S band are shown in Fig. 2.22, Fig. 2.23, Fig. 2.24 and Fig. 2.25 respectively.

2.2.4 Results Analysis

The simulated results for mono-band antennas have already been discussed in sections 2.1.4 and 2.1.5 respectively. In this section, we are going to discuss the analysis and the comparative performances of simulated and measured antenna parameters. The simulated bandwidths in L band and S band are found to be 40 MHz and 210 MHz respectively. These acquired

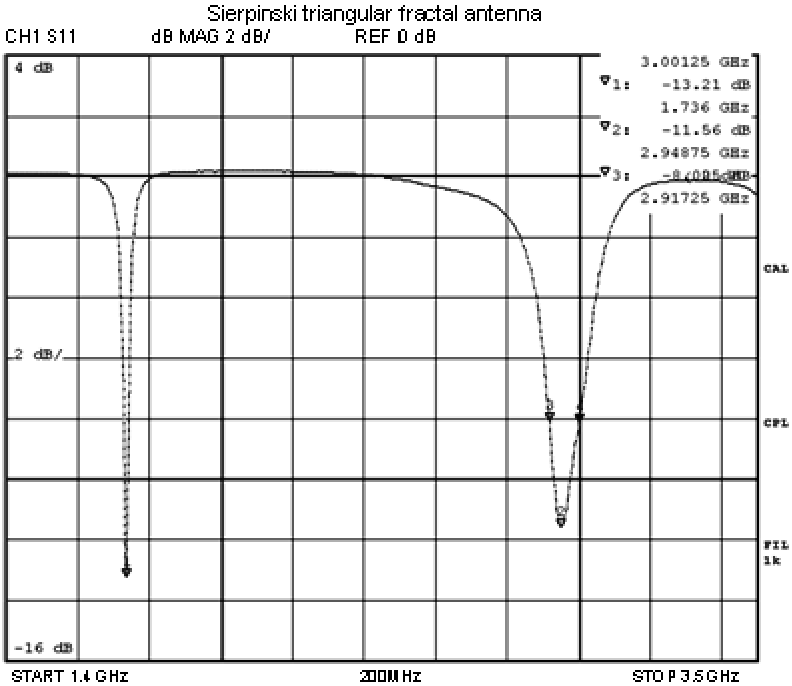

Figure 2.21: Measured Return Loss of Dual Band Fractal Antenna

bandwidths fulfill the desired characteristics of the antenna as per the specification in Table 2.4. The bandwidth of the fabricated antenna is measured with vector network analyzer. Fig. 2.20 illustrates appreciable bandwidth in both bands. Fig. 2.22 and Fig. 2.23 respectively show the simulated impedance plots simulated with Ansoft Designer and measured impedance plot with vector network analyzer. These plots clearly show that there is formation of a loop near unity. This implies impedance matches.

From gain radiation pattern shown in Fig. 2.24 and Fig. 2.25, it can be stated that the gains along the bore sight are respectively 7.59 dBi in L band and 2.17 dBi in S band. The radiation pattern is drawn for three different angles of Phi i.e. 0°, 45° and 90°, which gives the pattern appropriate to the desired specification of the antenna. For dual band, Fig. 2.26 is showing three layers of fractal antenna. These layers are active patch, lower parasitic patch and upper parasitic patch. Active patch is fabricated on Rogers RO3003 dielectric material where as lower and upper parasitic patches are fabricated on glass epoxy substrate. The measured resonant frequencies of the fractal antenna are 1.736 GHz and 2.95 GHz in L and S band respectively. It has been noticed that there is a gap between simulated and measured frequency. The shifting of frequency to the right from 1.176

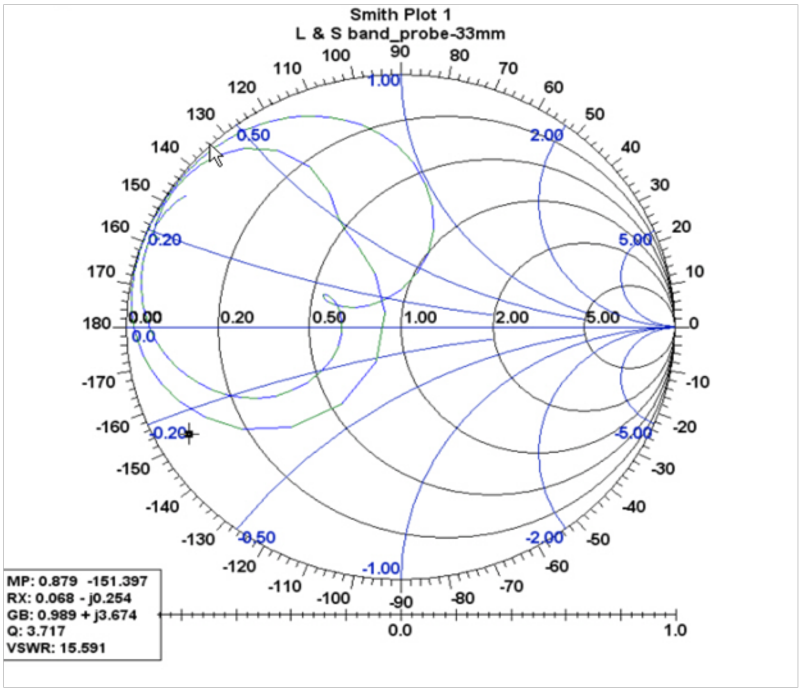

Figure 2.22: Simulated Impedance Plot

GHz and 2.487 GHz is due to the following reasons:

- Stacking of the layers is not ideal
- The effective dielectric constant must decrease due to insertion of some gaps among these three layers of glass epoxy.
- Substrate 2 and substrate 4 are made up of white foam. Their ideal thicknesses are 10 mm and 4 mm respectively. As their thicknesses are not uniform, it causes change in dielectric constant.

Fig. 2.27 is the actual dual band Sierpinski fractal antenna developed fulfilling the required specification. The figure shows its active patch side where as the other side of the antenna has a coaxial probe, soldered with the patch through 3 mm via. As glass epoxy substrate material is used, the cost of the antenna is low. The stacked patches construct the structure of antenna compact.

2.3 Chapter Summary

The research results reveal that successive and iterative optimization on the parameters of microstrip antenna leads to achieve the required performances

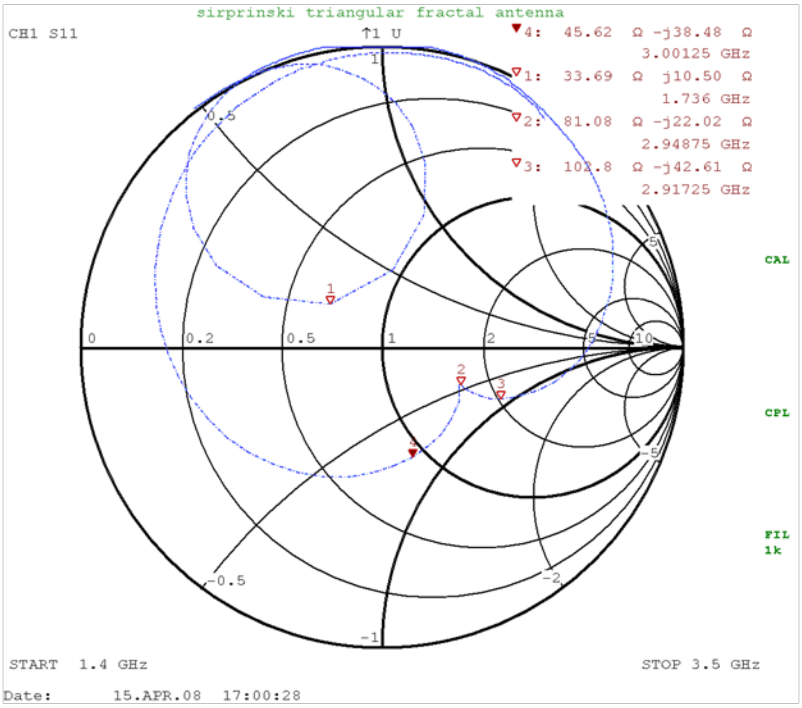

Figure 2.23: Measured Impedance Plot

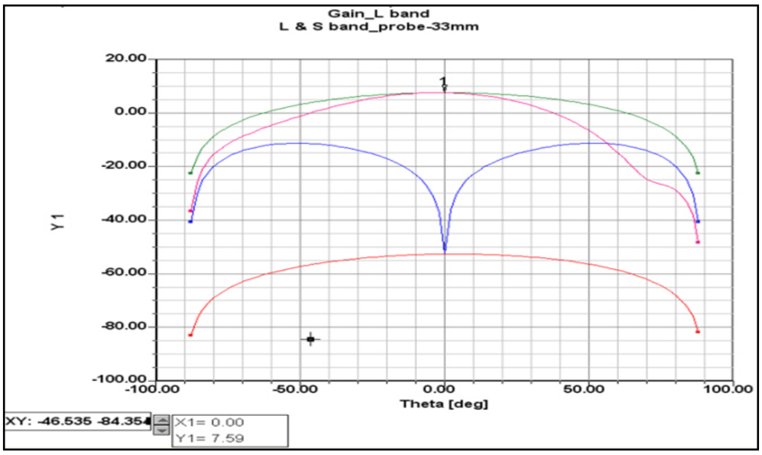

Figure 2.24: Gain in L band

suitable for specific applications. We performed the modelings based on glass epoxy as a substrate material and copper as a radiating patch. The measured performances such as return loss, frequency of operation, bandwidth and axial ratio have the similar characteristics as of obtained theoretically using simulating tool. We have found slight shift in the frequencies due to stacking

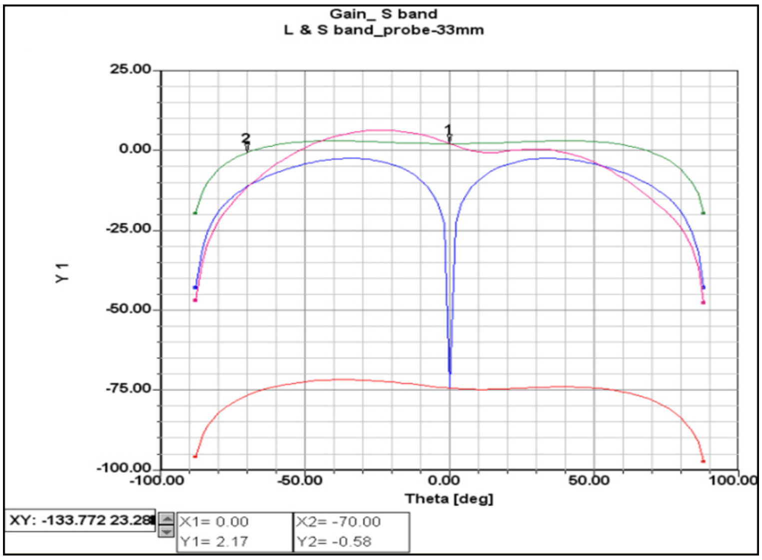

Figure 2.25: Gain in S band

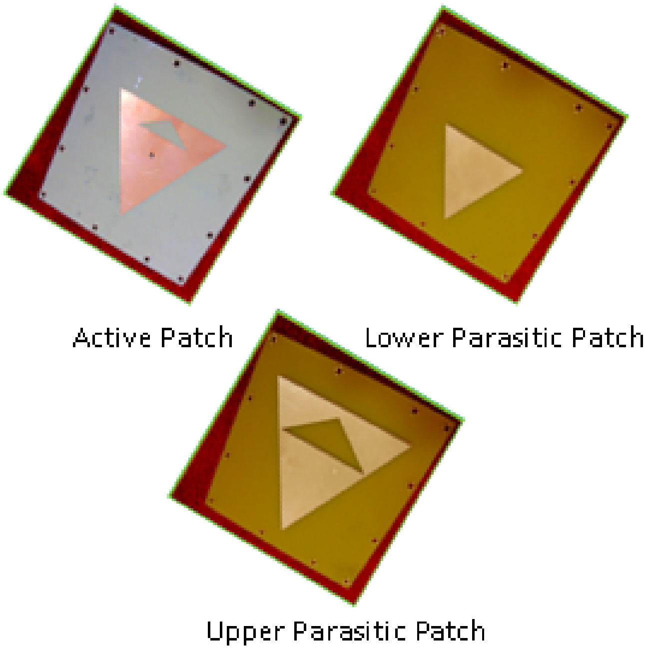

Figure 2.26: Layers of Fabricated Fractal Antenna

of the glass epoxy sheets. The gain radiation pattern has been measured and found better than expected. This research has made possible to fabricate an antenna satisfying the required specifications and allowing us to create a

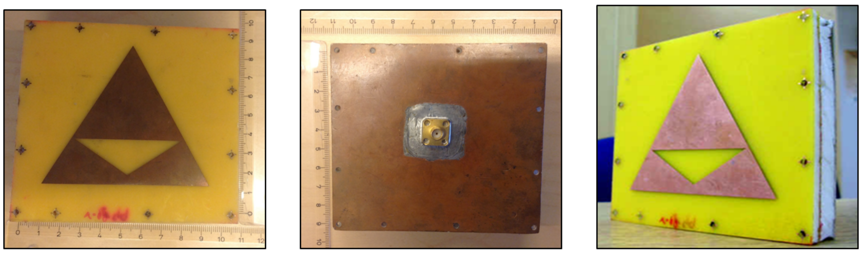

Figure 2.27: (a) Radiating Patch View (b) Ground Coaxial Probe View (c) 3D View

compact and low cost tip truncated triangular antenna as well as dual band fractal antenna.

The first important future work is to reflect on optimization of technology. We have considered subtractive printing methodologies for satellite navigation based applications and investigated different design aspects for printed antenna. Therefore first important future work is to analyze several printing methodology for such antenna technology and evaluate their environmental impacts and resources utilized in both the technologies. Another imperative future work is to improve the efficiency of the designed antenna using latest numerical techniques and recent electromagnetic modeling tool. Finally, it would be worthwhile to examine the role of copper traced printed antennas and to explore its environmental emissions during manufacturing process.

Chapter 3

Metamaterial Based and Electronically Tunable Printed Antennas

The successful design and fabrication of two separate L and S band microstrip printed antennas and the development of Sierpinski dual band fractal antenna has motivated to carry out further study on electromagnetic band gap behavior of metamaterial and electronically tuned circular polarized printed antennas. Metamaterial antenna are a class of antennas which use metamaterials to increase electromagnetic performance over normal structures. Metamaterials are the artificial composite materials engineered to produce desired electromagnetic behavior. In this chapter, the design and performance analysis of metamaterial based and electronically tunable printed antennas are described.

Metamaterial structures are used in slotted microstrip antennas and mobile handset applications to increase the efficiency and enhance return loss characteristics. It is an acknowledged investigation that traditional microstrip antennas have inferior signal bandwidth quality. An antenna, employed with slotted ground plane patch, is proposed in which electromagnetic band gap structure is created using a metamaterial substance above the ground plane. This configuration of the antenna structure usually reduces surface wave losses. The desired characteristics for such antenna configuration are utilizing them in mobile communications at two frequency bands namely UMTS band (2067 to 2245 MHz) and ISM band (2390 to 2795 MHz), whereas antennas using EBG (Electromagnetic Band Gap) structure can be operated at multi (three) frequency bands covering GSM, UMTS and ISM bands. The patch size of this antenna included with EBG structure is relatively small and is compatible with circuit board integration as well as all three frequency bands.

In the second part of this chapter, an electronically tuned circular patch antenna is proposed that holds a good radiation pattern and excellent electromagnetic performance. Here our attempt is to design a patch antenna that has predictable and achievable tuning range. Electronic tuning potentiality is achieved by coupling a varactor diode along with the antenna that alters the capacitance of the patch and hence the resonant frequency. Although this antenna has a low bandwidth, electronic tuning allows it to cover larger band and also maintaining the same narrow band operational characteristics. RT-duroid 5880 substrate ($\varepsilon_r = 2.3$) with thickness of 0.8 mm is used for this specific design. The performance of the proposed antenna is evaluated by comparing the results.

3.1 Scopes and Approach

Microstrip patch antennas have been widely used in satellite communication, aerospace, radars, biomedical and navigational applications, and in reflector feeds because of their advantages for being low profile, light weight and compatible with integrated circuits. Traditional antennas have a number of drawbacks such as low bandwidth, larger size, less efficient and not easily compatible with microwave integrated circuits. These are important design considerations need to be taken into account for robust and practical RF applications. The size of antenna is extremely important over other characteristics because most ordinary developed antennas are bulky in size and are incompatible with emerging compact mobile devices. There are limits to how small an antenna can be, however the most important features are return loss, gain radiation and the bandwidth. The size and weight of mobile handsets have rapidly been miniaturized due to the development in modern integrated circuit technology and the requirements of the users. Conventional monopole-like antennas have remained relatively large compared to handsets itself. Thus, built in antennas are becoming very promising candidates for mobile and handheld applications. Most built in antennas currently used in mobile phones are based on planer inverted F antennas (PIFAS).

The popularity of these antennas are increasing in wireless applications due to their low profile structures. They can be easily integrated on the circuit board of a communication device to reduce the packaging cost [25],[11]. Therefore they are extremely compatible for embedded antennas in hand held wireless devices such as cellular phones, pagers, laptops, tablet personal computers, personal digital assistants, etc. [26]-[28]. The telemetry and communication antennas on missiles need to be thin and conformal and are often planar antennas [29]-[30]. Smart weapon systems use planar antennas because of their thin structural profile [11]. Radar altimeters use small array of planar antennas. Another area where they have been used successfully is in satellite communication [31]-[34] and in satellite imaging systems [11]. To overcome the multipath fading problem and to enhance the system performance, novel planar antenna designs for achieving broad band circular polarization and dual polarized radiation in WLAN band are demonstrated in [25] and [33]. Planar antennas are also commonly used in remote sensing, biomedical applications and in personal communication systems.

In the first part of this chapter, we are going to discuss a new, relatively simple technique for PIFA to achieve both bandwidth enhancement and size reduction. A few decades ago, Veselago [35] introduced the concept of DNG (negative epsilon and negative mu, also known as double negative-DNG) materials and postulated several interesting applications of such materials, such as focusing and anomalous refraction [36]. However, there were little activities in the area of such materials for quite some time, since DNG materials were not readily available in nature, especially toward microwaves circuit design. This in turn, led the researchers to search for artificial dielectrics also known as metamaterials because they may not be found in nature. Many new technologies [37]-[40] have emerged in the modern antenna design state-of-the-art and one exciting breakthrough is the discovery and development of electromagnetic band gap (EBG) structures. In the following sections, we begin by critically examining the claims regarding the role of metamaterial or EBG in enhancing the properties of antenna such as directivity enhancement and return loss value.

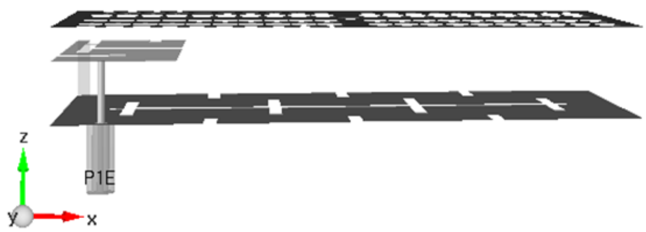

Figure 3.1: Side view of antenna with slotted plane and with EBG Structure

3.2 Metamaterial Based Antenna

The side view of slotted patch antenna is shown in Fig. 3.1. The antenna is designed in a way that it resembles three layers; slotted ground, mid layer and EBG structure. The geometry and dimensions of the proposed microstrip antenna for both mid layer patch and slotted ground plane are demonstrated in Fig. 3.2 (a) and (b) respectively. This antenna is designed

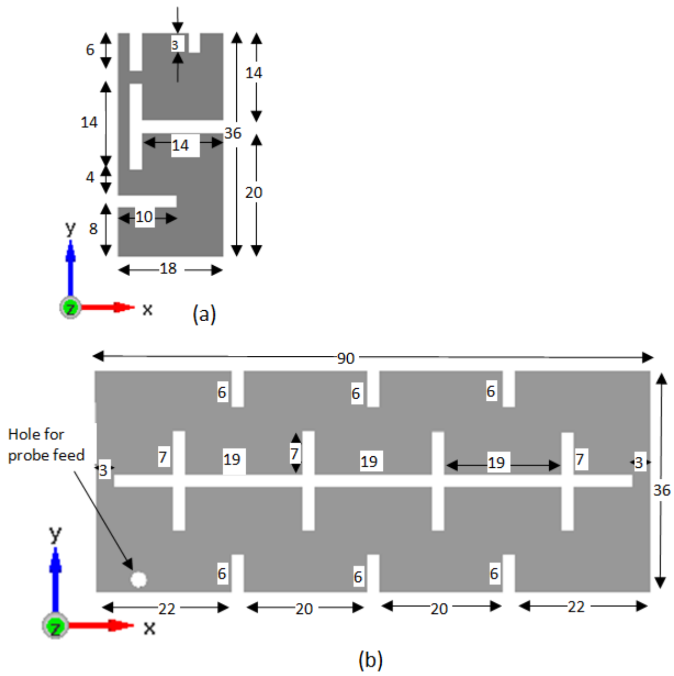

Figure 3.2: Dimensions of top view of (a) Upper Patch of four equal cell slotted antenna (b) Ground plane of Patch Antenna

to operate at two frequencies 2.14 GHz and 2.76 GHz, hence being suitable for WLAN applications. The antenna has two radiating patches on the top with a single via strip which provides electrical connection between ground and two upper patches.

Here we consider air as a substrate material with overall dimension of 90 mm×36 mm×9 mm and a flat copper of thickness 0.1 mm for fabricating the entire layers of the antenna. The thickness of the EBG structure is also considered as 0.1 mm and its dimensions are 90 mm×36 mm. There is a circular air gap of radius 2 mm in the center of rectangular EBG structure, which is mounted 20 mm above the ground plane.

Each type of antenna has a mechanism to feed the signal into it for transmission. In this case we devise a thorough hole, also known as via, is inserted on the surface of the patch for connecting probe feed. By hit and trial method, the position of the feed point is selected so that an excellent impedance match has achieved. The optimization process for choosing the feed point and the dimensions of the proposed antenna takes several iterations to execute. In each iteration, the impedance match, polarization and bandwidth are examined. The optimized dimensions for the proposed antenna, shown in Fig. 3.2, are obtained after several iterations and this particular dimension matches with the requirement. The proposed slotted antenna resonated at two frequency bands 2.14 GHz and 2.75 GHz is designed using planer copper sheet of thickness 0.1 mm with air as substrate of thickness 9 mm. In this design shorted via is at one edge which is 2 mm wide as shown in Fig. 3.1. The probe feed of radius 1 mm is relatively located at the position (-38,-16) if center of antenna is taken as origin.

3.2.1 Parametric Study

In the following section, parametric study is carried out. Various parameters such as patch height, fed location and equal cell slots variation at ground plane are explored. In each case, diagrams are plotted to describe the possible phenomena.

(A) ***Variation in Patch Height***

In Fig. 3.3, frequency versus return loss diagram is displayed with

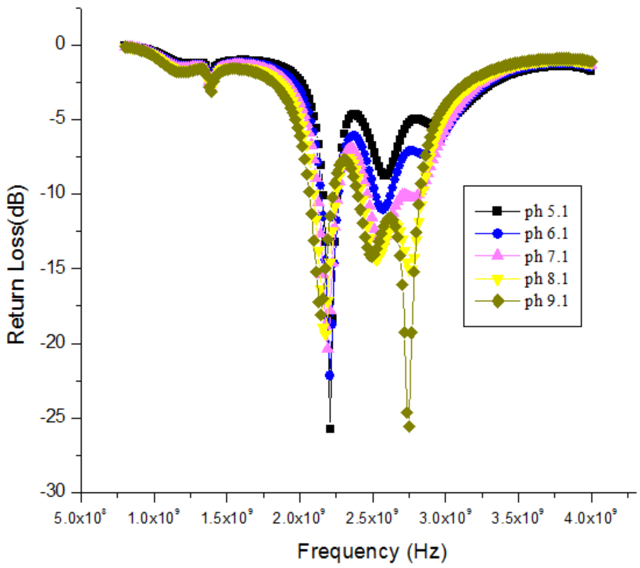

Figure 3.3: Graph compared with variations in patch height(ph) and feed location (-38,-16) with four equal cell slots at ground place

different antenna patch heights variation. It is clearly demonstrated that by configuring four equal cell slots at ground plane and positioning feed location at (-38,-16), where center of antenna plane is taken as the origin, two distinct resonant frequencies with sufficient bandwidths are obtained for higher value of patch height. From this comparative chart we can conclude that patch height of 5.1 mm have lowest return loss value of -25.75 dB at resonant frequency of 2.21 GHz while patch

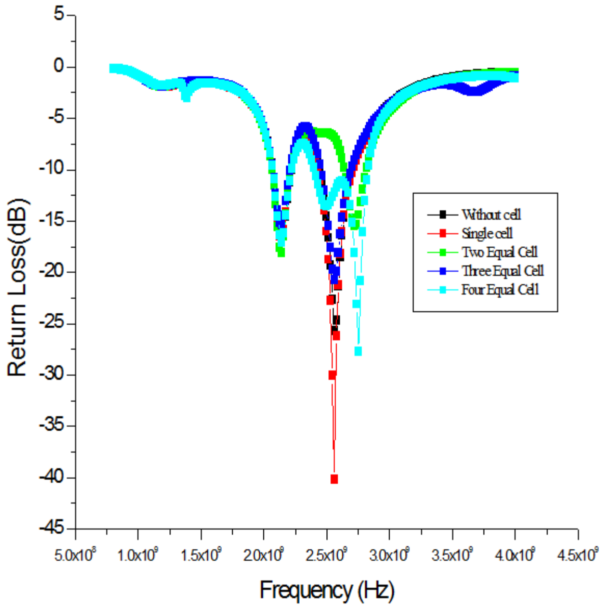

Figure 3.4: Graph showing variation in number of cell slots at ground place with with feed location (-38,-16) keeping patch height 9.1 mm

height 9.1 mm have the highest bandwidth of 428 MHz at the resonating frequency 2.75 GHz.

(B) ***Variations in Number of Cell Slots on Ground Plane***
The frequency band versus return loss (dB) with the variation of cells number at ground plane having feed point location at (-38,-16) and keeping the antenna patch height of 9.1 mm is illustrated in Fig 3.4. The parametric analysis for number of cell slots in Fig. 3.4, explicitly shows that with single cell at ground plane have lowest return loss value -40.15 dB. It is also evident that with four equal cell slots at the ground plane causes reasonable return loss value of -28 dB. The two and three cell slots configured at ground plane gives return loss values less than -22 dB.

(C) ***Variations in Feed Location***
Here we have attempted to optimize the feed location with four cell slots configured at ground plane having patch height of 8.1 mm. The comparative graph is shown in Fig. 3.5. We can demonstrate that while arranging the feed location at (-40,-16) in the ground plane where center of ground plane is taken as the origin have lowest return loss value of -29.99 dB. At this feed location point, two distinct and desirable resonant

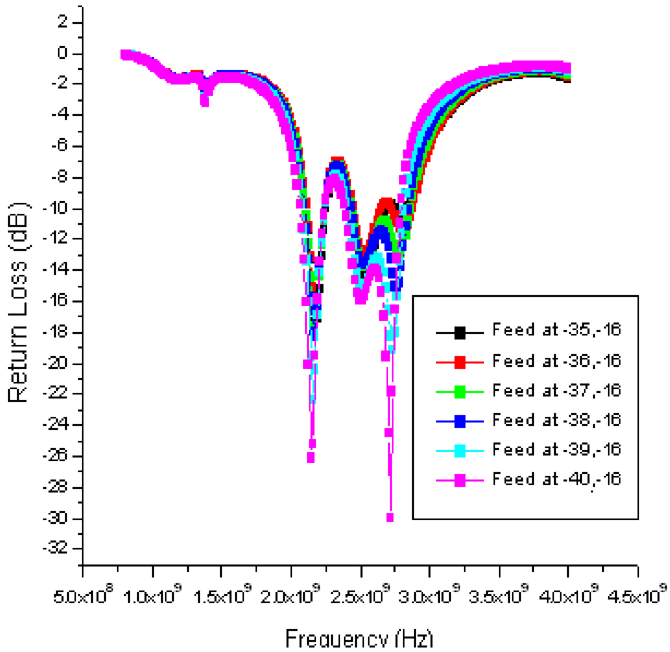

Figure 3.5: Graph showing variation in feed location with four cell slots at ground plane with patch height 8.1 mm

frequencies are obtained. Another important parameter, bandwidth in case of feed location (-37, -16) are found to be 425 MHz which is the greatest value among all other configurations.

3.2.2 Antenna Using EBG Structure

As we have discussed earlier, the insertion of EBG structure into the layers of patch antenna enhances the electromagnetic behavior. The antenna using EBG structure is shown in Fig. 3.1 and Fig. 3.2. In this section we are going to discuss the performance analysis of the antenna using EBG structure and without using EBG structure.

At first, we have simulated the return loss of the antenna as shown in Fig. 3.6. with four equal cell slots at ground plane, with patch height of 9.1 mm and with feed location at (-38,-16). The comparison of return loss values with and without EBG structure are displayed. It is evident from the Fig. 3.6 that with EBG structure set above ground plane generates return loss value of -32.60 dB while without EBG structure, the return loss value is found to be -30.44 dB. The antenna that utilizes EBG structure is capable of resonating at three distinct frequencies of 830 MHz, 2.12 GHz and 2.81 GHz which covers GSM 800, UMTS and ISM bands where as antenna without EBG structure shows only two resonant frequencies 2.14 GHz and

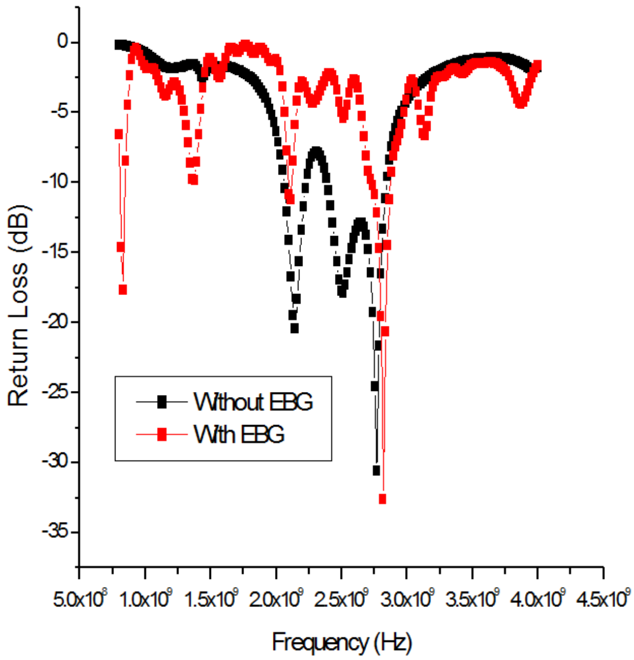

Figure 3.6: Graph showing variation in feed location with four cell slots at ground plane with patch height 8.1 mm

2.75 GHz covering UMTS and ISM band. Hence using EBG structure inside the antenna makes it more efficient than the conventional antenna.

It is a known fact that EBG structures in an antenna suppresses the surface waves and gives a better electromagnetic performance. The directivity and gain radiation pattern of the antenna are shown in Fig. 3.7 and Fig. 3.8 respectively. The antenna with EBG structure is more directive than without EBG. The simulated result illustrated in Fig. 3.8 clearly demonstrate that the performance in terms of gain radiation pattern for the EBG antenna has higher value of gain than antenna without EBG. For both the simulations, four cell slots at ground plane and patch height 8.1 mm are considered.

3.3 Design of Electronically Tunable Antenna

In the section, we will be discussing electronically tuning behavior of the circular patch antenna. The considerable increase in the demand of small size, light weight, high performance, low cost, low profile and inexpensive to manufacture using modern printed-circuit technology [41] has raised the usage of patch antennas in different RF applications. Patch antenna is one of most promising candidate for various communication systems. These an-

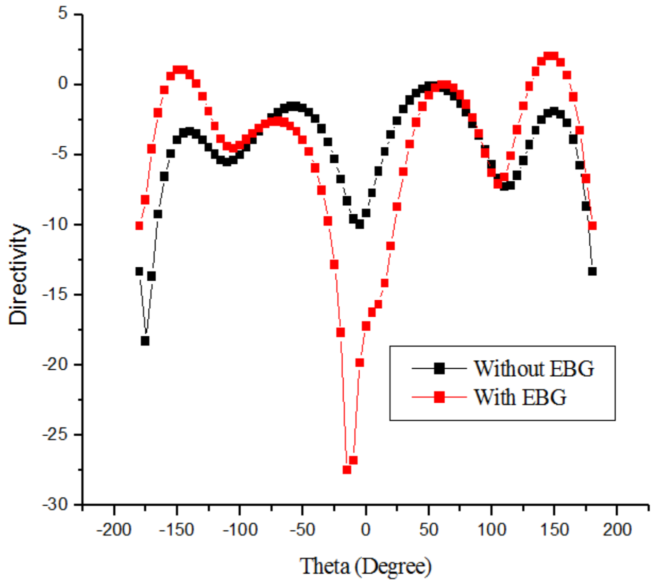

Figure 3.7: Graph showing variation in feed location with four cell slots at ground plane with patch height 8.1 mm

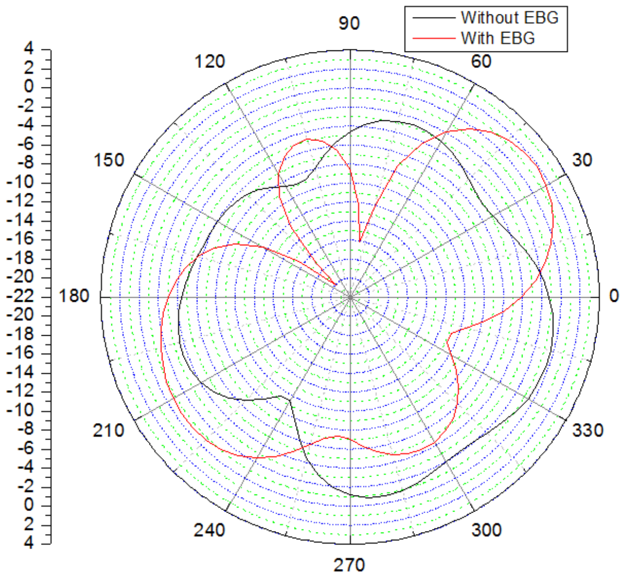

Figure 3.8: Graph showing variation in feed location with four cell slots at ground plane with patch height 8.1 mm

tennas are widely used in wireless communication systems such as aircraft, spacecraft, satellite and missile applications, where size, weight, cost, performance, ease of installation and aerodynamic profile are the constraints. Hence low profile antennas are highly recommended in these sensitive communication appliances. Presently there are many government and commercial communication services such as mobile radio which employ low profile antennas for wireless communication. To meet these requirements low profile microstrip antennas are suitable devices to be employed. However, the main disadvantage of microstrip antennas are narrow bandwidth, but this can be improved by variety of techniques. The other drawbacks are poor polarization purity, high Q factor, spurious feed radiations, and low power handling capacity. In the situations when there is no need for high instantaneous bandwidth, like frequency hopping in cell phone systems, one can improve the operating frequency range of antennas by making them tunable. Several types of tunable antennas are reported, including dipoles in [42] and [43] and microstrip antennas [44], among which microstrip antennas are the most widely used as tunable antennas. Varactors [45] and shorting posts are mainly employed for this purpose to make microstrip antennas electronically tunable.

The rectangular patch is one of the most popular configurations of microstrip antenna. Other than rectangular patch, circular or annular patch are next substantially employed antennas in several wireless communication applications. It also has received a lot of attention, not only as a single element but also as multiple arrays configurations. The modes supported by the circular patch antenna can be found by dealing with patch, ground plane, and the material between the two as a circular cavity. The modes that are supported primarily by a circular microstrip antenna whose substrate height is small (h$<<\lambda$) are TM^z where z is taken perpendicular to the patch. As far as the dimensions of the patch, there are two degrees of freedom to control the length and width of the rectangular microstrip antenna. Therefore the order of modes can be configured by varying the relative dimensions of the length and width of the patch, which is also known as variation of aspect ratio. However for the circular patch, there is only one degree of freedom to control. This control parameter is radius of the patch.

3.3.1 Modeling Key Parameters

The lumped model of antenna consists of resistor, capacitor and inductor in parallel combination as shown in Fig. 3.9. The resonant frequency of antenna is a function of susceptance. Microstrip antenna can be made tunable by using variable susceptance. In electrical engineering, susceptance is the imaginary part of admittance and its SI unit is siemens. The value of susceptance can be varied by varying circuit capacitance. In this approach a varactor diode is connected between the radiating edge of a microstrip patch and the ground plane [46]-[49]. When a reverse bias voltage is applied to the varactor, the capacitance offered by it loads the patch and changes its effective electrical length and hence its resonant frequency. As the reverse bias voltage of the varactor increases, the capacitance offered by the varactor decreases and hence the resonant frequency increases. The resonance

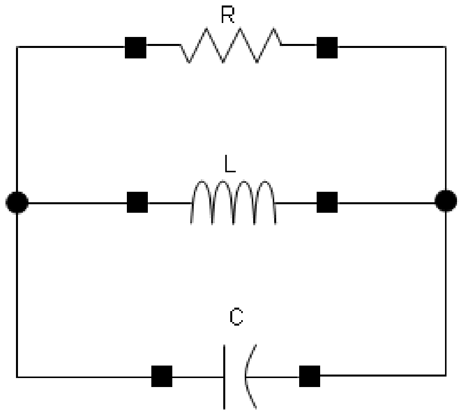

Figure 3.9: RLC Equivalent of Microstrip Antenna

frequency of the antenna is give by the equation 3.1. [50]-[52]

$$(f_r)_{mn0} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\left(\frac{X'_{nm}}{a}\right) \tag{3.1}$$

where:
$X^{'}$ represents the zeroes of the derivative of the Bessel function
For the dominant mode, m=n=1 and hence the equation will look like 3.2.

$$(f_r)_{110} \approx \frac{1.8412}{2\pi a\sqrt{\mu\varepsilon}} \approx \frac{1.8412 v_0}{2\pi a\sqrt{\varepsilon_r}} \tag{3.2}$$

where:
v_0 = speed of light in free space
ε_r = dielectric constant of substrate
a = effective radius of circular patch antenna
Voltage-controlled capacitance of a p-n junction can be used for the tuning purpose, which is given by the following equation:

$$C_J \propto (V_A)^{-n} \tag{3.3}$$

where $n = 1/2$ for an abrupt p-n junction. However, n can be made higher than 1/2 by suitably changing the doping profile. If varactor diode is operated at zero bias or a small forward bias, it effectively become a short circuit, and therefore can be used, when required to suppress a radiating mode. The high impedance quarter wave microstrip line is used as a bias decoupling network to bias the varactor diodes. The purpose of the bias dc-coupling network is to provide isolation between the RF signals and DC power supply. The biasing network is included while performing electromagnetic simulation. Varactors are placed such that there is minimum disturbance of currents on the patch. The radiating edges of the patch have minimum current density, that can be confirmed by electromagnetic simulation. The efficiency of the varactor tuned microstrip patch antenna can be defined as:

$$\eta_d = \frac{(P_{in} - P_d)}{P_{in}} \tag{3.4}$$

Where P_{in} is the total input power to the antenna which includes radiated power, power lost to surface wave, and power dissipated in lossy substrate as well as power dissipated in the diode and P_d is the power dissipated in the diode. The total input power may be found as:

$$P_{in} = \frac{1}{2Re\frac{1}{Z_d}} \tag{3.5}$$

Assuming the driving source is a one volt delta gap generator at the base of the probe feed. The power dissipated in the diode is given by:

$$P_d = \frac{1}{2|I|^2 Re\frac{1}{Z_d}} \tag{3.6}$$

Where I is the coefficient of the attachment mode associated with the diode and Z_d is the diode impedance. The efficiency varies from 95% at high reverse bias to about 30% at the low bias. The cross section area of the patch decreases as a direct consequence of the reduced efficiency of the antenna.

3.3.2 Design Methods

Circular patch loaded with varactor diodes at each radiating edge can be adjusted to radiate linear polarization with the electric vector in anyone of three planes. The configuration of the proposed antenna with varactor tuning method is illustrated in Fig. 3.10. The proposed antenna is designed on RT-Duroid 5880 substrate ($\varepsilon_r = 2.2$) with thickness of 0.8 mm and size of 44 mm×44 mm. The quarter wave matching transformer of width 0.45 mm is used to match the radiating circular patch with 50 ohm feed line. A high impedance quarter wave line (width 0.2 mm) is used as DC feed, connected at feed line. This DC feed does not affect the antenna radiation characteristics. Three varactor diodes (GMV 9821) are selected for frequency tuning.

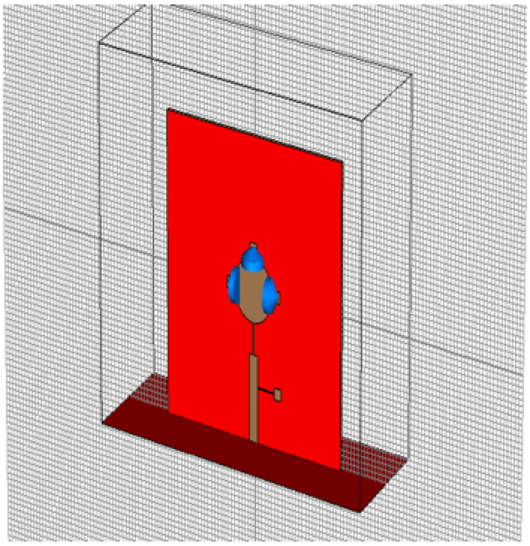

Figure 3.10: Reconfigurable Circular microstrip antenna using varactor diode

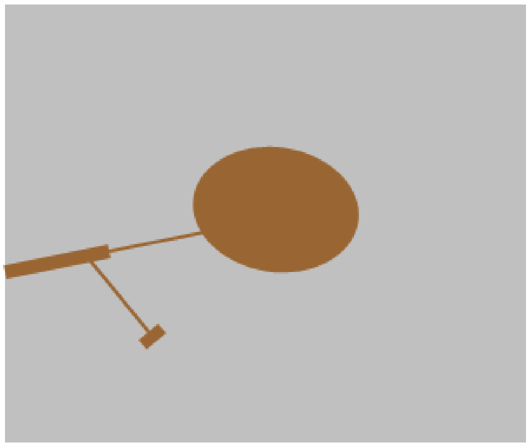

Figure 3.11: X-band linearly polarized circular microstrip antenna: Frequency is 10 GHz, $\varepsilon_r = 2.2$, Dielectric thickness is 0.8mm.

The geometry of the patch element is circular, while the bottom of the patch is connected with feed line, hence three diodes are mounted on remaining three sides (left, right and up) of the circular patch. One terminal of the diode is connected at the radiating edge of the patch and other terminal is grounded. The bias to the Varactor diode is given through the DC feed network. The X-band linearly polarized circular microstrip antenna is shown in Fig. 3.11, that operates on 10 GHz and the dielectric thickness is 0.8 mm.

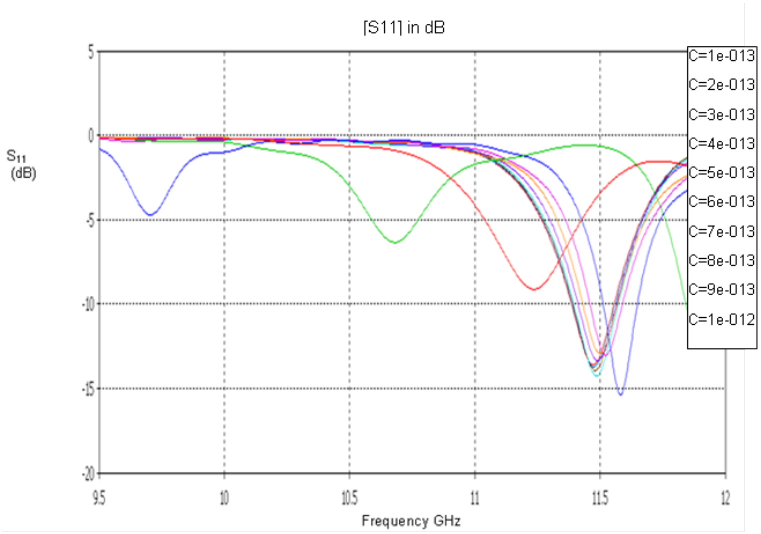

Figure 3.12: Return loss graph of different resonance frequencies at different capacitance

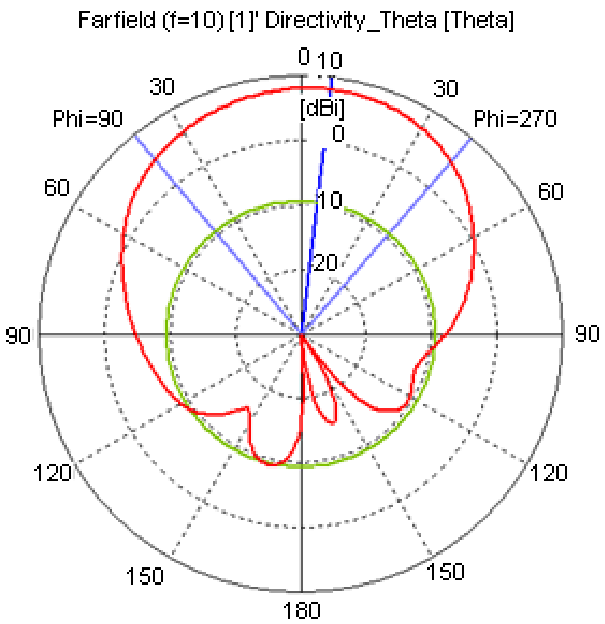

Figure 3.13: Simulated E-plane pattern for circular antenna at 10 GHz

3.3.3 Results Analysis

The performance of the antenna is measured. The S_{11} parameter gives the return loss characteristics of the antenna and is measured using Vector

Network Analyzer. The capacitance values of the varactor diodes are varied from 0.1 pF to 1.0 pF with continuously associated the dc bias voltage from 0 V to 10 V. Simulated return loss at different capacitance value is shown in Fig. 3.12. The lower and higher resonant frequencies are operating at 1.6 GHz and 1.8 GHz while changing the bias voltage from 0 V to 12 V respectively. By varying the diode bias we are able to tune the resonant frequency of the antenna over a 50% bandwidth. Fig. 3.13 and Fig. 3.14 show the simulated radiation patterns corresponding to E-plane and H-plane respectively at 10 GHz. The real radiation pattern of the tunable circular patch antenna is measured in anechoic chamber corresponding to dc bias voltage at 0 V. The E and H planes simulated radiation pattern at 10 GHz show the good agreement with measured radiation patterns shown in Fig. 3.15.

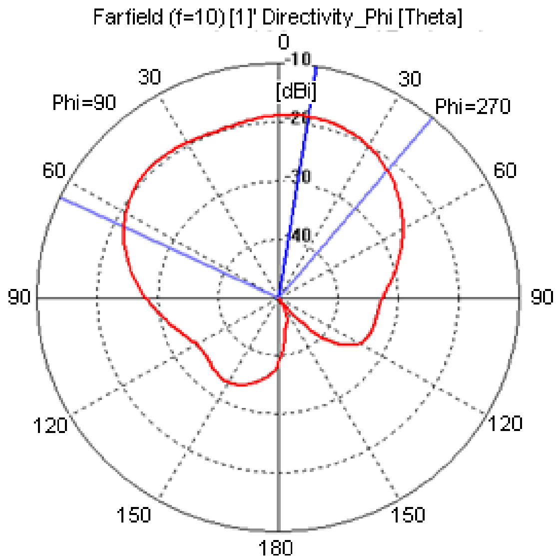

Figure 3.14: Simulated H-plane pattern for circular antenna at 10 GHz

3.4 Chapter Summary

In this chapter, we have performed an efficient design to develop a slotted microstrip antenna, that can be employed in mobile and hand-held applications. We have analyzed the return loss and directivity of the designed antenna in different conditions of patch height, dielectric and meta-materials. Based on the achieved results, we can conclude that with the use of meta-material in antenna, there are chances to increase its efficiency, return loss and radiation pattern characteristics. There are also improvements in di-

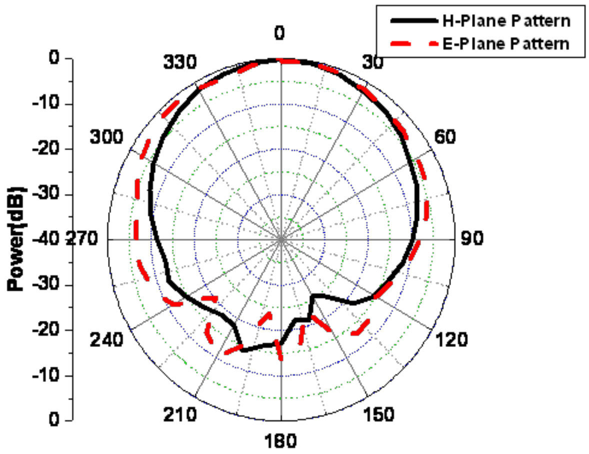

Figure 3.15: Measured E-plane and H-place pattern for circular antenna at 10 GHz

rectivity and bandwidth. Without use of EBG, the antenna was working at two frequency bands but use of EBG make it possible to operate at three frequency bands i.e. GSM800, UMTS and ISM band.

In the latter part of this chapter, Electronically tunable circular patch antenna is designed. The resonant frequency of the patch antenna can be altered by reactive loads using varactor diodes embedded on the patch surface. Experimental results are reported for a circular microstrip patch antenna that's scattering and radiation responses are tuned by varying the bias voltage across varactor diode that is mounted between the conducting patch and ground plane. The developed microstrip patch antenna offers substantially wider bandwidth and other electromagnetic behavior than the same microstrip antenna without the varactor embedded in it.

Chapter 4

Design of Sierpinski Grid Patch Antenna for Multiband Application

In this chapter, we have attempted to design a planar Sierpinski fractal antenna with stacked configuration for multiband applications. The stacked configuration of Sierpinski fractal patch and Sierpinski grid are employed to improve the multiband characteristics. The operating frequencies obtained are at 3.3 GHz, 5 GHz, 5.74 GHz and 5.9 GHz which covers the bands useful for HIPERLAN2 frequencies and for implementation in futuristic WiFi enabled devices and PCI Cards for mobile internet. The Simulated results show that the operating frequencies obtained are spread over a wide range of frequency band compared to the simple Sierpinski fractal patch antenna.

The rapid progress in telecommunication technology deals with a great variety of communication systems like cellular, global positioning, and satellite communication systems. Each of these systems operates at several frequency bands employing a number of small to large antennas depending on the choices of applications. Printed antennas offer an excellent performance in a wide variety of wireless communication applications. Moreover, due to low weight, low profile and low cost production of patch and fractal structures, these antennas are becoming more popular in wireless and telecommunication industry. Various multiband designs employing parasitic patches or shorting pins have been proposed to date [53]-[54]. However, these techniques usually lead to an increase in antenna size or manufacturing cost. The recent trends establish evidence that production of antennas for different applications are growing rapidly. This has initiated antenna research in various directions, one of which is using fractal shaped antenna elements. Fractal geometries have two common properties, space-filling and self-similarity. The self-similarity properties of certain fractals result in

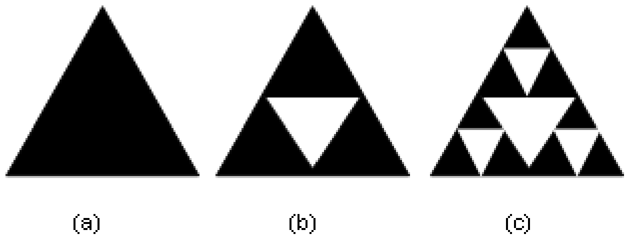

Figure 4.1: Sierpinski fractal generation up to 2nd iteration (a) Original Triangle-Stage 1 (b) 1st Iteration-Stage 2 (c) 2nd Iteration-Stage 3

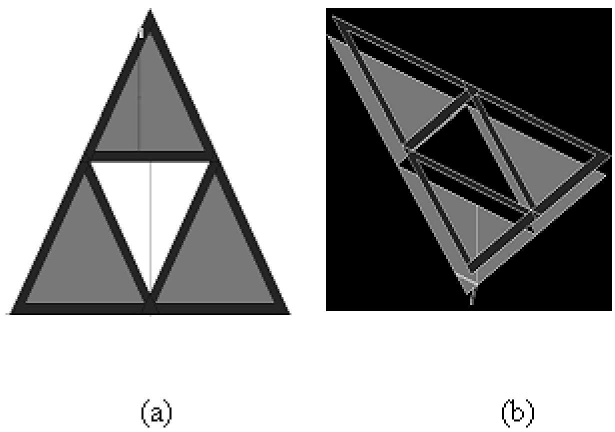

Figure 4.2: Sierpinski grid patch antenna in stacked configuration (a) Top view and (b) 3-D view

a multi-band behavior [55]-[58], while the space-filling properties of fractals make possible to reduce antenna size [59]. Fractal objects have self-similar shapes, which mean that some of their parts have the same shape as the whole object but at a different scale. In this paper the Sierpinski patch antenna has been considered for the investigation. The Sierpinski gasket is named after the Polish mathematician Sierpinski who described some of the main properties of this fractal shape in 1916. The original gasket is constructed by subtracting a central inverted triangle from a main triangle shape as shown in Fig. 4.1. After the subtraction, three equal triangles remain on the structure, each one being half of the size of the original one. This is the first iteration of the Sierpinski fractal generation [15]. One can iterate the same subtraction procedure on the remaining triangles and if the iteration is carried out an infinite number of times, the ideal fractal Sierpinski gasket is obtained. In such an ideal structure, each one of its three main parts is exactly equal to the whole object, but scaled by the factor of two and so is each of the three gaskets that compose any of those parts. Due to this particular similarity property, shared with many other fractal shapes, it is said that the Sierpinski gasket is self-similar [16], [60]. The following sections constitute the whole paper. The next two sections describe the antenna design criteria and the results obtained respectively. Section 4.3 deals with sustainability model and explores environmental impacts assessment. The last section gives the chapter summary of this work.

4.1 Antenna Design

In this chapter, only up to the second stage of the Sierpinski gasket is considered. For the first stage, which is a simple triangular patch with the length of each side 32 mm is placed on a substrate of thickness 1.6 mm and permittivity 4.4. Location of the coax feed placed on the patch is -3, 20.5 (x_f, y_f) from the centre of the patch's base (offset). Resonant frequencies obtained were 5.07 and 5.72 GHz. The second stage of the Sierpinski gasket (1st iteration) is then obtained using the Sierpinski gasket design method described above. With this configuration the resonant frequencies obtained were at 5.51 and 5.62 GHz. But in this case, too, there were only two operating frequencies with the slight frequency shift. In the next step a grid

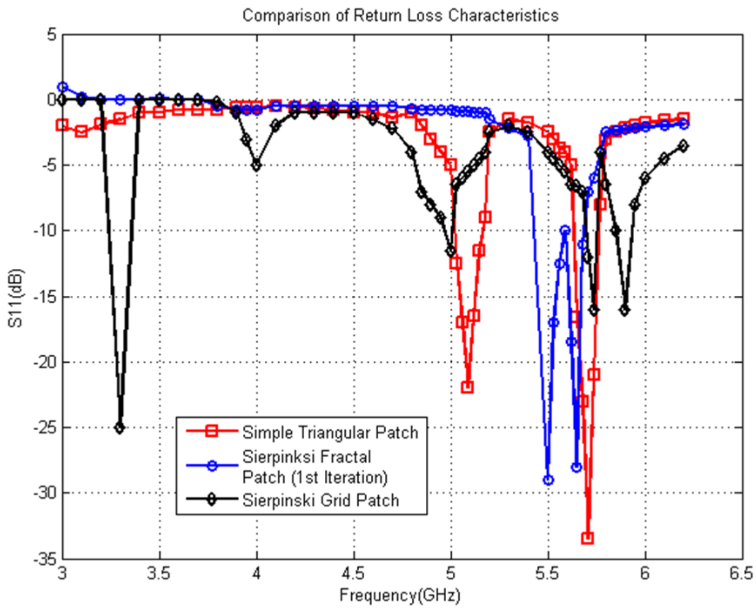

Figure 4.3: Comparison of return loss characteristic of three structures

with the width of 1.0 mm is formed, whose dimensions are same as that of the second stage of the Sierpinski gasket. This Grid is constructed on a foam

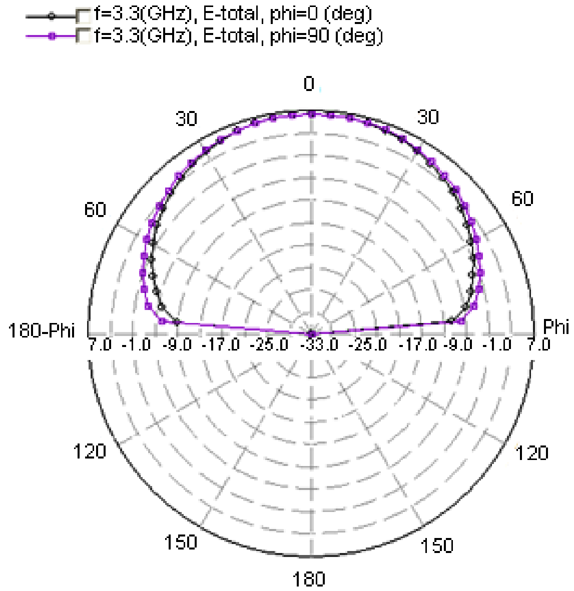

Figure 4.4: E and H plane radiation pattern of Sierpinski grid patch antenna in stacked configuration at 3.3 GHz

substrate of thickness 1.6 mm and permittivity of 1.06 and is placed over the previous structure. This way a stacked configuration is obtained in which the lower structure is Sierpinski gasket on FR4 where the upper structure is grid on a foam of thickness 1.6 mm. The lower patch is co-axially fed. This final configuration of the antenna is shown in Fig. 4.2. With this configuration the operating frequency obtained are 3.3 GHz, 5 GHz, 5.7 GHz and 5.9 GHz, which are widely spreaded over the frequency band.

4.2 Results and Discussion

Return loss characteristics of the three structures are shown in Fig. 4.3. It is evident from the figure that within the range of 6 GHz, only two operating frequencies were obtained with the simple triangular patch and the Sierpinski fractal patch (1st iteration). With the Sierpinski fractal patch (1st iteration) resonant frequencies were at 5.51 and 5.62 GHz and give rise to a wide band antenna whose return loss is less than -10 dB from 5.49 GHz to 5.67 GHz.

The third configuration in which Sierpinski fractal patch and Sierpinski grid were considered in the stacked configuration, with Sierpinski fractal patch as probe fed and Sierpinski grid as parasitic patch, the resonant frequency obtained are four, which are at 3.3 GHz, 5 GHz, 5.7 GHz and 5.9

GHz.

Characteristics related to these frequencies are tabulated in the Table 4.1. The gain of this novel antenna is, within the desired frequency, always more than 5.5 dBi. The simulated radiation pattern in E and H plane at four frequencies 3.3 GHz, 5 GHz, 5.7 GHz and 5.9 GHz are shown in the Fig. 4.4, Fig. 4.5, Fig. 4.6 and Fig. 4.7 respectively.

The radiation pattern characteristics at all the frequencies are almost same. At frequency 5.9 GHz the gain is slightly reduced but is still greater than 5 dBi.

Table 4.1: Return Loss, VSWR and Gain Characteristics of Sierpinski Grid Patch Antenna in Stacked Configuration

S.N	Frequency	Return Loss (dB)	Bandwidth (MHz)	Gain (dBi)
1	3.3 GHz	-24.8	100	6.37
2	5 GHz	-11.6	70	6.47
3	5.7 GHz	-15.3	120	6.18
4	5.9 GHz	-15.9	50	5.6

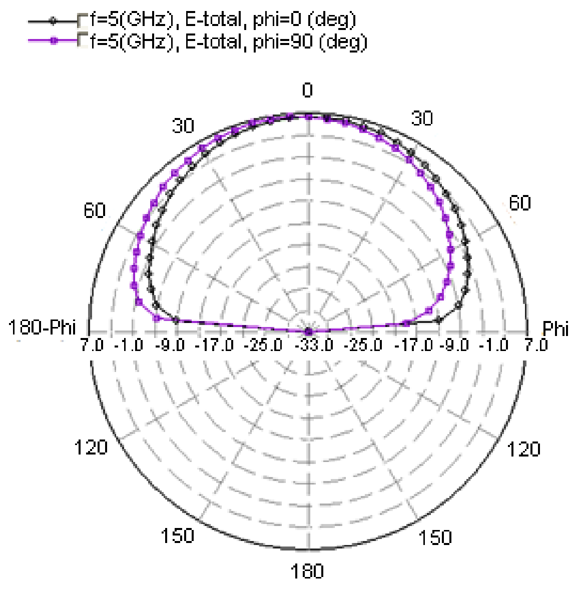

Figure 4.5: E and H plane radiation pattern of Sierpinski grid patch antenna in stacked configuration at 5 GHz

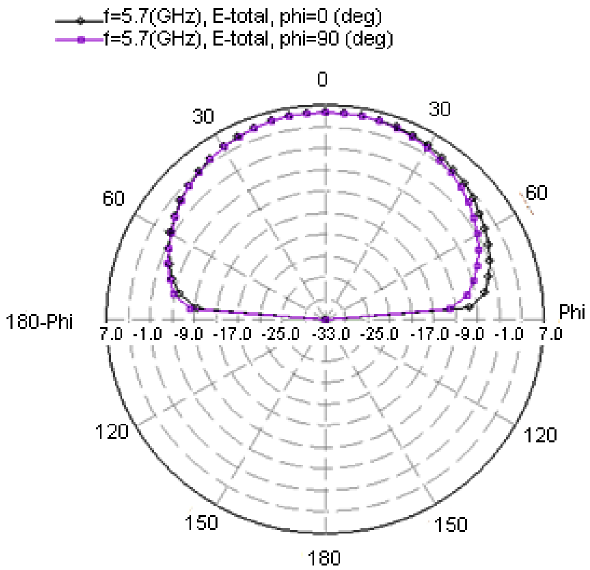

Figure 4.6: E and H plane radiation pattern of Sierpinski grid patch antenna in stacked configuration at 5.7 GHz

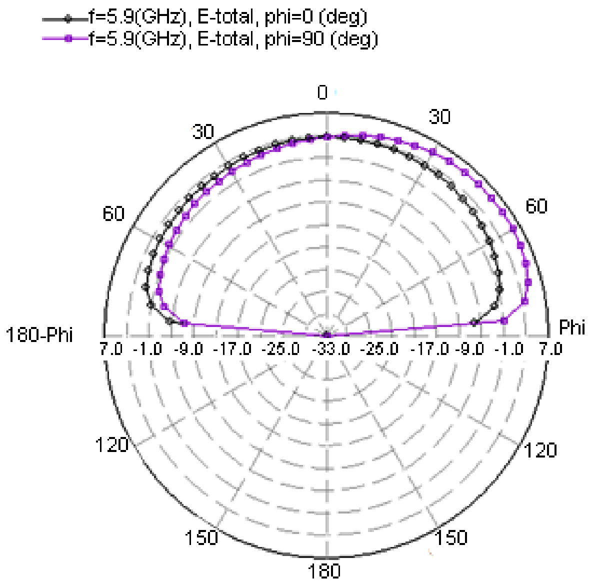

Figure 4.7: E and H plane radiation pattern of Sierpinski grid patch antenna in stacked configuration at 5.9 GHz

4.3 Sustainability Analysis

This section provides an overview of sustainability and environmental impacts assessment [61]-[65] in production process of Sierpinski structure based microstrip printed antennas. The sustainable model for this antenna has been made using Gabi 5.0 environmental assessment tool. In this work, we have considered two stages of life cycle analysis: production stage and end-of-life stage. The model in question has been depicted in Fig. 4.8. The numerical analysis of environmental emissions in these stages employed several materials the printed antenna has been composed of. Substrate, antenna trace material (may be copper, silver ink, or aluminum) and the associated energy have been taken into consideration as vital components as they cause most environmental impacts. The recent trends of using

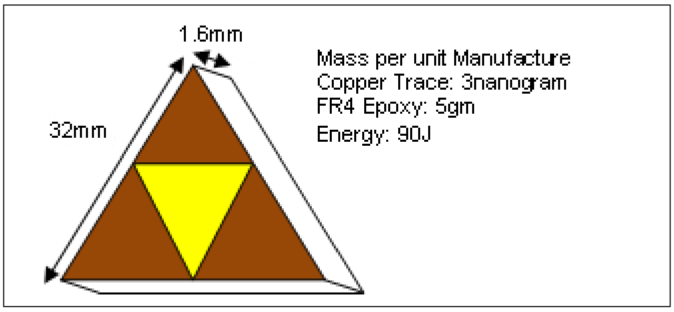

Figure 4.8: Model and Mass of the Antenna Materials

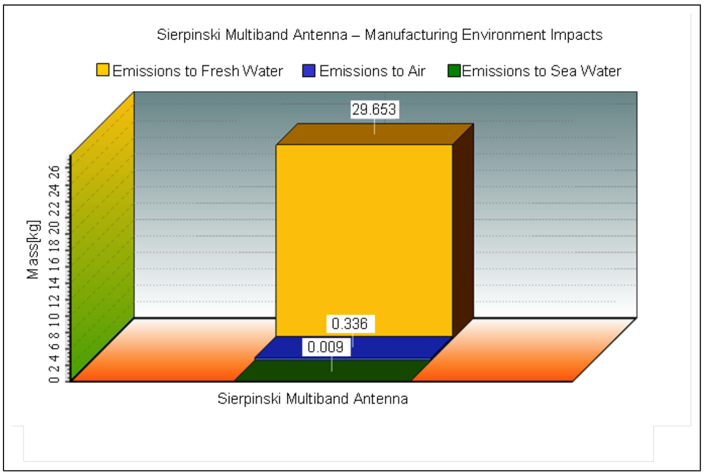

Figure 4.9: Environmental Emissions during Manufacturing of Sierpinski multiband antenna

conductive inks for tracing antenna patterns are gradually turning toward low cost printing material such as copper. Although this element has several limitations for example poisoning the circuits, copper oxidation, and high temperature annealing process. The higher demand of silver conductive ink for tracing massive amount of UHF antennas and billions of RFID tags caused shortage of silver nano ink [120]. Hence manufacturers are considering of using copper nano inks with improved performance. In this work inkjet printing technology has been employed to trace the required Sierpinski fractal pattern. Our published work [66]-[70] presents the environmental impacts in different antenna systems. The mass of FR4 (flame retardant epoxy material), copper antenna trace and the manufacturing energy have been estimated on the basis of antenna structure and its Sierpinski fractal layout. The model that have been developed for this research comprises of copper and epoxy masses 3 nanogram and 5 gm respectively.

The inkjet printing methodology consumes 90 Joule of energy for tracing one pattern. The equivalent environmental emissions during the manufacturing process have been depicted in Fig. 4.9. The relative contribution shows that the impact on emissions to fresh water is larger than emissions to air and sea water.

4.4 Chapter Summary

In this chapter, we have attempted to give an overview of designing fractal patch antennas in stacked configuration as well as environmental impacts during its manufacturing process. The proposed antenna is designed in such a way that second stage of the Sierpinski gasket (1st iteration) is used as a the lower patch and fed with coaxial probe, where as the Sierpinski grid has been used as the upper parasitic patch. This antenna has four operating frequencies 3.3 GHz, 5 GHz, 5.7 GHz and 5.9 GHz. The major applications of this antenna falls within area of HIPERLAN2, wi-fi enabled devices and PCI Cards for mobile internet. We have also explored the environmental impacts in manufacturing process of this Sierpinski type multiband printed microstrip antenna.

Chapter 5

Life Cycle Assessment of Printed Antenna

Environmental Life Cycle Assessment is a system analytical method and model by which the potential environmental impacts can be estimated. In this chapter, cradle to grave life cycle assessment of printed antennas have been presented. An attempt has been made to investigate and evaluate the life cycle assessment and environmental impacts of printed electronics like polymer and paper substrate printed RFID antenna. Life cycle inventory analysis of the materials that are used in printed antenna has been carried out to quantify total systems' inputs and outputs that are relevant to the environmental impacts especially emissions to air, fresh water, industrial soil and sea water. In this work, we have tried to look at to quantify the environmental impacts in modern printed technology over conventional PCB technology. The results show that printed electronics materials are considerably more environment friendly than materials needed for PCB electronics. We have obtained the mass of emissions in each life cycle stages which verify that technology wise printed antenna causes less harmful and hazardous impacts to the environment.

This chapter is structured as follows. The next section gives a brief description of Life Cycle Assessment. The next two sections provide the theoretical underpinnings of our assumptions in procedural flow diagram and process interpretation. Section 5.4 describes our research analysis in each life cycle stages. Comparative Analysis and toxic emissions are described in sections 5.5 and 5.6 respectively and conclusion and future works are presented in section 5.7.

5.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is potentially the most important method for assessing the overall environmental impacts of products, processes or services. LCA is a tool which involves the collection and evaluation of quantitative data on the inputs and outputs of material, energy and waste flows associated with a product through its entire life cycle so that the environmental impacts can be determined. Fig. 5.1 shows the life cycle assessment stages and boundaries of a product: the resource flows (e.g., material and energy inputs) and the emissions, waste, and product flows (e.g., outputs) within each life-cycle stage, as well as the interaction between each stage are evaluated to determine the environmental impacts. The first step lays out

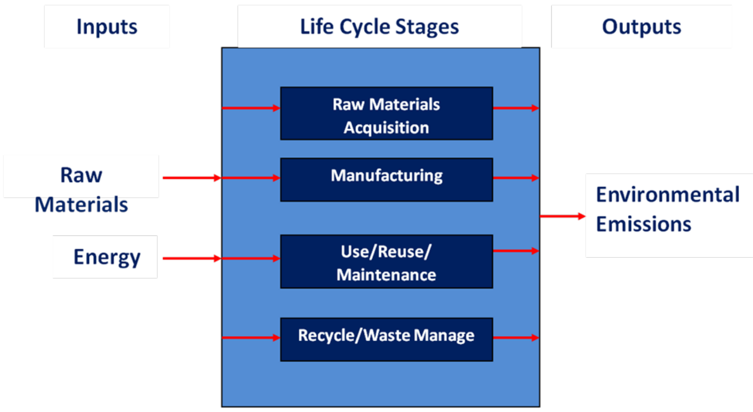

Figure 5.1: Product life-cycle stages

the rationalization for conducting the LCA and its general intent, as well as specifying the product systems and data categories to be studied (ISO 10140). An objective, data-based process of quantifying energy and raw material requirements, air emissions, waterborne effluents, solid waste, and other environmental releases throughout the life cycle of a product. (ISO 14141). A technical, quantitative or semi-quantitative process to characterize and assess the effects of the environmental loadings identified in the inventory component. The assessment should address both ecological and human health considerations, as well as other effects such as habitat modification or noise pollution. (ISO 14142). A systematic evaluation of the needs and opportunities to reduce the environmental burden associated with energy and raw materials use and environmental releases throughout the whole life cycle of the product, process or activity. This assessment should include both quantitative and qualitative measures of improvements. (ISO 14143).

5.1.1 Variants of Life Cycle Assessment

At the beginning stage of LCA development, the classification of LCA study was limited but as the research progresses forward, the rapid development of around five decades after the year 1960's causes to emerge several variants of LCA. Some of these LCA variants are briefly discussed as below:

(A) ***Cradle-to-Grave***
Cradle-to-grave is the full Life Cycle Assessment from raw material resources ('cradle') including use phase and up to end-of-life stage ('grave'). In other words, we can say that this includes the material, process and energy from the raw material extraction through the production, transportation and use phase up to the product's end-of-life treatment. A simple example is as follows: The trees produce paper, which can be recycled into low-energy production cellulose insulation, then used as an energy-saving device in the ceiling of a home for 40 years, saving 2000 times the fossil-fuel energy used in its production. After 40 years the cellulose fibers are replaced and the old fibers are disposed of, possibly incinerated. All inputs and outputs are considered for all the phases of the life cycle.

(B) ***Cradle-to-Gate***
Cradle-to-gate is an assessment of a partial product life cycle from manufacture ('cradle') to the factory gate (i.e., before it is transported to the consumer). In other words, this includes all processes from the raw material extraction through the production phase to determine the environmental impact in production of a product. The use phase and disposal phase of the product are usually omitted. Cradle-to-gate assessments are sometimes the basis for environmental product declarations (EPD).

(C) ***Cradle-to-Cradle***
Cradle-to-cradle is a specific kind of cradle-to-grave assessment, in which the end-of-life or the disposal stage of the product is considered as a recycling process. The recycling process originates new, and the identical products (e.g., glass bottles from collected glass bottles), or different products e.g. glass wool insulation from collected glass bottles.

(D) ***Gate-to-Gate***
Gate-to-Gate is a partial LCA looking at only one value-added process in the entire production chain. Therefore gate-to-gate life cycle assessment is used to determine the environmental impacts of a single production step or process.

(E) ***Well-to-Wheel***
Well-to-wheel is normally considered an LCA for determining efficiency

of fuels used for road transportation. The analysis is often broken down into stages such as well-to-station and station-to-wheel, or well-to-tank and tank-to-wheel.

(F) ***Economic Input Output LCA***
EIOLCA, or Economic Input-Output LCA involves use of aggregate sector-level data on how much environmental impact can be attributed to each sector of the economy and how much each sector purchases from other sectors. Such analysis can account for long chains (for example, building an automobile requires energy, but producing energy requires vehicles, and building those vehicles requires energy, etc.), which somewhat alleviates the scoping problem of process LCA; however, EIO-LCA relies on sector-level averages that may or may not be representative of the specific subset of the sector relevant to a particular product and therefore is not suitable for evaluating the environmental impacts of products. Additionally the translation of economic quantities into environmental impacts is not validated.

(G) ***Ecologically Based LCA***
While a conventional LCA uses many of the same approaches and strategies as an Eco-LCA, the latter considers a much broader range of ecological impacts. It was designed to provide a guide to wise management of human activities by understanding the direct and indirect impacts on ecological resources and surrounding ecosystems

5.1.2 System Boundaries and LCA Steps

The first step of performing LCA is to determine the scope and boundaries of the assessment. In this step, the reasons for conducting the LCA are identified, i.e. the product, process or service to be studied is defined. All operations that contribute to the life cycle of the product, process or activity of interest fall within the system boundaries. The environment is the surrounding for the system. Inputs to the system are natural resources, including energy resources while the outputs of the system are collection of releases to the environment. The boundary system concept is illustrated in Fig. 5.2. The boundaries for the LCA encompass the acquisition of raw materials, manufacture of intermediate materials, manufacture of the final product, use phase of the product and final disposition. Recycling or reuse of the product is also a part of the LCA analysis. Defining the scope and boundaries is the first step to perform LCA. The systems to be evaluated are determined, and various geographic, spatial, and time parameters are set. In addition to these activities, specific information about the systems to be studied is needed. Sometimes it is needed to perform the comparative LCA of two products say product A and product B. In this situation,

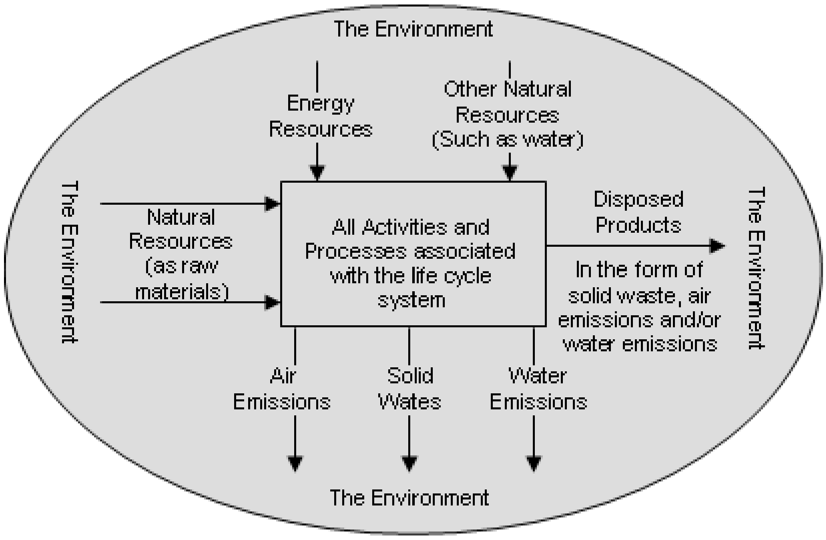

Figure 5.2: Concept of System Boundary

each product and the associated packaging needs to be obtained to analyze the environmental impacts assessment.There are five basic steps to perform LCA:

- Define the scope and boundaries,
- Collection of data,
- Create a computer model,
- Analyze and report the study results,
- Interpret the results and draw the conclusions.

5.1.3 Software Systems and Databases

Environmental processes are often very complex and convoluted. This makes it difficult to model an LCA. Additionally LCA is often data intensive. Computers and adequate software tools are thus used to support the user in managing and editing these amounts of data. LCA software further helps to structure the modeled scenario, displaying the process chains and presenting and analyzing the results. LCA software tools can be used whenever the method of LCA is applied. [71]

The main reason for using LCA is to calculate the environmental aspects and potential impact associated with a product (ISO 14040). Also environmental hot spots (processes that have a large impact on the environment) can be identified. A more environmentally-friendly production process can thus be developed where they are most effective. LCA can also be used for a cleaner approach to production. It can help to improve and optimize resource management, which leads to a more efficient use of materials and energy.

There is a large variety of LCA software tools on the market, based on a survey of LCA practitioners carried out in 2006 most life cycle assessments are carried out with dedicated software packages. 58% of respondents used GaBi , developed by PE International, 31% used SimaPro developed by PR Consultants, and 11% a series of other tools such as EcoLab developed by Nordic Port and so on.

The software system GaBi 5 is a tool for building up life-cycle-balances and provides solutions for different problems regarding cost, environment, social and technical criteria. GaBi 5 gives support with handling with a large amount of data and within modeling of the product life cycle. In addition the software helps optimizing processes and managing the external representation in these fields. GaBi [72] software assists the user to perform the followings:

- Greenhouse Gas Accounting,
- Life Cycle Engineering,
- Design for Environment,
- Energy Efficiency Studies,
- Substance Flow Analysis,
- Company Eco-balances,
- Environmental Reporting,
- Strategic Risk Management,
- Total Cost Accounting.

5.2 LCA Research Problems

The present research scenario towards the embedded or telecommunication system shows that analysis of life-cycle has not been a core focus for the researchers, such topics typically being left to the expertise of other communities. To maximize a researcher's contribution to efficient products, manufacturing industry processes and services, there is a strong need to increase life-cycle awareness among embedded or telecommunication systems researchers, so that the next generation of engineers will be better able to integrate the goal of a sustainable life-cycle. Market analysis and research

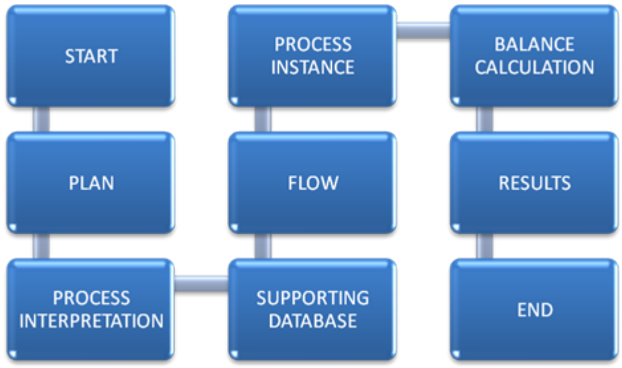

Figure 5.3: Procedural Flow Diagram for Life Cycle Assessment of Printed Antenna

reports estimate that printed and organic electronics will become a huge, several hundred billion dollar business in the near future [73]. Motivated by the evidence of increasing demand of printed electronics in the near future, our aim is to develop an understanding of the life cycle assessment of printed electronics materials and to analyze the environmental impacts in terms of emissions to air, fresh water, sea water and industrial soil. In this chapter, we have attempted to examine the following research questions. What are the quantitative emissions in each life cycle stage of printed RFID antenna? How severe are the impacts of environmental emissions with the case of using PCB technology? What are the amounts of toxic emissions in each technology?

The rapid progress in telecommunications deals with a great variety of communications systems like cellular communications, global positioning, and satellite communications. Each of these systems operates at several frequency bands employing a number of small to large antennas depending upon the choices of applications. Moreover printed antenna offers an excellent performance in wide range of applications of wireless communication. The recent trends give evidence that production of antenna for several wireless applications are growing rapidly. Hence we chose printed antenna as a case study. At the outset, it is useful to explain what we mean by life cycle assessment and printing methodologies in context with this research [74]-[81]. We have considered inkjet printing methodology in production of RFID antenna and have developed a model using life cycle assessment (LCA) software. The major compositional components of printed electronics materials are studied with reference to emissions into the environment. The goal of this study is to quantify the environmental emissions in different life cycle stages such as raw materials preparation, production process and end of life cycle of the printed antenna. In order to facilitate analysis, the environmental evaluation of the printed technology has been carried out and compared with the conventional PCB technology. The key parameters for comparison include the energy usage, hazardous emissions from raw materials preparation, production process and end-of-life of the printed antenna.

Substantial research has been conducted on several key areas related to the life cycle assessment and environmental impacts of printed electronics materials. Some of them are printed electronics manufacturing line with sensor platform application, LCA of carbon nanofibers and inkjet print cartridges [82]-[85]. The academic literature has not focused on quantitative environmental emissions in air, fresh water due to production of antenna in printed and PCB technologies. Therefore here our work is to quantify the total environmental emissions due to production of printed RFID antennas in all three life cycle stages of raw materials preparation, production processing and end of life cycle and also to compare them with PCB technology. A model has been realized in both the technologies using Gabi 4.0 environmental assessment tool to obtain the results in terms of input resources utilization and environmental emissions. With analysis of fabricating one million printed RFID antennas and PCB antennas, our results show that resource consumption in PCB technology is considerably larger than that of the printed electronics technology. We have also investigated the life cycle assessment and environmental impacts of printed RFID antennas in all three life cycle stages.

5.3 Procedural Flow Diagram

The procedural flow diagram shown in Fig. 5.3, describes the start to end flow in the process of life cycle assessment of printed antenna. A plan is the basis for connecting different processes and thereby, modeling the steps of printed electronics life cycle. It is a representation of the system boundaries. A flow is the base unit in life cycle assessment software. It describes the material or energy flow between two processes. Processes are connected to one another by product flows. The process instance is the local process settings after the plan is completed with the set of processes and corresponding flows. The supporting database comprises of inputs and outputs for the specified process. The inputs are in the category of renewable resources, non renewable resources, minerals, waste for recovery, thermal energy. In similar way, output represents environmental impacts such as inorganic/organic emissions to fresh water/air/sea water, heavy metals to air, and hydrocarbons to fresh water and so on. Balances are used to view the results of the proposed model. They can be evaluated in a variety of different ways. Balances can be calculated based on single or multiple processes and plans.

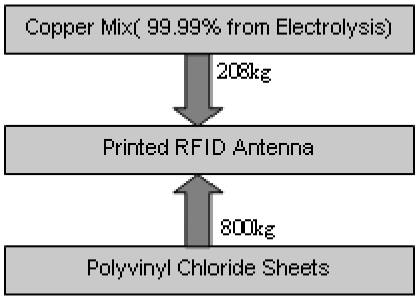

Figure 5.4: Plan of polymer based RFID tag Antenna. The Rectangle shows the processes where as arrow shows the flows.

5.4 Process Interpretation

A process is defined by its input and output flows. The plan comprises of different manufacturing processes. Usually manufacturing process of printed antenna requires two major substances. These are the input parameters for LCA. During the process interpretation one has to consider quantity, amount and particular unit of the materials. The output results of LCA depend on how input parameters and their magnitudes are considered during the process. The real composition and magnitudes of the printed RFID antenna can be obtained after life cycle inventory analysis (LCIA). Table 5.1 and Table 5.2 show the process interpretation for manufacturing printed RFID antenna and traditional PCB antenna respectively. In both the technologies, the total masses of materials utilized are different. The masses of materials are chosen as per the knowledge of fabrication of antenna [86]-[91], [13], [14] in both the technologies. For the production of 1 million printed RFID antennas, it requires 800 kg of PVC sheet and 208 kg of copper mix.

Table 5.1: Process Interpretation of Printed RFID Antenna

S.N	Flows	Quantity	Amount	Unit
1.	PVC Sheet	Mass	800	kg
2.	Copper Mix	Mass	208	kg
3.	Total Productions (No. of Pieces)		1 Million	

5.5 Life Cycle Stages

The main objective here is to quantify the environmental emissions in different life cycle stages such as raw materials preparation, production process and end of life cycle of the printed and PCB antennas. Beginning from Raw materials preparation stage, we have estimated consumption of raw materials in fabricating one million of printed and PCB antennas. For printed RFID antenna polyvinyl chloride sheets and copper mix are usually employed. The PCB antenna comprises of raw materials such as active and passive electronic components, plastics and copper strips. The modeling plan for printed and PCB antenna are shown in Fig. 5.4 and Fig. 5.5 respectively. According to these plans. we have attempted to visualize the environmental impacts in each case. The rectangles illustrate the processes and flows give an idea of amount of materials to construct the antenna. The total environmental emissions in the raw material preparation stage are

Table 5.2: Process Interpretation of PCB Antenna

S.N.	Flows	Amount	Unit
1.	Plastic Injection	2900	kg
2.	Copper wire (0.6mm)	575	kg
3.	Resistor Flat Chip Type	950	kg
4.	Capacitor tantal SMD	400	kg
5.	Transistors Signal 3 leads	175	kg
6.	Total Productions (Pieces)	1 Million	

shown in Fig. 5.6 and Fig. 5.7 respectively. The emissions to the air dominate clearly in both the technologies. The production process of printed antenna solely employs inkjet printing methodology that consumes conductive ink. The conductive ink is an alloy of carbon and silver deposited on the substrate. The production process of PCB antenna comprises of power grid mix, capacitor, filter, solder paste, resistors, transistors, silicon mix, ICs, printing wiring board and assembly line. The third stage is end of life. Here we have considered incineration and land filling techniques of printed antennas. In both the techniques we have computed the emissions to air, fresh water, sea water and industrial soil.

5.6 Comparative Analysis

In each life cycle stages, comparative emissions in both the technologies are shown in Table 5.3. In raw material preparation stage the results show that input resources utilized for the production of PCB and Printed RIFD antennas are 95% and 5% respectively. Hence we can save resources by 95% when implementing antenna with printed technology instead of PCB technology. Similarly the environmental emissions in the raw material preparation stage depicts that only 1% of emissions occurred due to printed technology while remaining 99% of emissions occurred in production of antenna using PCB technology. In production processing stage, the results show that the quan-

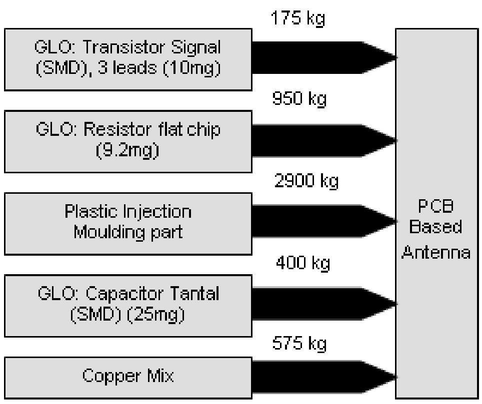

Figure 5.5: Plan of PCB based Antenna. The Rectangle shows the processes where as arrow shows the flows.

titative measure of input resource consumption is significantly lower in production of antennas using printed technology. Similarly the environmental emissions depicts that only 2% of emission occurs in one million production of antenna using printed technology while remaining 98% of emissions occurs in the case of PCB technology. Observing the intent data in Table 5.3 clears that each component (to air, fresh water, sea water and industrial soil) of emissions is sky-scraped relative to printed technology. We have explored the end of life cycle stage of polymer RFID antenna. The results include both incineration and land filling processes. The total emissions for the production of one million units are 2258 kg in incineration process and 792 kg in land filling process. Hence land filling process is devisable to minimize emissions

Table 5.3: Comparative Environmental Emissions(kg)in one million Production

S.N	Environmental Impact	RMP* Stage		PP** Stage		EOL*** Stage	
		PCB Antenna	RFID Antenna	PCB Antenna	RFID Antenna	Incineration	Land Filling
1.	Emissions to Air	613184kg	7392kg	39516248kg	701904kg	1886kg	725kg
2.	Emissions to Fresh Water	103375kg	122kg	802588kg	1528kg	372kg	67kg
3.	Emissions to Sea Water	304kg	4kg	14596kg	178kg	0	0
4.	Emissions to Industrial Soil	2kg	0.019kg	132kg	2.3kg	0	0.067kg
5.	Total	716865kg	7518.019kg	40333564kg	703612.3kg	2258kg	792.067kg

*RMP:Raw Material Preparation

**PP: Production Process

***EOL: End of Life

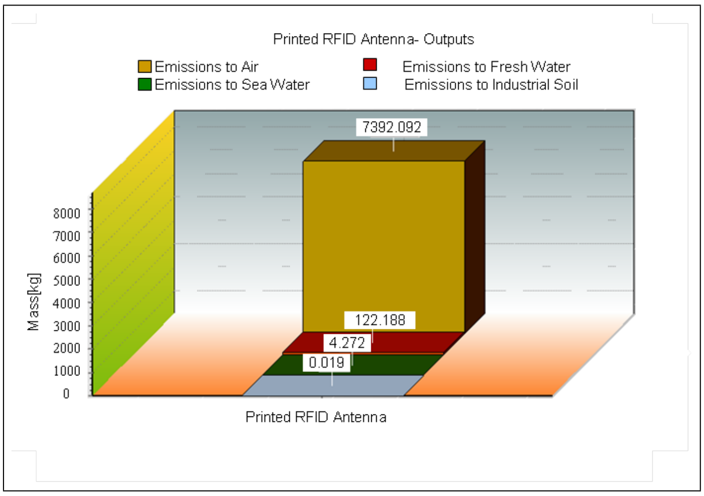

Figure 5.6: Total Environmental Emissions in Printed Antenna

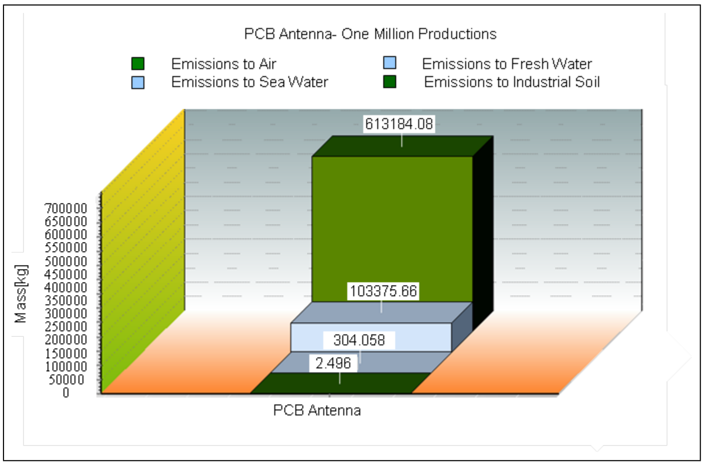

Figure 5.7: Total Environmental Emissions in PCB Antenna

5.7 Toxic Emissions

Here toxic emissions in raw material preparation stage have been illustrated. We are focused on exploring hazardous emissions within inorganic emissions to air in each technology. With production of 1 million printed RFID antennas, it is evident that the toxic gas such as carbon dioxide, carbon monoxide, hydrogen, nitrogen dioxide, nitrogen oxides and sulpher dioxide are evolved during the raw material preparation stage. The amount of different toxic gas emissions are shown in Fig. 5.8. The emission of carbon dioxide is largest among all toxic emissions. Similarly in a production of one million PCB antennas, it is evident that the toxic gases are evolved during the raw material preparation stage. These different toxic gas emissions are shown in Fig. 5.9. The mass of different emissions are as follows. Carbon dioxide - 89530 kg, Carbon monoxide - 62 kg, Hydrogen - 583 gram, Nitrogen dioxide - 150 gram, Nitrogen oxides - 211 kg and Sulpher dioxide - 728 kg. Beside these toxicants, there are also few emissions which are not illustrated in Fig. 5.9. The amounts of these toxic emissions are significantly low even than masses of nitrogen dioxide and carbon mono-oxide. In Figs. 5.8 and 5.9, the amount of toxic emissions in each technology reveals how severe toxic emissions in case of PCB antenna compared to printed RFID antenna.

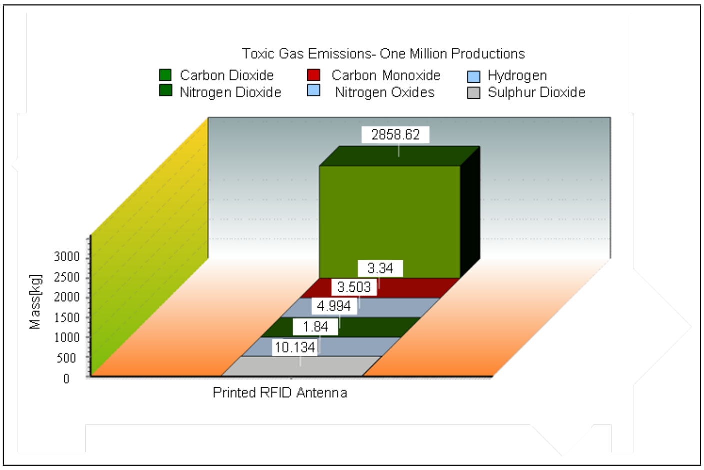

Figure 5.8: Toxic Gas Emissions- RFID Antenna

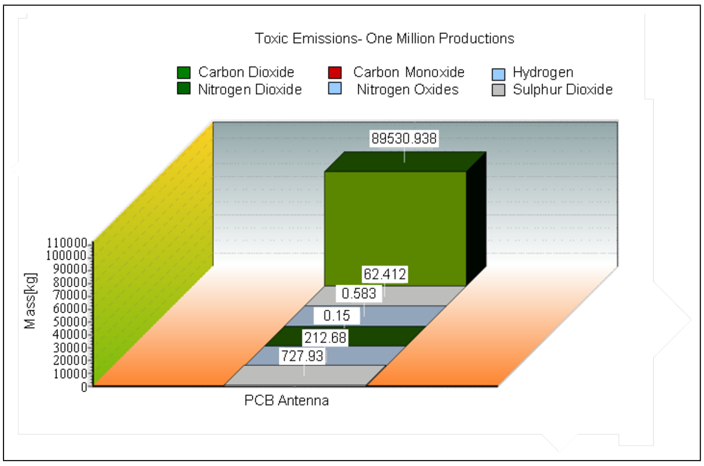

Figure 5.9: Toxic Gas Emissions-PCB Antenna

5.8 Chapter Summary

Obvious practical implications of our results show that technology wise RIFD printed antenna causes less harmful and hazardous impacts to the environment. We performed the modeling based on conventional PCB technology and polymer substrate printed RFID technology. These two technologies have been compared in terms of input resources utilization, and emissions to air, fresh water, sea water, industrial soil and hazardous emissions. After several iterations of database analysis we reached to a conclusion that printed electronics materials are environment friendly.

There are many avenues for further research. The first important future work is to reflect on optimization of technology. There are tremendous amount of parameters that need to be consider during LCA process. One should focus on each parameters of the life cycle assessment and see how severe their significance is. Another imperative future work is to consider the recyclability and end of life issues of PCB antenna to achieve the complete cradle to grave life cycle assessment. Finally, it would be worthwhile to examine the role of resources utilizations in manufacturing process of printed and PCB antennas.

Chapter 6

Environmental Footprint

Over the years, the use of Information Communication Technology has emerged in several areas, improving lives and productivity of human beings and offering convenience along with several other benefits. We are passionate about advances in and widespread adoption of ICT. However ICT has been contributing to environmental problems, which most people do not realize. The total carbon footprint of ICT sectors including personal computers and peripherals, telecoms network and devices and the data centers was 830 Megaton in the year 2007 [92]. An antenna is one of the essential components in wireless communication devices. The design and development of different structures of printed microstrip antennas has motivated to carry out further research on life cycle assessment, analysis of environmental impacts in its manufacturing process. This chapter presents a study and analysis of sustainability and quantitative environmental footprint in the manufacturing process of the printed antennas. Here it is important to letting the readers to know about rigid and flexible substrate printed antennas. A simple example of rigid substrate is glass epoxy resin while the flexible substrates are paper or polymer. In this chapter we will be focusing on analysis of rigid substrate printed antennas.

Quantifying environmental footprint is an important task for the information and communication system researcher as this study keep them aware of environmental impacts' threat toward green and healthy living of human beings. Life cycle assessment approach has been employed to quantify and asses the environmental footprint. A case study is carried out for epoxy resin substrate based tip truncated equilateral triangle microstrip antenna. The subtractive printing methodology have been conducted to trace the required antenna pattern. The output parameters have been analyzed in terms of global warming potential, ozone layer depletion potential, human toxicity and acidification potential. Gabi's balance approach has been utilized to analyze the environmental emissions to the air, fresh water, sea water, agricultural and industrial soils. The consumption of resources has also been shortly described in this chapter.

6.1 Environmental Footprint of Printed Antenna

With the rapid ecological downfall, increasing pollution and massive production of electronics and communication devices in the recent years, there is a need to carry out research on sustainable design, environment friendly products and assessment of environmental footprint. In the past, study on sustainability analysis, life cycle assessment and quantification of environmental emissions during raw material acquisition, production stages and end of life stage were intentionally left for other community of the researchers rather than information and communication system researchers. But in recent years, the researchers are capable of performing the analysis of sustainability and environmental assessment of the electronic or communication devices for which they worked longer and have sufficient design knowledge of those devices. The recent trend in the research of embedded system technology also reveals that the scientists and engineers are carrying out their research work not only on the core embedded devices but also on green and sustainable philosophy in their design and development. Hence quantifying environmental impacts in manufacturing process of the embedded devices like mobile phones, integrated circuits, printed circuit boards, printed antenna and so on are the scopes of future research. With this initiation, we are pleased to share through this chapter our research insight to figure out the types of emissions and their quantitative footprint in fabrication process of rigid substrate printed antenna.

We have developed a low profile rigid substrate tip truncated triangular printed antenna operating at 1.176 GHz based on epoxy resin substrate shown in Fig. 6.1. This is a novel antenna design for low cost, triangular patch and usage in satellite navigation based applications. The detailed design and development process are discussed in Chapter 2 [70]. The rigid substrate based antenna is very common in electronic circuit and systems, therefore such kinds of devices are fabricated and manufactured massively in the electronic devices industries. This motivation led us to explore and quantify environmental footprint of rigid substrate printed antennas during their manufacturing process and disposal.

The characteristic performance of an RF(radio frequency) devices depends on the dielectric constant of the substrate. A substrate is an electrically insulated portion of a PCB (printed circuit board) or in other words the material upon which a semiconductor devices or metal trace pattern is grown up. FR4-glass epoxy resin is a popular flame retardant substrate used in PCBs, patch antennas and several electronic circuit boards due to its high performance physical, mechanical, thermal and electrical characteristics.

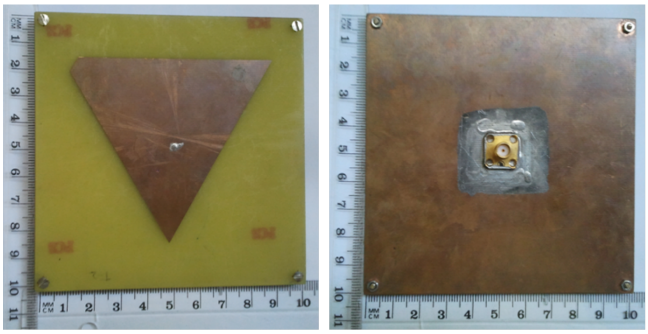

Figure 6.1: Developed Printed Antenna: Left- Active patch side, Right- Ground face with coaxial probe feed

6.2 Related Works

Substantial experiments and investigations have been carried out on several key areas related to design, development and analysis of printed microstrip and patch antennas [12]-[15], [93]-[95]. The existing research environment do not include the frontier on sustainability, environmental impacts assessment for these widely used antennas. In our published literature [96]-[97], [66], [69] we have evaluated sustainability, environmental assessment and toxic emissions during manufacturing process of RFID based systems [66]. Similarly an insight into quantitative environmental emission analysis of printed circuit board [97] is another published literature where the environmental emissions has been depicted in raw material and production processing stages. we found a number of published articles [62-64, 78-81, 98] that focus on quantifying environmental footprint, life cycle assessment and sustainability issues of ICT equipments.

Table 6.1: Process Interpretation of Epoxy Resin Printed Antenna

S.N.	Flows	Amount(kg)	Unit
1.	Copper[Metals]	0.1	kg
2.	Epoxy Resin[Plastics]	1	kg
3.	Thermal Energy	0.001	Mega Joule

6.3 Employed Methodology and Database Constraints

The research report [99] entitled as "Analysis of Existing Environmental Footprint Methodologies for Products and Organizations: Recommendations, Rationale and Alignment" published by Institute for Environment and Sustainability, European Commission Joint Research Centre has proposed and recommended a most preferable methodological approach that aims to calculate the environmental footprints of the products and organizations. For product environmental footprint, "ISO 14044: Environmental management- Life Cycle Assessment" is a recommended method. This method is employed to analyze the environmental footprint of the printed antenna. Life cycle approach refers to taking into consideration the spectrum of resources flows and environmental interventions associated with the product, service, or organization from a supply chain perspective, including all phases from raw material acquisitions through processing, distribution, use and end of life processes. The life cycle approach which utilizes all the above considerations is known as cradle to grave life cycle assessment.

This work does not execute a complete cradle to grave life cycle assessment of the printed antenna, but we have considered all processes from the raw material extraction through the fabrication phase, therefore we say that this is cradle to gate life cycle assessment of the printed antenna. The LCIA (Life Cycle Inventory Analysis) database of epoxy resin, copper metals and associated energy for several nations are available into the LCA simulating software.

6.4 Modeling and Assumptions

The modeling plan of the developed antenna is shown in Fig. 6.2. To achieve the environmental footprint of the specified antenna, LCA approach is employed. The quantity of the materials and energy flows are also shown in Table 6.1. The physical dimension of the antenna is $10cm \times 10cm$. The thickness of the substrate is 4.8 mm. Tip truncated equilateral triangle microstrip patch has been grown up on the epoxy resin substrate. The physical length of the triangular side is approximately 78.55 mm with 6.11 mm tip truncated at the upper left corner. The masses of the copper metals and epoxy resin substrate are assumed to be 0.1 kg and 1 kg respectively for production of the antennas. The subtractive printing process has been employed to trace the antenna pattern. The energy required for this tracing is also assumed as 1 Kilo Joule. The drilling process is considered under cutoff criterion. This means that drilling does not have significant environmental footprint compared to the complete product fabrication process.

The Environmental emissions contain the emissions to air, fresh water, sea water, agricultural soil and industrial soil. The amount of emissions and their relative contributions are shown in Table 6.2. In the similar way, the other findings are shown in Fig. 6.3, Fig. 6.4, Fig. 6.5, Fig. 6.6 and Fig. 6.7 respectively.

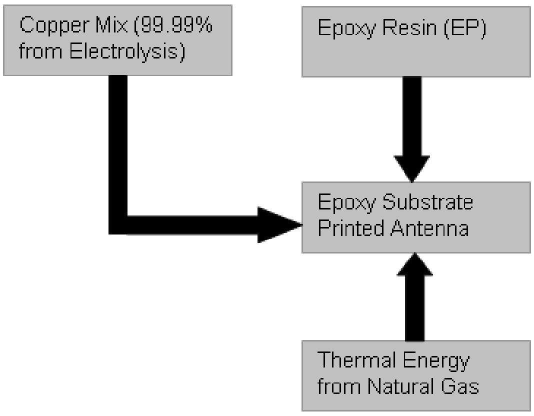

Figure 6.2: Modeling Plan for Epoxy Substrate Printed Antenna

Table 6.2: Environmental Emissions During Production

S.N.	Outputs Emissions to	Amount(kg)	Unit	Relative Contribution
1.	Air	74.8	kg	1.37%
2.	Fresh Water	5380	kg	98.6%
3.	Sea Water	1.79	kg	0.0327%
4.	Agricultural Soil	1.14E-6	kg	2.07E-8%
5.	Industrial Soil	0.000668	kg	1.22E-5%

6.5 Findings

Our work contributes a number of useful findings. Quantifying environmental footprint for a rigid substrate printed antenna is a major contribution. The environmental emissions such as emissions to air, fresh water, sea water, agricultural and industrial soil during the production processes are estimated in terms of amount of mass (kg) and their relative contribution to the total emissions. The subsidiary findings are estimation of global warming potential, acidification potential, eutrophication, ozone layer depletion and human toxicity potentials.

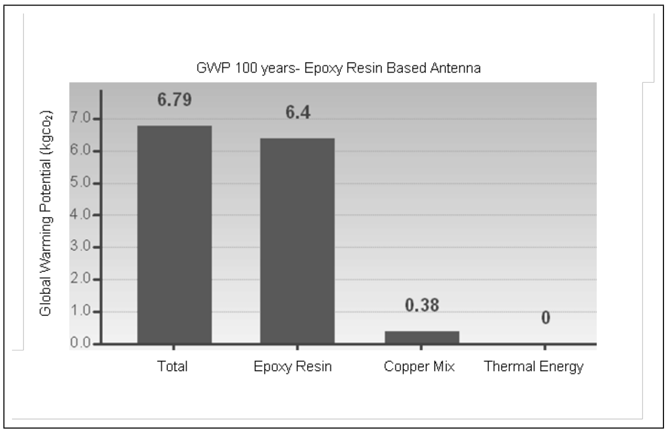

Figure 6.3: Global Warming Potential kg CO2 Equivalent

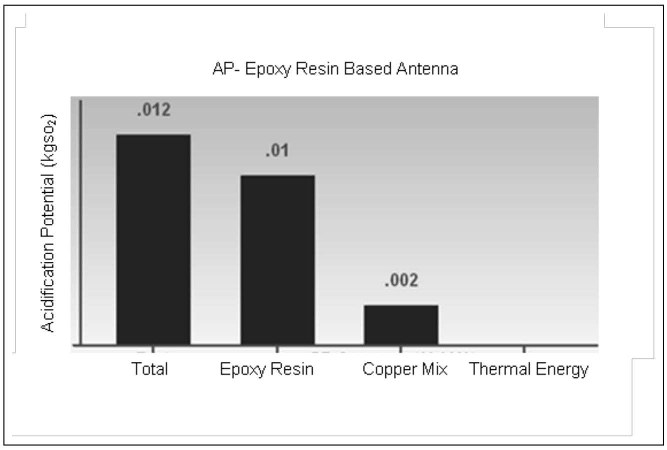

Figure 6.4: Acidification Potential kg SO2-Equivalent

6.6 Methodologies and Analysis

The modeled plan contributes environmental emissions as shown in Table 6.2 during the production process of the epoxy resin printed antenna. The relative contributions depict that the impact to fresh water is larger than emissions to air, sea water, agricultural soil and industrial soil. The other environmental impact categories are global warming, acidification, eutrophication and ozone layer depletion. There are different methods such as TRACI (Tools for reduction and Assessment of Chemical and other Environmental Impacts) and CML (Centre for Environmental Studies, University of Leiden) [100] that has been employed to perform life cycle impact assessment. We have considered the LCIA-CML methodology to achieve our research results.

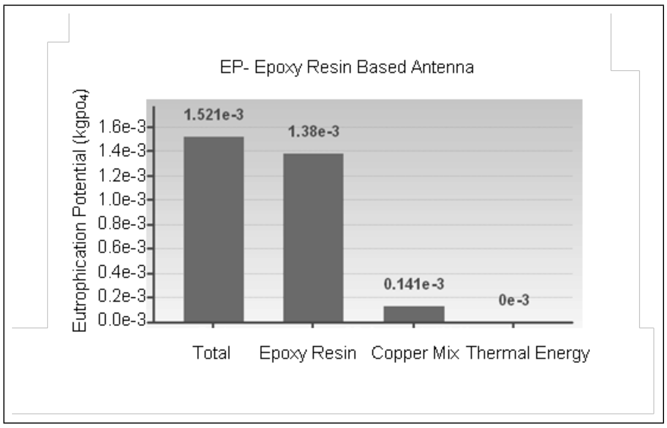

Figure 6.5: Eutrophication Potential kg Phosphate-Equivalent

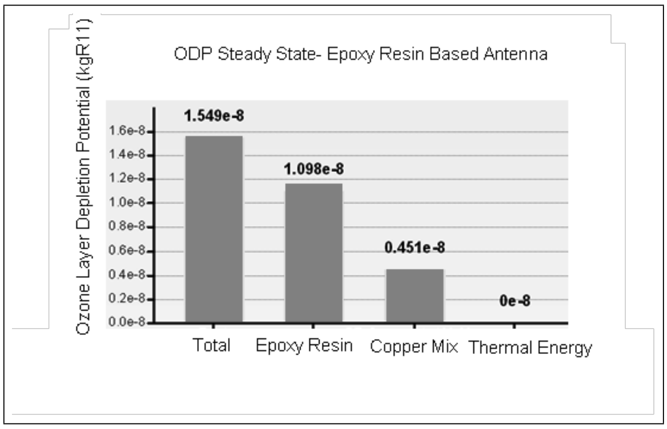

Figure 6.6: Ozone Layer Depletion Potential kg R11-Equivalent

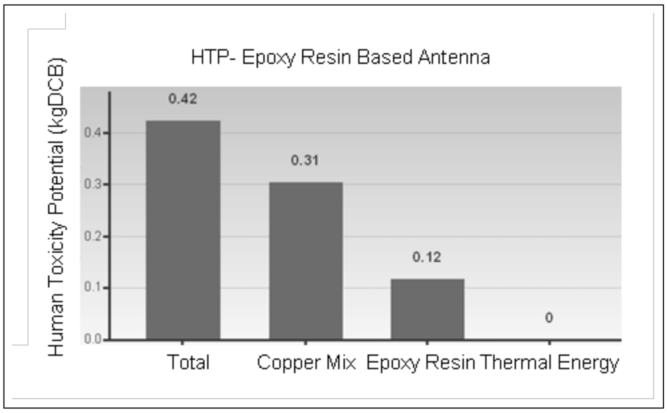

Figure 6.7: Human Toxicity Potential kg DCB-Equivalent

The global warming index for the epoxy resin printed antenna is the sum of the emissions weighted GWPs for each chemicals where m_i is the mass emission rate of the chemical i from the entire product system [101] as shown in Equation 6.1.

$$I_{GW} = \sum_{i=1}^{n}(GWP_i \times m_i) \tag{6.1}$$

where GWP_i is a common index for global warming potential, which is the time integrated climate forcing from the release of 1kg of a greenhouse gas relative to that from 1kg of carbon dioxide. Similarly acidification potential and eutrophication potentials are characterized by the following equations.

$$I_{AP} = \sum_{i=1}^{n}(AP_i \times m_i) \tag{6.2}$$

$$I_{EP} = \sum_{i=1}^{n}(EP_i \times m_i) \tag{6.3}$$

Where AP_i is acidification potential of any acid forming chemical relative to benchmark compound SO_2(sulphate) and EP_i is eutrophication potential relative to PO_4(phosphate). Similarly ozone layer depletion potential has been computed by the release of a specific quantity of the chemical relative to that caused by the same quantity of a benchmark compound trichlorofluoromethane (CFC-11, also known as R11) shown is the following equation.

$$I_{ODP} = \sum_{i=1}^{n}(ODP_i \times m_i) \tag{6.4}$$

On the basis of above equations (6.1) to (6.4), the several environmental impacts have been demonstrated. Figs. 6.3 to 6.6 clearly depict that epoxy resin causes more harmful impacts than the copper metals. Among total impacts, the magnitude of epoxy resin is dominating the others. Human toxicity potential has been analyzed on the basis of release of dichlorobenzene (DCB).

6.7 Consumption of Resources

The consumption of resources is shown in Table 6.3. Input resources comprise of energy resources and material resources. The energy resource is further classified into non-renewable and renewable energy resources. Non-renewable energy consumes resources from crude oil, hard coal, lignite, natural gas and uranium while renewable energy resources utilize the energy

Table 6.3: Resources Utilized for Production of Printed Antenna

S.N		Resources	Amount	Unit
		Total Resources	5260	kg
1.		Total Energy Resources	3.53	kg
	1.1	Non-renewable	3.53	kg
	1.2	Renewable	0	kg
2.		Total Material Resources	5256.47	kg
	2.1	Non-renewable Elements	0.242	kg
	2.2	Non-renewable Resources	28.1	kg
	2.3	Renewable Resources	5228.12	kg

form biomass and wood. Similarly material resource is classified into three categories. They are non-renewable elements, non-renewable resources and renewable resources. Non renewable elements are chromium, copper, iron, lead etc, non-renewable resources are materials like inert rock and sodium chloride. Renewable material resources are water, air, carbon dioxide, nitrogen and oxide.

6.8 Chapter Summary

We have presented cradle to gate life cycle impact assessment of the epoxy resin printed antenna. The outcomes such as global warming, acidification, eutrophication, ozone layer depletion and human toxicity potentials have been analyzed in the production process of the printed antenna. our results show that in production process, the emissions to fresh water is significantly larger than emissions to air, sea water and soils. There are several aspects of future research. The first important future work is to parametric analysis of the materials and energy associated with the processes. Secondly, consideration of use phase impacts and end of life impacts give rise to a complete cradle to grave life cycle assessment.

Chapter 7

Sustainable Production of Polymer and Paper Based RFID Antennas

This chapter will discuss sustainability, environmental assessment and toxic emission impacts during production process of polymer and paper based RFID tag antenna. At first, we will be discussing the evaluation of paper substrate printed RFID antenna. A novel environmental assessment approach, also known as computation of balance using associated databases is employed to determine the quantity of environmental emissions particularly in emissions to air, fresh water, sea water and industrial soil, in production process of polymer and paper based RFID tag antenna. We have developed a low profile antenna design for passive UHF RFID tags using both polymer and paper substrate with copper and aluminum for the antenna trace as shown in Fig. 7.1. Comparative analysis of toxic emissions during production process of polymer and the paper based RFID antennas are discussed in this chapter. Our results show that the paper based RFID antennas yield lower organic emissions to the environment in general while considerably higher inorganic emissions to the air. The results also depict that air is highly affected with the toxic emissions compared to emissions to fresh water, sea water and industrial soil.

7.1 Background

In recent years, environmental awareness has increased in all sectors of electronic device manufacturing. With the growing demand of printed electronics and radio frequency based products, the toxic emission generated during manufacturing process has become an important issue for an RF designer. “Silicon Systems for Sustainability” and “Electronics for Healthy

Living" have become the recent themes for ICT designers, and manufacturing industry. Hence, in this work, we undertake an attempt to analyze the comparative emissions of toxic gases during the production of polymer and paper based RFID tags. RFID technology falls under Restriction of Hazardous Substances and Services (RoHS 2002/95/CE) regulation regarding environmental issues just like other electrical and electronic devices. We have considered inkjet printing methodology in production of RFID antennas and have developed a model using a life cycle assessment (LCA) software. The major compositional components of printing materials and RFID antenna are studied with reference to emissions to the environment. Substantial research has been conducted on several key areas related to the technological sustainability, life cycle assessment and environmental impacts of printed electronics materials. The academic literature has not focused on quantitative toxic environmental emissions to air, fresh water sea water and industrial soil in production of RFID based printed antennas. Hence we have made an effort to quantify the total environmental emissions, its impacts analysis, to figure out amount of resources consumption and toxic emissions during the manufacturing process.

In the existing literature and research results published in [66], [68], [96], [102], [103], it was found that emission to the air is one of the significant emissions that lead to produce toxic gases during the production process of RFID based antennas. In the similar way, a research result in [97] reveals that printing process is one of the most important environmental hot spot in production process of printed circuit board (PCB). In addition, these literature offer end results dealing with sustainability, environmental assessment, life cycle analysis (LCA) and end-of-life (EOL) of printed electronic devices.

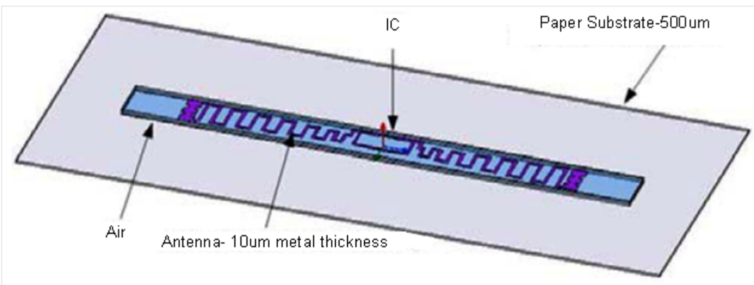

Figure 7.1: Development of Paper based RFID tag. The substrate and antenna trace material are respectively paper and Aluminum metal

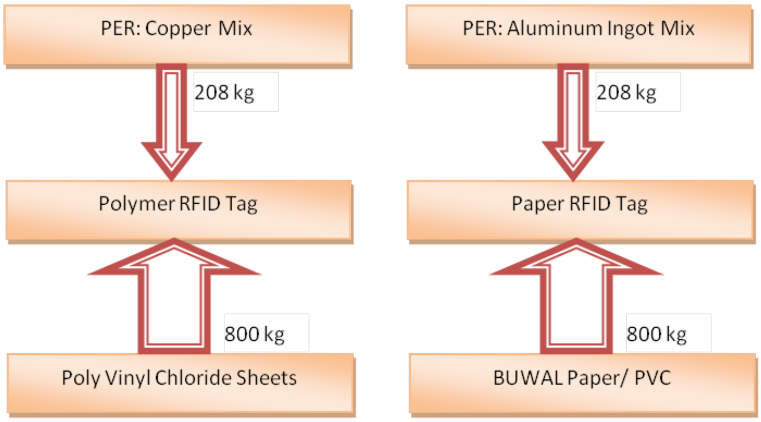

Figure 7.2: Plan for Polymer and Paper Based RFID Tags. The rectangle shows the processes where as arrow shows the flows

7.2 Paper Based RFID tags

State of the art technology has substantial contribution in attainment of environmental sustainability [62-64, 98, 104]. To keep the environment green and healthy, researchers should focus on the environmental assessment, sustainability and toxic emissivity during design and manufacturing of RFID based systems. Here we have put our effort to analyze the environmental impacts in terms of emissions to air, fresh water, sea water and industrial soil. In this section, we have attempted to examine the following research questions. What are the quantitative emissions in manufacturing process of printed RFID tag antenna? How severe are the impacts of environmental emissions to air, fresh water, sea water and industrial soil? What are the major resources consumptions? What is the amount of toxic emission during its manufacturing process?

7.2.1 Environmental Assessment

One of the main objectives of this work is to quantify the environmental emissions during manufacturing process of polymer and paper substrate printed RFID Antenna. The plan for paper substrate printed RFID antenna is shown in Fig 7.2. It comprises of a plan 'paper RFID antenna' along with two connected processes 'aluminum ingot mix' and 'paper wood free coated'. We have estimated consumption of raw materials in fabricating 6.3 million of printed antennas.

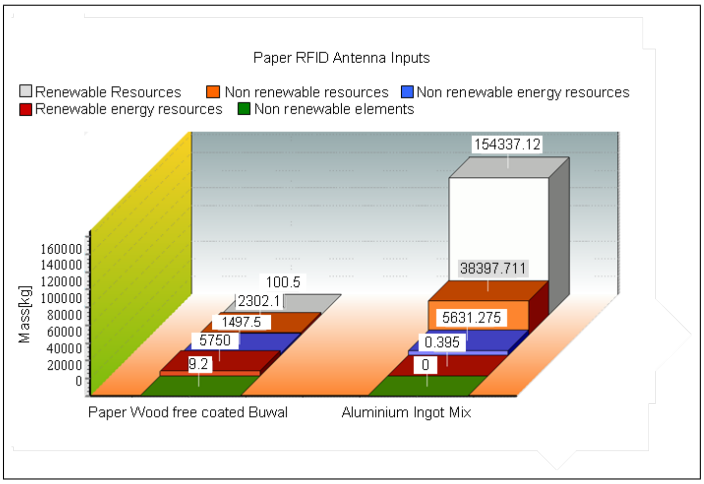

Figure 7.3: Paper RFID Antenna-Input resources

Resources Utilization

For the production of paper substrate printed RFID antennas, Fig. 7.3 shows that aluminum ingot mix utilizes 154337 kg of non renewable energy resources where as wood free coated paper uses mostly renewable energy resources and its quantity is 5750 kg. Non renewable resources normally contain bauxite and limestone as a majority composition where as calcium chloride, chromium ore, copper ore, ferromanganese and natural aggregate are the minority components. Similarly the majority components of renewable resources are water and air. There are different categories of water resources such as feed water, ground water, river water, sea water, surface water and well water. Among these categories coated wood free paper mostly consumes ground water and its quantity is 15059 kg.

Emissions to Air

Paper RFID antenna produces harmful emissions to air caused by inorganic components such as ammonia, carbon dioxide, carbon monoxide, steam and so on. Fig. 7.4 shows emissions to air. The percentage of other emissions to air such as heavy metals to air, particles to air and organic emissions to air are comparatively less significant. From the output database, it has been mentioned that during the use phase of paper RFID antenna, it emits 40698 kg of inorganic emissions to the air.

Emissions to Fresh Water

An emission to fresh water includes the following components: Analytical measures to fresh water, heavy metals to fresh water, inorganic and organic

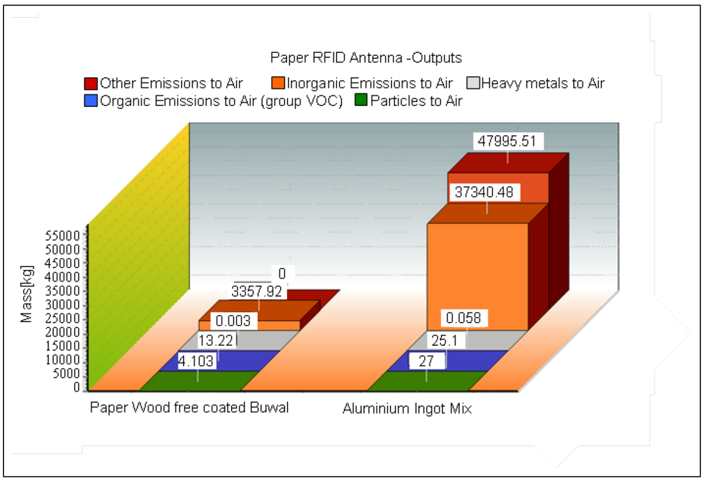

Figure 7.4: Emissions to Air

emission to fresh water and other emissions (release of waste water). It is illustrated in Fig. 7.5 that 286 kg of emissions to the fresh water have produced in use phase of RFID antenna out of which 180 kg produced by coated paper and 106 kg by aluminum ingot mix.

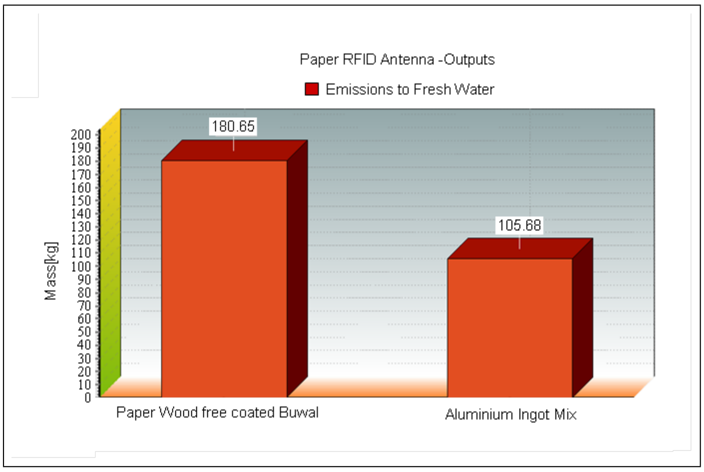

Figure 7.5: Emissions to Fresh Water

Emissions to Sea Water and Industrial Soil

An emission to sea water is mainly due to copper component of the paper based RFID antenna. There is no emission due to PVC sheet to the sea water. The total quantity of emissions to the sea water is around 45 kg for specified RFID antenna mass in its use phase period. The analytic measures to the sea water contains absorbable organic halogen compound (AOX), biological oxygen demand (BOD) and chemical oxygen demand (COD). Beside these components heavy metals is also one of the pollutants to sea water. Inorganic emissions to sea water, hydrocarbons to sea water, heavy metals and analytical measures are shown as the major composition of the emission. The inorganic emissions to sea water dominate among others, 44 kg of emissions occur due to inorganic components.

Manufacturing process of paper substrate RFID antenna causes insignificant amount of emissions to the industrial soil. In total, 294 gram of emissions to the industrial soil take place in the production of printed RFID antenna. The emissions to industrial soil comprise of inorganic, organic and heavy metal components.

7.2.2 Sustainability Issues

The core concentration has focused on the sustainability and environment friendly issues while designing and developing the antenna. This section describes potential sustainable and environment friendly issues which need to be consider while developing the antenna. The most prominent issue is to follow ROHS 2002/95/CE EU regulation during development of RFID based systems. The directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment which is commonly referred to as the Restriction of Hazardous Substances Directive (ROHS) was adopted in February 2003 by the European Union [105]. A number of sustainability issues have been carried out during the analysis. They are bulleted as follows:

- We have used aluminum for antenna trace. Possibly aluminum is one of the world's most available resources. Aluminum has superior characteristics over copper in terms of disposability viewpoint. Normally RFID tags are likely to be used only once or twice and then be disposed either into incineration or landfills. Aluminum is more environment friendly than copper if it is being incinerated.

- Another potential sustainability issue during manufacturing RFID based system is printing methodology. The traditional printing employs subtractive process using mask plates. Here we have used an inkjet printing method which is an additive process and the valuable materials are deposited only on the desired location. Mass and energy savings, reduction of unwanted emissions and low production cost are the benefits over subtractive printing process.

- The developed antenna is ROHS regulation complaint. It does not employ any components which violates the regulation.

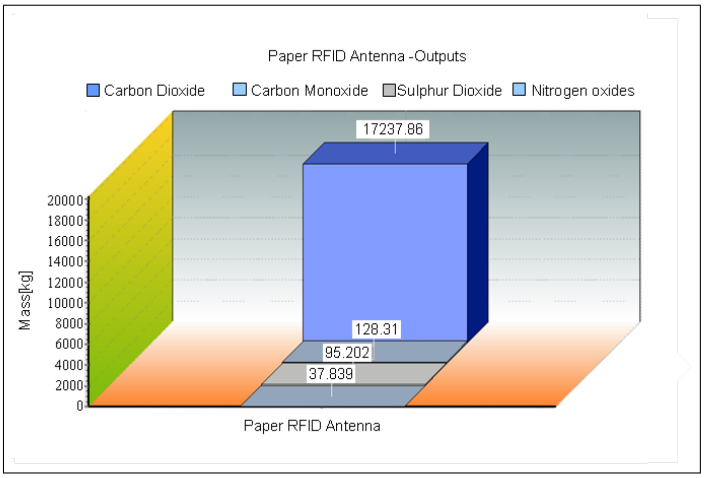

Figure 7.6: Toxic Gas Emissions-RFID antenna

7.2.3 Toxic Emissions

Here toxic emissions in the manufacturing process of paper substrate printed RFID antenna is illustrated. The emissions to air comprise of heavy metals, inorganic, organic and exhaust air. Inorganic emissions to air include hazardous discharges. In the production of printed RFID antennas, it is evident that toxic gases such as carbon dioxide, carbon monoxide, hydrogen, nitrogen dioxide, nitrogen oxides and sulpher dioxide are evolved during the manufacturing process. The amount of different toxic gas emissions are shown in Fig. 7.6. The emission of carbon dioxide is clearly the largest among all toxic emissions.

7.2.4 Results Analysis

System boundaries of an LCA system consume resources as inputs and generate outcomes in terms of environmental emissions. Input resources are classified into two types: energy resources and material resources. The energy resources are further classified into non-renewable and renewable energy resources. Non-renewable energy consumes resources from crude oil, hard coal, lignite, natural gas and uranium while renewable energy resources utilize the energy form biomass, wood water and air. Similarly material resource is classified into three categories. They are non-renewable elements, non-renewable resources and renewable resources. Non renewable elements are chromium, copper, iron, lead etc, non-renewable resources are materials like inert rock and sodium chloride. Renewable material resources are water, air, carbon dioxide, nitrogen and oxide. Table 7.1 shows the amount of resources utilized in production of paper substrate RFID antenna. Our

Table 7.1: Resources Utilized in Production Process of Paper Based RFID antenna

S.N		Resources	Amount	Unit
		Total Resources	2.08E5	kg
1.		Total Energy Resources	12879	kg
	1.1	Non-renewable	7128	kg
	1.2	Renewable	5750	kg
2.		Total Material Resources	1.95E5	kg
	2.1	Non-renewable Elements	9.2	kg
	2.2	Non-renewable Resources	40700	kg
	2.3	Renewable Resources	1.54E5	kg

results shown in Table 7.2 depict that 99.6% of the total emissions occurred to the air and remaining to the fresh water, sea water and industrial soil. Table 7.2 also shows the amount of specific components that cause emissions to air, fresh water, sea water and industrial soil.

7.3 Comparative Toxic Emission Study

The low profile antenna shown in Fig. 7.1 is a design for passive UHF RFID tags using both polymer and paper substrate with copper and aluminum respectively for the antenna trace. In this part of the chapter, study and analysis of comparative toxic emissions in production process of polymer and paper substrate printed RFID tags are carried out. Based on the quantity of materials and type of devices employed for fabricating the antenna, we have analyzed the types of toxic emissions and their quantities during production process. So far we have considered inkjet printing process for tracing the pattern of the tag. The published research results in [86]-[91] provide the knowledge of design of printed antenna, wight, dimension and size of antenna's elements, substrate selection and printing methodologies. It is important to become familiar with this knowledge to model the schematic of polymer and paper based RFID tag antennas shown in Fig.7.2 and compute toxic emissions during production process. The detail database of the environmental impacts for the paper based RFID antenna are shown in Appendix A.

7.3.1 Modeling Layout

The modeling layout of the proposed RFID tags are shown in Fig. 7.2. Copper mix and polyvinyl chloride sheets are considered as the major fundamental components of the polymer based RFID tags that generate substantial

Table 7.2: Environmental Impacts Assessment Production Process

S.N	Environmental Impact	Amount	Unit
1	**Emission to Air**	88763	kg
1.1	Heavy Metals	0.06	kg
1.2	Inorganic Emissions	40698	kg
1.3	Organic Emissions	38	kg
1.4	Other Emissions	47996	kg
1.5	Particles to Air	31	kg
2	**Emission to Fresh Water**	286	kg
2.1	Heavy Metals	3.42	kg
2.2	Inorganic Emissions	117	kg
2.3	Organic Emissions	0.33	kg
2.4	Other Emissions	0	kg
2.5	Particles	15.5	kg
2.6	Hydrocarbons	0.3	kg
3	**Emission to Sea Water**	46	kg
3.1	Inorganic Emissions	44	kg
3.2	Organic Emissions	0.02	kg
3.3	Particles	1.11	kg
4	**Emission to industrial Soil**	0.29	kg
4.1	Heavy Metals	0.06	kg
4.2	Inorganic Emissions	0.22	kg
4.3	Organic Emissions	0.005	kg

toxic emissions into the environment. Likewise aluminum ingot mix and paper wood free coated BUWAL are significant constituent of paper based RIFD tags. The amounts of those constituents for respective tags are also presented in Fig. 7.2. The masses of every essential component were chosen such that proposed quantities of the tags would be one million. Gabi's balance optimization approach has been implemented to explore possible toxic emissions in production process of the respective tags. The explicit plans for both tags are composed considering their boundary conditions, i.e. actual processes taking place and the flows representing all the inputs and outputs related to the system.

7.3.2 Comparative Toxic Emissions

The inorganic and organic emissions to the air is shown in Fig. 7.7. Inorganic and organic emissions contain toxic gases. In the production of polymer and paper RFID tags, it has been noticed that manufacturing polymer RFID tags release a total of 3786.35 kg of inorganic emissions while paper RFID tags yield 6460 kg in their manufacturing process which is 70.6% more polluting compared to the aforementioned tags. The diagram illustrates the masses of emissions caused by each individual component of both the tags. The appearance of the inorganic emissions act as predominant over organic emissions while highly toxic gases like methane and dioxins fall into this category. The inorganic emissions are composed of the toxic gases like ammonia, carbon dioxide, carbon monoxide, hydrogen, nitrogen dioxide, sulphur dioxide. The quantitative emission of carbon dioxide is highly abundant compared to other toxic gases. The classification and labeling guide of European Industrial Gases Association (EIGA) has mentioned [106] that one gram of dioxins is significantly more harmful and health hazardous than one kilogram of carbon dioxide.

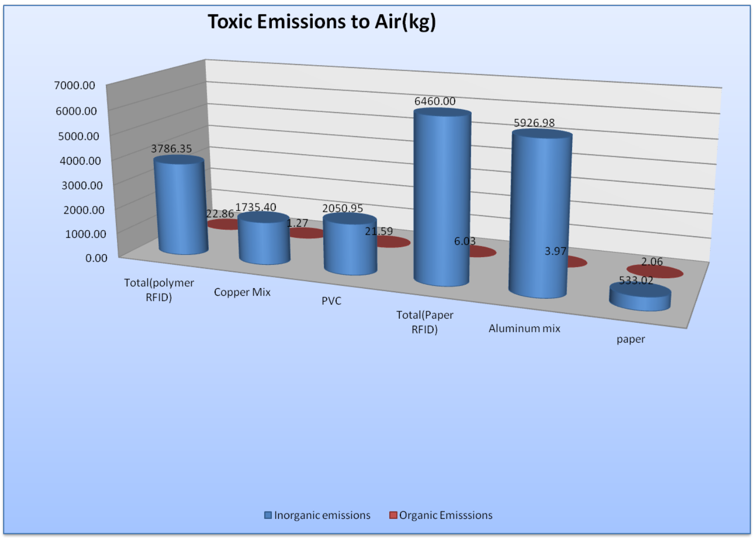

Figure 7.7: Mass of Emissions caused by each component of Polymer and Paper RFID Tag

Table 7.3: Comparative Toxic Emissions in Production of one million Polymer/Paper RFID Tags

S.N	Polymer RFID Tag				Paper RFID Tag			
	Major Inorganic Components		Major Organic Components		Major Inorganic Components		Major Organic Components	
	Types	Amount	Types VOC*	Amount	Types	Amount	Types VOC	Amount
1.	Carbon Dioxide	2835kg	Methane	20kg	Carbon Dioxide	2736kg	Methane	4.76kg
2.	Carbon Monoxide	3.1kg	Dichloro Ethane	38g	Carbon Monoxide	20kg	NMVOC**	1.27kg
3.	Hydrogen	3.3kg	Chloroethane	62.5g	Hydrogen	14.6kg	Chloroethane	0g
4.	Nitrogen Dioxide	4.5kg	Dioxins	23mg	Nitrogen Dioxide	1.11kg	Dioxins	0g
5.	Nitrogen Oxides	1.7kg	Ethane	36g	Nitrogen Oxides	5.8kg	Ethane	0g
6.	Sulphur Dioxide	10kg	Propane	55g	Sulphur Dioxide	15kg	Propane	0g

*VOC:Volatile Organic Compounds

**NMVOC: Non-Methane Volatile Organic Compounds

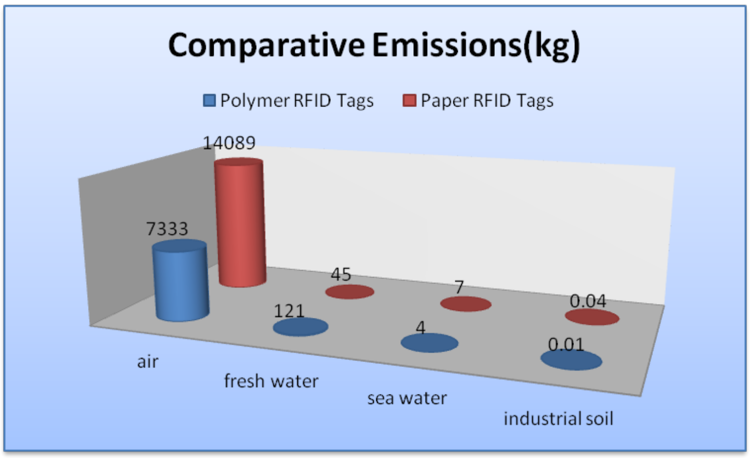

Figure 7.8: Comparative Emissions to Air, Fresh Water, Sea Water and Industrial Soil

Table 7.3 shows the comparative inorganic and organic emissions to air in production of polymer and paper based RFID tags. If we notice the emission data in Table 7.3, we will find that polymer based RFID tag releases more carbon dioxide but considerably lower amount of carbon monoxide than paper based RFID tag. The odorless organic hydrocarbon gas, methane whose NFPA (National Fire Protection Association) [107] health and fire ratings are respectively 1 and 4 is introduced during production of polymer and paper RFID tags. The quantity of emission of methane gas is 20 kg and 4.76 kg respectively in both the tags. The organic toxic gases like Chloroethane, Dioxins, Ethane and Propane are found only in polymer RFID tag production.

In Fig. 7.8, comparative quantities of emissions to air, fresh water, sea water and industrial soil have been illustrated. This figure demonstrates that air is highly affected compared to other ecological elements (fresh water, sea water and industrial soil). The fresh water and sea water categories include toxic emissions like ammonia, metal chlorides, phosphorous, and halogenated organic hydrocarbons. Industrial soil is least affected in both polymer and paper RFID tags production. Radioactive emission has appeared to the air but not appeared to fresh water, sea water and industrial soil. 127 mg and 788 mg of radioactive emissions have been found in polymer and paper based RFID tags respectively.

7.4 Chapter Summary

Two different RFID structures have been examined for their materials content and have been analyzed with the toxic potential indicators such as carbon dioxide, carbon monoxide, hydrogen, methane, chloroethane and dioxins. We have analyzed that air is one of the hot environmental spots in the ecosystem, which is highly affected with the toxic emissions produced during manufacturing process of polymer and paper based RFID tags. The analyzed inorganic and organic emissions to air depict that paper RFID tags produces considerably higher inorganic emissions while they produce a smaller amount of organic emissions. Comparative emission chart shown in Fig. 7.8 renders that paper RFID tags which consume aluminum materials for antenna trace cause more toxic emissions to the environment.

Chapter 8

End-of-Life Study of Polymer and Paper Based RFID Antennas

In the previous chapter, we have discussed toxic emissions analysis and in production process of polymer and paper substrate RFID antenna. In this chapter, end-of-life (EOL) analysis of polymer and paper based radio frequency devices are carried out. End-of life of a product is an important phase of the life cycle, that needs to be explored to carry out essential investigation for pursuing a complete cradle to grave life cycle assessment. Polymer and paper based RFID antenna has been chosen as a radio frequency devices for exploring the necessary life cycle investigations. Precisely, in this chapter, an attempt has been made to investigate and evaluate the environmental emissions at end-of-life-cycle stage and to explore type and quantity of emissions at their disposal. Each significant component of the antenna and their corresponding emissions has been investigated in this chapter. We have also compared the corresponding emissions to air and fresh water in both the technologies i.e. incineration and land-filling at EOL stage.

8.1 Background

People around the world are voicing about the state of the physical environment, global warming and growing adverse environmental effects. The rapid increases in products manufacturing around the globe undoubtedly affect the natural environmental conditions. With the rapid manufacturing technology, one should also consider the quantity and type of emissions in the process of raw material preparation, production and end-of-life stages. Beside this, there is a need to explore environmental assessment, sustainability aspects and disposing methodologies of the manufactured products.

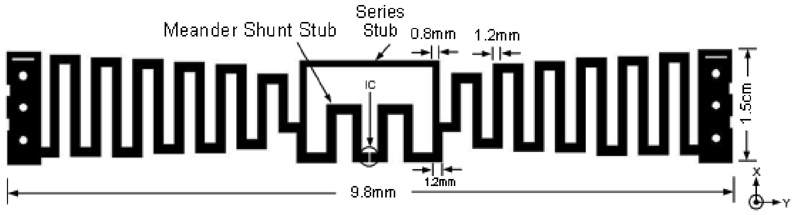

Figure 8.1: Layout of UHF RFID tag antenna for European frequency band

The study of End-of-Life (EOL) of a product has been demanded among the people due to increased concerns of the environment [61, 65]. EOL is a term used with respect to a product supplied to customers, indicating that the product is at the end of its useful life time and a vendor will no longer be marketing, selling, or sustaining a particular product and may also be limiting or ending support for the product. In the specific case of product's sales, the term end-of-sale (EOS) has also been used. The term life time, after the last production date, depends on the product and is related to a customer's expected product life time. Different life time examples include electronic products from fast food chains (weeks or months), cars (10 years), and mobile phones (3 years).

Based on the above facts, we have motivated to investigate the environmental assessment, to analyze the emissions into the air and fresh water and to explore the disposal methodologies of the fabricated RFID antenna [88].

We have developed an efficient flexible UHF RFID tag antenna operating at 866-868 MHz based on polymer and paper substrate as shown its layout in Fig. 8.1 [88]. This is a novel antenna design for passive UHF RFID tags using polymer or paper substrate with aluminum metal for antenna trace. We have presented the sustainability evaluation, environmental assessment and hazardous emissions during raw material and production processes in the chapter 7. This work is a continuation of the earlier works. The research questions for this chapter are: What are the emissions to the air and fresh water at the end-of-life of paper and polymer substrates? What are the comparative amount of emissions in incineration and land filling EOL technologies?

The chapter is structured as follows. The next two sections provide descriptions about the related work and proposed methodologies respectively. The section 8.4 describes the achieved results and their analysis. We have also presented the tabular explanation about the emissions in the process of incineration and land-filling this section. Chapter summary has been presented in section 8.5.

8.2 Related Works

Substantial research has been conducted on several key areas related to end-of-life of the electronic products. Some of them are methods of estimating end-of-life electronics exports [108], prioritizing material recovery for end of life printed circuit board [61] and tracking the material, energy and value of end of life of lithium ion batteries [65]. In our previous work, we focused on life cycle assessment of printed antennas particularly on raw material and production processes [66] and presented an insight into quantitative environmental analysis of printed circuit board [97]. The present academic literature has not focused on analysis of end-of-life of RFID based antennas. Hence here our work is to quantify the environmental emissions in particular to the air and fresh water, and to explore the quantities of emissions in the process of incineration and land-filling at the end-of-life stage of RFID based antennas.

8.3 Proposed Plan

A process is defined by its input and output flows. The plan comprises of different manufacturing processes. Usually manufacturing process of printed antenna requires two major substances i.e. paper or poly vinyl chloride (PVC; here also named as polymer) as a substrate and aluminum ingot mix as an antenna trace. These are the input parameters for life cycle assessment (LCA). During the process interpretation one has to consider quantity, amount and particular unit of the materials. The output results of LCA depend on how input parameters and their magnitudes are considered during the process. The real composition and magnitudes of the printed RFID antenna can be obtained after life cycle inventory analysis (LCIA). Table 8.1 shows the process interpretation for manufacturing printed paper and polymer substrate RFID antennas. The masses of materials are chosen as per the knowledge of materials and devices employed for fabrication of antennas. The plan for paper or polymer substrate printed RFID antenna is similar to the figure shown in Fig 7.2. It comprises of a plan ‘paper/polymer RFID antenna’ along with two connected processes ‘aluminum ingot mix’ and ‘paper wood free coated or polymer’. We have generated the model such that the production of 6.3 million printed RFID antennas require 5000 kg of wood free coated paper or polymer and 1300 kg of aluminum ingot mix. The total number of products (printed RFID antennas) is scalable with the masses of substrate and antenna trace material.

Table 8.1: Process Interpretation of Paper/Polymer RFID Antenna

S.N.	Flows	Amount(kg)	Unit
1.	Paper Coated/PVC	5000	kg
2.	Aluminum ingot	1300	kg
3.	Total Production (No. of Pieces)		6.3 Million

8.4 Results Analysis

A number of useful outcomes have been generated which explicitly describes the theme of this chapter. Initially we have considered unit mass(kg) of paper, polymer and aluminum to figure out the quantities of emissions at end-of-life stage. We have achieved the quantities of emissions for each significant component of the polymer and paper based RFID antennas after several iterations of simulation. In our next attempt we configure the proposed plan with the specified amount of components to constitute two separate antennas, one is made from paper substrate and the other is from polymer substrate. These results have been illustrated in the following subsections.

8.4.1 Emissions: Significant Components

We have computed the quantity of emissions for both EOL processes i.e. incineration and land-filling. The concerned outputs for both the processes have been exemplified in the following paragraphs. Paper, polymer and aluminum have been considered as the significant components for polymer and paper based RFID antennas. Fig. 8.2 and Fig. 8.3 show the numerical assessment for the amount of emissions to each significant component (paper, PVC and aluminum) in the process of incineration and land-filling

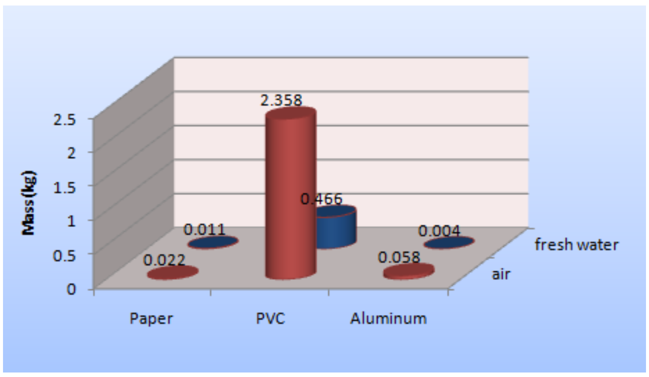

Figure 8.2: Amount of emissions in incineration process

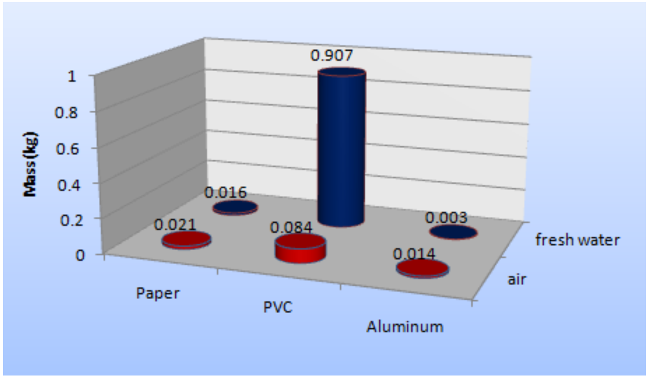

Figure 8.3: Amount of emissions in land-filling process

Table 8.2: Emissions from Significant Components

1.		**Incineration**		
S.N.	Unit Mass(kg)	To air	To fresh water	Unit
1.1	Paper	0.022	0.011	kg
1.2	Polymer	2.358	0.466	kg
1.3	Aluminum	0.058	0.004	kg
2.		**Land-filling**		
S.N.	Unit Mass(kg)	To air	To fresh water	Unit
2.1	Paper	0.021	0.016	kg
2.2	Polymer	0.084	0.907	kg
2.3	Aluminum	0.014	0.003	kg

respectively.

The incineration of paper produces less polluting emissions to the air and fresh water compared to polymer and aluminum. The exact figures for these emissions have been shown in Table 8.2.

8.4.2 Comparative EOL Emissions: RFID Antenna

The comparative end-of-life emissions have been computed for both the processes of incineration and land-filling. Fig. 8.4 demonstrates the comparative analysis for amount of emissions to the air where as Fig. 8.5 exemplifies the amount of emissions to the fresh water. The essential elements and their proportions causing emissions to the air and fresh water in process of incineration and land-filling have been illustrated in Table 8.3. Heavy metals, Inorganic, Organic and particles are the common forms of emissions to the air and fresh water. The results depict that the polymer based RFID antenna causes more polluting emissions to the air and to the fresh water

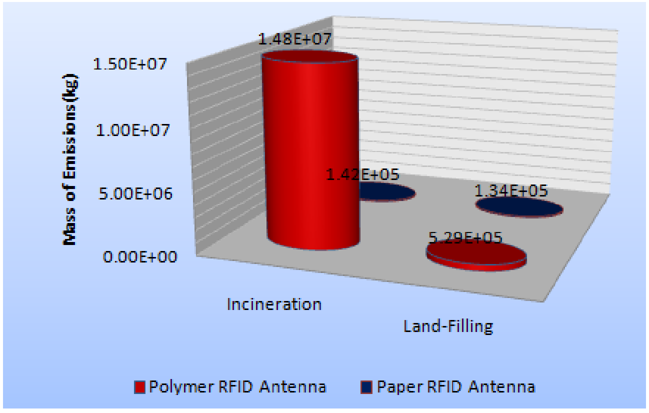

Figure 8.4: Comparative emissions to air

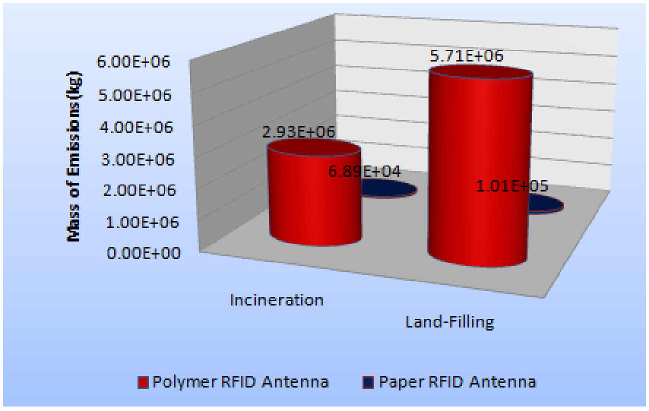

Figure 8.5: Comparative emissions to fresh water

compared to the paper based antenna in both EOL technologies.

8.5 Chapter Summary

This research work offers several essential contributions. The results show that incineration and land-filling of paper causes polluting emissions to the air and fresh water. The emissions to the air contain key toxic components such as carbon dioxide, carbon monoxide, and hydrogen chloride, and ammonia. A smaller proportion of emissions to the industrial soil have been observed additionally in the process of land-filling of paper in spite of emanating identical emissions to the air and fresh water in both EOL technologies of incineration and land-filling.

Another imperative outcome clearly demonstrates that the incineration and land-filling process of unit mass(kg) of aluminum release 56.1 gram and

Table 8.3: Environmental Imapcts at End-of-Life Stage

S.N.	Environmental Impact	Incin.: Polymer	Incin.: Paper	Land-Filling: Polymer	Land-Filling: Paper	Unit
1	Emission to Air	14854140	141567	529962	134013	kg
1.1	Heavy Metals	4.65	1.75	1.10	1.36	kg
1.2	Inorganic Emissions	14796810	140074	479864	132967	kg
1.3	Organic Emissions	6591	1024	50016	831	kg
1.4	Particles to Air	50922	467	79	215	kg
2	Emission to Fresh Water	2935359	68890	5715864	100705	kg
2.1	Heavy Metals	192	136	85	63	kg
2.2	Inorganic Emissions	2931768	60499	2962575	85982	kg
2.3	Organic Emissions	91	30	36	46	kg
2.4	Particles to Fresh Water	1029	94	83	113	kg

13.5 gram of carbon dioxide respectively. The amount of carbon foot print deposition in both EOL technologies suggests that land-filling is an environment friendly technique for disposing aluminum metals. The polymer shows a remarkable characteristic among several fabricating components of RFID antenna. The polymer needs to be disposed with substantial care as incineration of unit mass (kg) produces 2.358 kg emissions to the air and 0.466 kg emissions to the fresh water.

The comparative study on end-of-life of polymer and paper based RFID antennas concludes two important facts. The selection of substrates during manufacturing an RIFD antenna plays an important role in EOL stage. With the similar performance (Gain, Bandwidth and Resonant Frequency) obtained using polymer or paper material, the paper substrate RFID antenna would be advantageous in terms of environmental emissions in all the stages of its life cycle. Secondly land-filling process causes lesser harmful emissions to the environment for both polymer and paper based RFID antenna.

The important future work is to figure out amount of toxic emissions especially carbon dioxide, carbon monoxide and nitrous oxide in the manufacturing process of polymer and paper RFID devices.

Chapter 9

Course Development for Green ICT

In the earlier chapters, design, methodologies and the performances of the printed antennas have been carried out. This chapter addresses the development of a green ICT course for the curriculum of Master and PhD level studies at University of Turku. An attempt has been made to demonstrate its necessity, implementation issues and strategic plans to execute this course at university level education. General structural plans along with details of the course content are discussed in this chapter. The course aims to provide a unified view of sustainable embedded system technologies, practices of using efficiently computers and telecommunication equipments, environmental assessment strategies and life cycle management of electronic components as well as end-products. The objective of this new course is to give knowledge and foresight toward assessment of environmental impacts. This course will also be capable of imparting knowledge of sustainable design approach in life cycle of the materials, manufacturing processes, use, reuse and recycling of the electronic equipments and components. The course has been proposed of 5 ECTS credit units inclusive of extensive theoretical lectures and lab exercises using suitable environmental assessment software tools.

9.1 Introduction

Innovative research on environmental friendly products and green computing have been carried out in several Finnish Universities. University of Turku is one of the leading universities in Finland and presently offering study and research assistance schemes in several faculties such as humanities, mathematics and natural sciences, medicine, law, social science, education and Turku School of Economics. The aim and ambition of the University of Turku is to provide professionals with a high-standard, multidisciplinary education which enables them to be creative, problem-solving and thinking out-of-the-box.

The Department of Information Technology under the faculty of mathematics and natural sciences was founded with the aims to provide higher education and state-of-the-art research programs in the areas of computer science, embedded systems and telecommunication for example. The faculty of mathematics and natural sciences has been conducting master level programs on bio-informatics, embedded computing [111]-[113], information technology [114], environmental science and astronomy. Together with these postgraduate studies, licentiate and doctoral degrees are an integral part of the education and research activities.

In recent years, green information and communication technology (GICT) [109]-[110] has become a major attraction for technologists, system developers and manufacturers because present trend of manufacturing industries and the developed products is to minimize the ICT's carbon footprint and to be "green". The impact of ICT on the earth's climate and its dwindling resources is another major concern. The recent research in the area of green technology depicts that carbon dioxide emissions from the data centers alone surpasses the harmful emissions from many individual countries. This is in addition to the fact that current ICT devices contain toxic substances such as leads and mercury. Furthermore substantial amount of these substances enter into the environment after the disposal of the devices.

Moreover, in present context of Green ICT research, environmental awareness has increased in all the sectors of electronics product manufacturing (EPM). With the growing demand of ICT devices, products and services and its adverse affect on earth's atmosphere, green manufacturing process has become one of the key focuses for ICT researchers. "Silicon Systems for Sustainability" and "Electronics for Healthy Living" have become recent themes for ICT designers, and manufacturing industry.

Based on the above facts, serious collaboration among technologists, system developers, researchers, consumers, and politicians is required to achieve green and sustainable ICT. For positive discussion about this course, we propose a course entitled as "Green ICT" which will be available in the upcoming curriculum of master and doctoral level studies at Department of Information Technology. The specific objectives of this course are:

- How to improve the efficiency of the ICT infrastructure: Utilizing energy efficient resources, equipments and deploying technologies such as virtualization and autonomic power optimization.[115]

- To impart students knowledge of environmental emissions impacts and sustainable design approach in context with life cycle assessment of the materials used in the design, manufacture, and recycling of ICT products

- To assist students in developing new technology, such as new materials, low voltage operations, increased integration and power aware ICT equipments and networks (both hardware and software).

- To give understanding how to improve the efficiency of ICT operations by deploying advanced cooling technologies, improving power distribution and optimizing physical placements of the resources used in the circuits and systems [115].

- Providing necessary knowledge to the students about recyclability and end of life management of the ICT equipments and the products [116].

- Increasing social awareness through policies

The chapter is structured as follows. The next two sections provide description about requirements of the course at university level and proposed structure of the course respectively. Section 9.4 describes the detailed content of the proposed course. In that section we have discussed all six chapter's topics and their contents. Course evaluation scheme and the chapter summary are the succeeding sections.

9.2 Requirement of the Course

The issue of man-made climate change and global warming has become a mainstream view of the environmental experts. Advanced research methodologies are developed at environmental research institutions to observe the impacts of ICT products on the environment. Even common people are increasingly aware of environmental issues and this change in attitudes is leading to increased demand for flexible, reusable and sustainable alternatives than throwaway consumer items. It has been observed that hazardous chemicals are often found in the soil, air and water surrounding the areas where ICT components are produced or disposed. ICT has significant environmental impact to these three main areas: [117]

- The production of computational equipment such as producing one PC together with an LCD monitor generates 193 kilos of greenhouse gases and releases of heavy metals and other pollutants.

- The use of computer equipment (mainly through electricity consumed both to run the machines and to cool data centers.

- The disposal of computer equipment i.e. electronic waste can release harmful substances that may have adverse effect on people's health

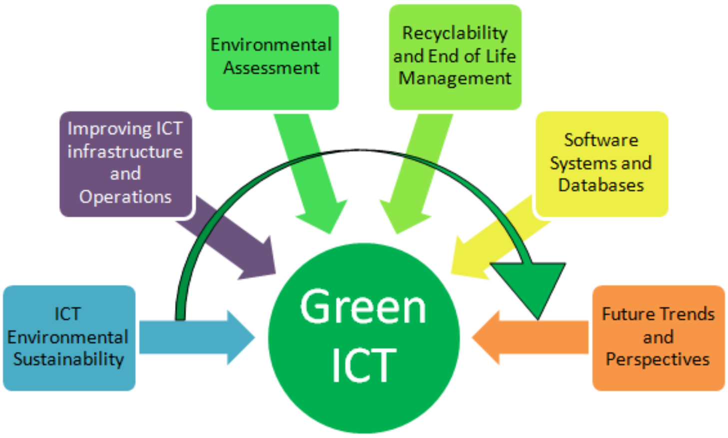

Figure 9.1: Flow of Topics in Green ICT Course

Hence there is a mounting pressure on the universities and research institutions to adopt more sustainable approaches to ICT production and in their use. This pressure basically comes from the government, from regulatory sources, and from the public, who are increasingly aware of the environmental impacts.

The present academic curriculum in master level embedded computing and information technology at university of Turku does not include courses on green computing or green ICT. Therefore, we made an attempt to develop a course on the subject. The theoretical lectures on sustainable life cycle of the ICT equipments and the products are expected to be covered in this course. Moreover this course will support the students in studying and analyzing a complete green solutions in ICT product manufacturing.

9.3 Proposed Course Structure

This 5 ECTS credit units course aims at conveying the flavor of green computing and sustainable design approaches to the master and PhD level students at department of Information Technology, University of Turku. Fig. 9.1 shows the topics to be covered in the green ICT course. Upon completion of this course, the student will be able to understand sustainable ICT design approaches and ICT environmental impacts. Specifically the students will be able to perform the followings:

- The students will be able to improve the efficiency of ICT infrastructures and operations by applying green design approaches. For example, they understand green approach of designing circuits and systems.

- The students will be able to quantify the emissions during the raw materials acquisition, production process and end of life of ICT products
- The students will be able to understand the role of ICT impact in context with global carbon footprint. They are capable of estimating releases of carbon dioxide emission of an organization

9.4 Detailed Course Contents

Fig. 9.2 shows the details of the topics to be covered in this course. In the following sub-sections, we are going to discuss strategic plans and implementation issues of each topic to carry out this course successfully.

9.4.1 ICT Environmental Sustainability

In this chapter, we will be focusing on green ICT definitions, global ICT footprint and systems optimization techniques. The system optimization technique refers to the efficient energy and power consumption in electronic equipments, circuits and chip level designs. It also refers to ROM and SSD memory operations. Power consumption in relation to the embedded memories will be also introduced in the chapter. This chapter is aimed at making students aware of the importance of ICT environmental sustainability and needs to environmentally friendly design for global atmospheric conservation. In short, the following sub-topics will be covered in chapter 1:

- Meaning of ICT environmental sustainability
- Green ICT definitions/ Global ICT footprint
- Energy and power optimization techniques
- Application specific embedded memory management
- Case study

Here case study refers to few examples i.e. estimating a carbon foot print of a data center, analyzing greenhouse gases and global warming using software simulation tools.

9.4.2 Improving ICT Infrastructures and Operations

The theme of this chapter is optimal use of information and communication technology services that contributes toward reduced environmental footprint. This can be achieved in two ways:

- Optimizing energy consumption in IT infrastructures and operations

- Enable sustainability improvements across the organization in business processes

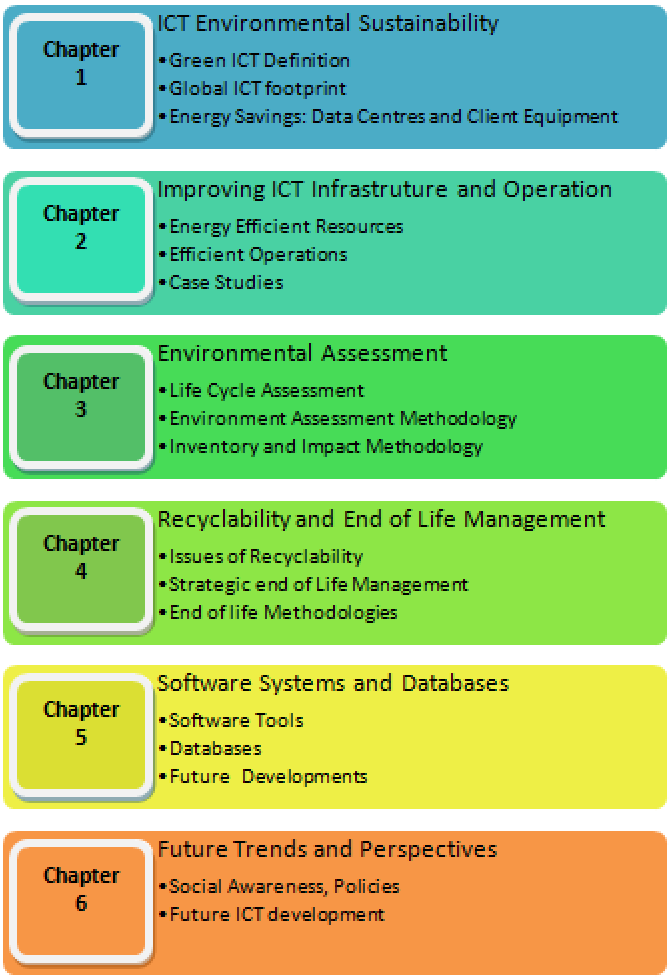

Figure 9.2: Basic Flow of Course Contents

Key areas of ICT infrastructures improvement include smart buildings, smart manufacturing, smart energy management, sustainable energy production, carbon accounting and tracking. In this chapter, students are given a case to study its environmental sustainability. The proposed case studies are as follows:

- Advanced cooling technologies
- Optimizing physical placement of the resources

- Integration techniques
- Centralized/ Distributed active power management
- Virtualization of infrastructures

9.4.3 Environmental Assessment

In this section we will discuss the basis of Life Cycle Assessment (LCA) concept, life cycle stages, LCA model, and principles of life cycle design and variants of life cycle assessment. Life Cycle Assessment Methodology and Inventory/Impact Methodology are the other two sub topics in this chapter. Content of the chapter will be taught to the students by demonstrating practical examples within the domain of ICT infrastructures, operations, networks and services. Here we will also focus on the steps needed to perform life cycle inventory (LCI) of an electronic products such as printed antennas or a printed electronic devices. There are five general steps to perform an LCI study:[118]

- Define the scope and boundaries
- Collection of data
- Creation of a computer model
- Analyze and report the study results
- Interpret the results and draw conclusions

9.4.4 Recyclability and End of Life Management

The recyclability and end-of-life (EOL) management of electronic products is of great concern not only to the governmental organizations but also to manufacturing industries as environmental protection laws have come up with strict legislation. This topic describes the activities involved in the recyclability and EOL management in ICT related operations, services, components and systems. With the enormous growth of Information Communication Technology as well as rapid advances in ICT equipments, networks and services, several organizations and manufacturing industries intend to take the best advantage of newest technological products and services. Before new technology is established, the vintage equipment and associated components must be dealt with, even though they might be still usable. The vintage or surplus components and the equipments may contain toxic components that must be handled in an environmentally friendly way. Specifically following contents will be covered in this chapter:

- Recyclability strategy

- Recycling methodology
- Potential health and environmental impacts associated with end-of-life management
- Sustainable methods of end of life management
- Waste management practices
- Case study

Here case study refers to several recycling and end of life management problems related to electronic products such as cellular phones, printed circuit boards, low voltage equipments, high voltage transformers, flat panel displays and so on. Each student will be given a problem to study in context with the recyclability and end of life management.

9.4.5 Software Systems and Databases

The Life Cycle Assessment (LCA) methodology has been developed extensively during the last decade. Moreover, a number of LCA related standards and technical reports have been published within the International Organization for Standardization (ISO) to streamline the methodology. A software system is a tool that provides approaches for the assessment of the technical, economic and environmental impacts of the products, services and systems. Moreover the software further helps to structure the modeled scenario, displaying the process chains and presenting and analyzing the results. We are proposing a software tool which is capable to assist the users with the following issues related to environmental sustainability.

- Green House Gas Accounting
- Life Cycle Engineering
- Design for Environment and Energy Efficiency Studies
- Substance Flow Analysis and Company Eco-balances
- Strategic Risk Management
- Total Cost Accounting

Along with the system software tool, extension databases are essential part of the tool, that are required to interpret the exact processes and flows of ICT for concerned operations, services and systems. There are several extension databases of the software tool. Inorganic/Organic, Energy, Plastics, end of life, manufacturing and electronic are some of the essential extension databases for interpreting ICT related operations and services. The evaluation of the extension databases are performed by examining the following:

- Contained databases should be independently accessible
- Straightforward input of a new data to the templates
- Easy copying or exporting of data modules
- Incorporation of basic materials data sets
- Easy Data accessibility

9.4.6 Future Trends and Perspectives

There are number of emerging trends in Information and Communication Technology that will impact to the environmental sustainability model. The literature shows that rate of growth in ICT development has continued to increase. Future ICT trends such as highly dense storage, enormous bandwidth, faster transistors, low power devices and increased systems integration obviously impacts to the models of life cycle assessment. This chapter will also focus on increasing social awareness regarding environmental sustainability through governmental regulations and policies.

9.5 Laboratory Exercises and Evaluation

We are proposing six laboratory exercises for the students. These laboratory exercises are grouped into two categories. First category comprises of the lab exercises based on power optimization techniques, advanced cooling technologies, assessing new materials and optimized physical placement of resources. The second category contain the lab exercises such as cradle to grave life cycle assessment, quantitative analysis in manufacturing/fabrication process of electronic products and the exercises based on end of life management. The exercises also include methods of life cycle inventory and impact analysis. These exercises will be performed in workstation classroom, equipped with recent set of computers and suitable environmental assessment software tool installed on them.

The main proposed course textbook is “Green ICT” of Tomw Communications Pty Ltd publication authored by Prof. Tom Worthington [119]. We complement this with the articles mainly from journal of IEEE Green Computing and yearly proceedings of IEEE sustainable systems and technology. The students of this course will be evaluated on the basis of their performances in the internal assessment, final exam and laboratory exercise completion. The students will be graded form a grade 1 to 5.

9.6 Chapter Summary

In this course curriculum, we have reviewed our approach for building up a concrete 5 ECTS credit unit "Green ICT" course for master and PhD level students. This course contains the several entities that are relevant to green computing, environmental impact assessment, sustainable ICT design. This course will provide an overview and in-depth knowledge on several advanced topics of green ICT. The course will also provide the student knowledge of ICT products' impacts and environmental sustainability in context to information and communication technology.

Chapter 10

Conclusions

Design of printed antenna and study of environmental sustainability analysis is one of the critical challenges for the researchers working in the domain of wireless communication technology. Particularly design works along with sustainability analysis at the same time make the thing more challenging. This thesis has described several aspects of printed antenna design including single and multiband operations, generation of fractal structures, and metamaterials and electronically tunable approach. This work also includes an investigation on environmental footprint, quantitative evaluation of the environmental emissions, and production methods and end of life strategies. We have also acted deliberately on the development of a course curriculum, which is described in chapter nine of this thesis.

Although, the summary and future work direction have been described at the end of each chapters, we are going to conclude this thesis with the following concluding remarks.

At the early stage of this research work, printed antennas such as microstrip, fractal, metamaterial based and electronically tunable are designed satisfying the required specifications along with the ideal performances. The simulation and measured results align to each other in terms of bandwidth, axial ration and antenna radiation patterns. The use of metamaterial in the design of antenna structures shows the ideal characteristics enhancing the efficiency, return loss and gain radiation, directivity and the bandwidth. With the proper use of EBG structure in antenna design confirms that traditional dual frequency band characteristics can be improved to operate at three frequency bands GSM 800, UMTS and ISM band simultaneously. It has been also noticed that how varactor diode easily tunes the antenna at different frequencies obeying the other electromagnetic behaviors. In the succeeding chapters, we have shown that stacked configuration in the antenna design is suitable for the application of HIPERLAN, wi-fi and mobile internet.

The general theory of life cycle assessment has been thoroughly studied. We have attempted to realize and create models based on life cycle assessment approach of these designed antennas. The study and investigation have been carried out for conventional PCB based and modern printing technology, this enables us to conclude that the modern printing technologies and the materials are more environmentally friendly. we had also carried out a study on comparative environmental impacts assessment for paper and polymer substrate based technology. For glass epoxy resin printed antenna, several environmental performance indicators such as global warming, acidification and ozone layer depletion potential have been quantitatively measured.

In the latter chapters we have worked on sustainable production and end-of-life strategies. Two different RFID structures have been examined to carry out a research on toxic potential indicators in their production process. The quantitative emissions of carbon dioxide, carbon mono oxide, hydrogen, methane, choloroethane and dioxins have been measured. It has been noticed that air is one of the hot environmental spots in the ecosystem, that is highly affected. Our results also show that in both raw material preparation and production processing stages, the emission to air is significantly higher than emissions to fresh water, sea water and industrial soil. The key components causing harmful emissions to air are inorganic contaminants such as carbon dioxide, carbon mono oxide, sulphur dioxide and ammonia.

10.1 Future Directions

There are many avenues for further research. The first important future work is to reflect on optimization of technology. There are tremendous amount of parameters that need to be consider during LCA process. One should focus on each parameters of the life cycle assessment and see how severe their significance is. Another imperative future work is to consider the recyclability and end of life issues of printed circuit boards to achieve the complete cradle to grave life cycle assessment. Finally, it would be worthwhile to examine the role of toxic emissions and potential impact assessment of toxicity in the manufacturing process of printed circuit boards and last but not the least is to explore the modern printing technologies and their environmental assessment in context with this thesis.

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Appendix A

Output Database for Paper Based RFID Antenna

APPENDIX OUTPUT RESULTS(Kg) FOR PRODUCTION OF 6.3 MILLION PAPER RFID ANTENNA			
	RFID Antenna	Paper Substrate	Aluminum mix (99.9%)
Flows	162599.6	3555.925	159043.7
Resources	73503.52	0	73503.52
Material resources	73503.52	0	73503.52
Renewable resources	73503.52	0	73503.52
Emissions to air	**88763.47**	**3375.271**	**85388.2**
Heavy metals to air	**0.060098**	**0.00253**	**0.057568**
Inorganic emissions to air	**40698.43**	**3357.945**	**37340.48**
Ammonia	0.307428	0.256	0.051428
Ammonium	9.65E-08	0	9.65E-08
Ammonium nitrate	1.09E-08	0	1.09E-08
Barium	0.008061	0	0.008061
Beryllium	3.64E-05	0	3.64E-05
Boron compounds (unspecified)	0.023454	0	0.023454
Bromine	0.007706	0	0.007706
Carbon dioxide	17237.81	3325	13912.81
Carbon disulphide	3.72E-06	0	3.72E-06
Carbon monoxide	128.3152	2.635	125.6802
Chloride (unspecified)	0.004817	0	0.004817
Chlorine	0.000565	0.000278	0.000287
Cyanide (unspecified)	6.32E-05	0	6.32E-05
Fluoride (unspecified)	0.002441	0	0.002441
Fluorides	0.840623	0	0.840623
Fluorine	3.72E-07	0	3.72E-07
Helium	0.000116	0	0.000116
Hydrogen	0.092488	0	0.092488
Hydrogen bromine (hydrobromic acid)	2.35E-05	0	2.35E-05
Hydrogen chloride	0.759787	0.119	0.640787
Hydrogen cyanide (prussic acid)	0.000133	0	0.000133
Hydrogen fluoride	0.848704	0.0117	0.837004
Hydrogen iodide	2.59E-08	0	2.59E-08
Hydrogen phosphorous	1.44E-05	0	1.44E-05

Hydrogen sulphide	1.010109	0.0535	0.956609
Lead dioxide	2.10E-08	0	2.10E-08
Nitrogen (atmospheric nitrogen)	1.247539	0	1.247539
Nitrogen dioxide	7.03E-07	0	7.03E-07
Nitrogen monoxide	4.22E-07	0	4.22E-07
Nitrogen oxides	37.83925	13.25	24.58925
Nitrous oxide (laughing gas)	0.308146	0.0695	0.238646
Oxygen	4.861137	0	4.861137
Scandium	4.18E-08	0	4.18E-08
Steam	23188.94	0	23188.94
Strontium	1.55E-06	0	1.55E-06
Sulphur dioxide	95.20221	16.55	78.65221
Sulphur hexafluoride	1.47E-06	0	1.47E-06
Sulphuric acid	0.00019	0	0.00019
Tin oxide	1.83E-09	0	1.83E-09
Zinc oxide	3.66E-09	0	3.66E-09
Zinc sulphate	9.12E-07	0	9.12E-07
Organic emissions to air (group VOC)	**38.36285**	**13.22079**	**25.14207**
Group NMVOC to air	8.388623	5.570789	2.817834
Methane	29.97278	7.65	22.32278
Organic chlorine compounds	5.60E-09	0	5.60E-09
VOC (unspecified)	0.001447	0	0.001447
Other emissions to air	**47995.52**	**0**	**47995.52**
Exhaust	47952.57	0	47952.57
Used air	42.94688	0	42.94688
Particles to air	**31.10833**	**4.1031**	**27.00523**
Dust (PM10)	0.367916	0	0.367916
Dust (PM2.5)	1.898605	0	1.898605
Dust (unspecified)	28.80371	4.065	24.73871
Metals (unspecified)	0.0381	0.0381	1.25E-08
Wood (dust)	6.75E-07	0	6.75E-07
Radioactive emissions to air	0.000788	0	0.000788
Uranium (total)	0.000788	0	0.000788
Emissions to fresh water	**286.3354**	**180.654**	**105.6815**
Analytical measures to fresh water	149.2763	145.834	3.442317
Adsorbable organic halogen	1.652644	1.65	0.002644

compounds (AOX)			
Biological oxygen demand (BOD)	16.06562	16.05	0.015621
Chemical oxygen demand (COD)	130.2704	127	3.270407
Solids (dissolved)	0.115733	0	0.115733
Total dissolved organic bounded carbon	0.019001	0.019	7.55E-07
Total organic bounded carbon	1.152912	1.115	0.037912
Heavy metals to fresh water	**3.432029**	**0.302516**	**3.129514**
Inorganic emissions to fresh water	**117.716**	**28.12122**	**89.5948**
Acid (calculated as H+)	1.181868	0	1.181868
Aluminum (+III)	0.371404	0.31	0.061404
Ammonia	7.62E-05	0	7.62E-05
Ammonium / ammonia	0.071148	0.01995	0.051198
Barium	0.048348	0.04655	0.001798
Beryllium	2.36E-06	0	2.36E-06
Boron	0.01296	0	0.01296
Bromine	3.43E-07	0	3.43E-07
Calcium (+II)	6.494218	0	6.494218
Carbonate	0.105495	0	0.105495
Chlorate	2.98	2.98	0
Chloride	55.74654	9.8	45.94654
Chlorine (dissolved)	0.084187	0	0.084187
Cyanide	6.38E-05	4.20E-05	2.18E-05
Fluoride	5.901108	0	5.901108
Fluorine	3.86E-05	0	3.86E-05
Hydrogen chloride	8.93E-07	0	8.93E-07
Hydrogen fluoride (hydrofluoric acid)	4.86E-07	0	4.86E-07
Hydroxide	3.643688	0	3.643688
Inorganic salts and acids (unspecified)	6.85	6.85	1.96E-13
Magnesium (+III)	0.404798	0	0.404798
Magnesium chloride	5.00E-06	0	5.00E-06
Neutral salts	1.95E-06	0	1.95E-06
Nitrate	2.74179	2.53	0.21179
Nitrogen	0.489047	0.4875	0.001547
Nitrogen organic bounded	0.020502	0.002055	0.018447
Phosphate	0.28777	0.284837	0.002933
Phosphorus	0.00048	0	0.00048

Potassium	0.000444	0	0.000444
Silicate particles	4.70E-07	0	4.70E-07
Sodium (+I)	10.95605	0	10.95605
Sodium chloride (rock salt)	9.90E-06	0	9.90E-06
Sodium hypochlorite	3.62E-05	0	3.62E-05
Sulphate	19.30013	4.81	14.49013
Sulphide	0.019758	0.000287	0.019471
Sulphite	0.00393	0	0.00393
Sulphur	1.03E-06	0	1.03E-06
Sulphuric acid	0.000115	0	0.000115
Organic emissions to fresh water	**0.334202**	**0.303231**	**0.030971**
Particles to fresh water	**15.57686**	**6.093**	**9.483856**
Metals (unspecified)	0.093	0.093	1.70E-07
Soil loss by erosion into water	9.14E-06	0	9.14E-06
Solids (suspended)	15.48385	6	9.483847
Emissions to sea water	**45.97664**	**0**	**45.97664**
Analytical measures to sea water	0.059417	0	0.059417
Adsorbable organic halogen compounds (AOX)	1.27E-09	0	1.27E-09
Biological oxygen demand (BOD)	0.0014	0	0.0014
Chemical oxygen demand (COD)	0.056617	0	0.056617
Total organic bounded carbon	0.0014	0	0.0014
Heavy metals to sea water	0.008752	0	0.008752
Inorganic emissions to sea water	**44.76779**	**0**	**44.76779**
Aluminum (+III)	8.77E-08	0	8.77E-08
Ammonia	2.61E-06	0	2.61E-06
Barium	0.008825	0	0.008825
Beryllium	1.09E-05	0	1.09E-05
Boron	1.42E-06	0	1.42E-06
Calcium (+II)	0.000155	0	0.000155
Carbonate	0.554876	0	0.554876
Chloride	43.83945	0	43.83945
Magnesium	0.000282	0	0.000282
Nitrate	0.00072	0	0.00072
Sodium (+I)	0.027963	0	0.027963
Sulphate	0.234657	0	0.234657
Sulphide	0.10084	0	0.10084

Sulphur	7.59E-07	0	7.59E-07
Organic emissions to sea water	**0.026289**	**0**	**0.02628**
Hydrocarbons to sea water	0.025998	0	0.025998
Acenaphthene	9.09E-06	0	9.09E-06
Acenaphthylene	3.47E-06	0	3.47E-06
Acetic acid	2.17E-05	0	2.17E-05
Anthracene	2.70E-06	0	2.70E-06
Aromatic hydrocarbons (unspecified)	1.40E-05	0	1.40E-05
Benzene	0.002158	0	0.002158
Benzo{a}anthracene	2.01E-06	0	2.01E-06
Benzofluoranthene	2.22E-06	0	2.22E-06
Chrysene	1.13E-05	0	1.13E-05
Cresol (methyl phenol)	1.96E-08	0	1.96E-08
Ethyl benzene	0.000244	0	0.000244
Fluoranthene	2.36E-06	0	2.36E-06
Hexane (isomers)	2.15E-09	0	2.15E-09
Oil (unspecified)	0.017192	0	0.017192
Phenol (hydroxy benzene)	0.003873	0	0.003873
Toluene (methyl benzene)	0.001224	0	0.001224
Xylene (isomers; dimethyl benzene)	0.001237	0	0.001237
Naphthalene	0.000291	0	0.000291
Particles to sea water	**1.114396**	**0**	**1.114396**
Solids (suspended)	1.114396	0	1.114396
Emissions to industrial soil	**0.294541**	**0**	**0.294541**
Heavy metals to industrial soil	**0.061643**	**0**	**0.06164**
Arsenic (+V)	1.04E-07	0	1.04E-07
Cadmium (+II)	1.14E-06	0	1.14E-06
Chromium (+III)	1.79E-08	0	1.79E-08
Chromium (unspecified)	0.000219	0	0.00021
Cobalt	3.30E-06	0	3.30E-06
Copper (+II)	1.97E-06	0	1.97E-06
Iron	0.000288	0	0.00028
Lead (+II)	8.30E-08	0	8.30E-08
Manganese (+II)	8.69E-05	0	8.69E-05
Mercury (+II)	3.91E-09	0	3.91E-09
Nickel (+II)	0.000218	0	0.000218

Strontium	0.060795	0	0.060795
Zinc (+II)	2.91E-05	0	2.91E-05
Ino. emissions to industrial soil	**0.226911**	**0**	**0.22691**
Aluminum (+III)	0.000288	0	0.000288
Ammonia	0.096754	0	0.096754
Bromide	2.83E-05	0	2.83E-05
Calcium (+II)	0.021599	0	0.021599
Chloride	0.034264	0	0.034264
Fluoride	0.000943	0	0.000943
Magnesium (+III)	0.002985	0	0.002985
Phosphorus	0.0099	0	0.0099
Potassium (+I)	0.030104	0	0.030104
Sodium (+I)	0.001889	0	0.001889
Sulphate	0.004022	0	0.004022
Sulphide	0.024133	0	0.024133
Org. emissions to industrial soil	**0.005987**	**0**	**0.005987**

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Joukahaisenkatu 3-5 B, 20520 Turku, Finland | www. tucs.fi

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- Department of Information Technology
- Department of Mathematics and Statistics

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- Institute of Information Systems Science

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