Design of High Performance RFID Systems for Metallic Item Identification

by

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in

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2008
To my parents
Contents

Chapter 1. Introduction and Motivation 1
  1.1 Area of Research ................................................. 2
  1.2 Motivation ....................................................... 3
  1.3 Original Contributions ......................................... 5
  1.4 Thesis Organisation ............................................ 7

Chapter 2. RFID: Background and Operation with Metallic Objects 11
  2.1 Introduction ..................................................... 12
  2.2 Introduction to RFID ........................................... 12
    2.2.1 History of RFID ............................................ 12
    2.2.2 RFID Types and Frequencies ............................. 14
    2.2.3 Regulations and Standards ............................... 15
Contents

4.2 Design Considerations .................................................. 76
4.3 Theoretical Calculations ............................................... 78
4.4 Simulations .............................................................. 81
  4.4.1 Tag in Free Space ............................................... 81
  4.4.2 Tag Above Metallic Surface ................................... 82
4.5 Design Implementation and Fine-Tuning ............................ 84
  4.5.1 Tag Fabrication and Measurement .............................. 85
  4.5.2 Tag Dimension Adjustment ..................................... 88
  4.5.3 Re-simulation and Re-measurement ............................ 89
4.6 Read Range Measurements ............................................ 92
4.7 Variation in Metallic Surfaces ....................................... 94
4.8 Tag Fabrication Improvement ....................................... 94
4.9 Effects of the Change in Antenna Width, $W_{rec}$ .................. 97
  4.9.1 Tag Antenna Parameters ....................................... 97
  4.9.2 Effective Volume and Coupling Volume ....................... 100
4.10 Conclusion ............................................................. 105

Chapter 5. Tags with Patch Antennas ................................. 107

5.1 Introduction ............................................................. 108
5.2 A Patch Antenna RFID Tag Design ................................. 109
  5.2.1 Design Considerations and Descriptions ..................... 109
  5.2.2 Theoretical Calculations ...................................... 114
  5.2.3 Simulations ........................................................ 116
  5.2.4 Tag Fabrication and Read Range Measurements ............. 122
5.3 Tag Size Reductions .................................................... 124
  5.3.1 Approach .......................................................... 124
  5.3.2 Read Range Measurements .................................... 126
5.4 Further Tag Size Reductions ......................................... 129
5.5 Conclusion .............................................................. 130
### Chapter 6. Tags for Metallic Cans

6.1 Introduction ........................................... 134
6.2 Design Considerations ................................. 134
   6.2.1 Basic Requirements ............................. 134
   6.2.2 Deciding a Location ............................. 135
6.3 Preliminary Investigations ............................. 137
6.4 A Novel Tag Design ..................................... 142
   6.4.1 Concept and Design Descriptions ................. 142
   6.4.2 Simulations ...................................... 144
   6.4.3 Antenna Fabrication and Read Range Measurement ... 148
6.5 Effect of Change in Slit Length ......................... 149
6.6 Further Read Range Measurements ...................... 152
6.7 Variation in Tag Antenna Material ....................... 157
   6.7.1 Material: Rogers RT/duroid 6010 (h = 1.27 mm; \(\varepsilon_r = 10.2\)) .... 158
   6.7.2 Material: Rogers RT/duroid 6010 (h = 0.64 mm; \(\varepsilon_r = 10.8\)) .... 161
6.8 Conclusion ............................................ 163

### Chapter 7. Tag in Metallic Depressions

7.1 Introduction ........................................... 168
7.2 Depression Types ...................................... 169
7.3 Concept For Read Range Prediction ..................... 169
7.4 Alternative Calculations ............................... 176
7.5 Prediction of Read Range ............................... 177
   7.5.1 Ratio \(|\mathbf{H}|_{\text{min,} m}/|\mathbf{H}|_{\text{min,} f_s}\) ............... 177
   7.5.2 Ratio \(|\mathbf{H}|_{\text{sim,} m}/|\mathbf{H}|_{\text{sim,} f_s}\) ............... 180
   7.5.3 Ratio \(r_{\text{max,} m}/r_{\text{max,} f_s}\) .................. 185
7.6 Read Range Measurement ............................... 189
7.7 Conclusions .......................................... 194
## Chapter 8. Conclusions and Future Work

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1 Thesis Conclusions</td>
<td>198</td>
</tr>
<tr>
<td>8.2 Recommendations for Future Work</td>
<td>202</td>
</tr>
<tr>
<td>8.3 Summary of Original Contributions</td>
<td>205</td>
</tr>
<tr>
<td>8.4 Conclusions</td>
<td>207</td>
</tr>
</tbody>
</table>

## Appendix A. Loss Estimation

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.1 Dielectric Substrate Loss</td>
<td>209</td>
</tr>
<tr>
<td>A.2 Surface Resistivity Loss</td>
<td>210</td>
</tr>
<tr>
<td>A.3 PSPICE Simulations</td>
<td>210</td>
</tr>
</tbody>
</table>

## Appendix B. Simulation Results for Patch Antennas of Various Widths

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.1 Tag Antenna in Free Space</td>
<td>215</td>
</tr>
<tr>
<td>B.2 Tag Antenna on Metallic Plane</td>
<td>216</td>
</tr>
<tr>
<td>B.3 Remarks</td>
<td>216</td>
</tr>
</tbody>
</table>

## Appendix C. Additional Result Plots for Tag in Metallic Depressions

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.1 Prediction of Read Range</td>
<td>219</td>
</tr>
<tr>
<td>C.1.1 Ratio $(1 - p_{loss,m})/(1 - p_{loss,fs})$</td>
<td>219</td>
</tr>
<tr>
<td>C.1.2 Ratio $R_{r,m}/R_{r,fs}$</td>
<td>222</td>
</tr>
<tr>
<td>C.1.3 Ratio $</td>
<td>H</td>
</tr>
</tbody>
</table>

## Bibliography

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
</table>
Abstract

Although the origins of Radio Frequency Identification (RFID) technology can be traced back for many years, it is only recently that RFID has experienced rapid growth. That growth is mainly due to the increasing application of this technology in various supply chains. The widening of the implementation of RFID technology in supply chains has posed many challenges and one of the biggest is the degradation of the RFID system performance when tagging metallic objects, or when the RFID system operates in a metallic environment. This thesis focuses on tackling the issue of having metallic objects in an Ultra High Frequency (UHF) RFID system.

The work presented in this thesis contributes to the research on UHF RFID systems involving metallic objects in several ways: (a) the development of novel RFID tags that range from a simple tag for general applications to tags suitable for metallic object identification; (b) the tag designs target the criteria of minimal tag size and cost to embrace the vision of item level tagging; and (c) the analysis of the performance (through theoretical predictions and practical measurements) of an RFID tag near metallic structures of various shapes and sizes.

The early part of this thesis provides a brief introduction to RFID and reviews the background information related to metallic object identification for UHF RFID systems. The process of designing a basic tag, and additional information and work done related to the process, are outlined in the early part of this thesis. As part of this fundamental research process, and before proceeding to the designing of tags specifically for metallic objects, a small and low cost RFID tag for general applications was developed. Details of the design of this tag, with the application of this tag for animal identification, are presented.

In the later parts of the work, different tag design approaches were explored and this has generated three rather different RFID tags suitable for attaching to metallic objects. The aim of this research is not just to design tags for metallic objects but also to tackle the constraints of having tags that are small in size, cost effective and suited in size
Abstract

to some familiar objects. Hence, in the later part of this research, the work took a step further where one of the three tags designed for metallic objects addressed the challenge of identifying individual small metallic beverage cans.

RFID involves tagging of different types of objects and a tag may be required to be located in a depression of a metallic object. In the final part of this research, the read range performance of one of the RFID tags designed for metallic objects was analysed when the tag was located in metallic depressions of various shapes and sizes. The analysis was performed from a combination of theoretical calculation and simulation perspectives, and also through practical real-life measurements.

Metallic objects are very common around us. Their presence is unavoidable and so to identify them, having the appropriate RFID tags suitable for operation on metallic surfaces is essential. Frequently the tags must be small in size and low in cost to allow identification at item level of individual small metallic objects. Understanding and being aware of the potential effects of metallic structures of various shapes and sizes on the tag performance is thus important. The research in this thesis into all the above can bring the industry further towards full deployment of RFID down to item level tagging.
Statement of Originality

This work contains no material that has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Signed ___________________________  Date ___________________________

Page xiii
First of all, I would like to express my sincere gratitude to my research principal supervisor, Professor Peter H. Cole, for his constant guidance and support throughout my Ph.D candidature. I am immensely grateful for all the time that he has dedicated for discussions on my work. I would also like to deeply thank my research co-supervisor, Associate Professor Christopher J. Coleman, for reviewing my research progress from time to time and providing fruitful insights during our discussions. I truly appreciate them.

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Mun Leng Ng  (June 2008)
Conventions

**Typesetting**

This thesis is typeset using the \LaTeX2e software.
The fonts used in this thesis are Times New Roman and Sans Serif.

**Referencing**

The referencing and citation style adopted in this thesis are based on the Institute of Electrical and Electronics Engineers (IEEE) Transaction style [1].
For electronic references, the last accessed date is shown at the end of a reference.

**Units**

The units used in this thesis are based on the International System of Units (SI units) [2].

**Prefixes**

In this thesis, the commonly used numerical prefixes to the SI units are “p” (pico; $10^{-12}$), “n” (nano; $10^{-9}$), “µ” (micro; $10^{-6}$), “m” (milli; $10^{-3}$), “k” (kilo; $10^{3}$), “M” (mega; $10^{6}$) and “G” (giga; $10^{9}$).

**Phasors**

Where phasors are used to represent sinusoidal quantities, peak value phasors rather than r.m.s. phasors are used.
Conventions

Spelling

The Australian English spelling is adopted in this thesis.

Illustrations

The illustrations in this thesis are drawn using the CorelDRAW 11 software.
Publications

Book Chapter


Journal


Conference


Publications


Non-refereed


# List of Figures

1.1 An overview of a basic RFID system ...................................................... 2
1.2 Structure of thesis .................................................................................. 8

---

2.1 Simplified illustrations of boundary conditions ................................. 22
2.2 Read range results of commercial label-like passive UHF RFID tags placed against a metal surface .................................................. 28

---

3.1 Tag design process .................................................................................. 33
3.2 RFID reader and reader antenna sets ..................................................... 35
3.3 HFSS simulation steps ........................................................................... 37
3.4 Four-terminal DC measurement .............................................................. 41
3.5 Results from the four-terminal DC measurement before using the $z$-axis conductive tape ................................................................. 42
3.6 Results from the four-terminal DC measurement after using the $z$-axis conductive tape ................................................................. 42
3.7 Short circuit measurement ..................................................................... 43
3.8 Smith Chart plot on the network analyser after normalisation to a short circuit ................................................................. 44
3.9 Smith Chart plots on the network analyser after the addition of $z$-axis conductive tape to the short circuit structure .................................. 45
3.10 Structure for microstrip line coupling measurement .......................... 46
3.11 Smith Chart plot on the network analyser after normalisation to an open circuit ................................................................. 47
3.12 Structure for microstrip line coupling measurement, with the short length microstrip line coupled to the half wavelength microstrip line ........ 48
List of Figures

3.13 Smith Chart plots on the network analyser showing a near critical coupling of the microstrip lines of the structure in Figure 3.12(a) .......................... 49
3.14 Smith Chart plots on the network analyser after the addition of z-axis conductive tape to the microstrip line coupling structure .......................... 49
3.15 Graphical concept to determine the resistance of the z-axis conductive tape using the measured results on a Smith chart .......................... 50
3.16 Graphical method to determine $R_{before}$ ........................................... 52
3.17 Graphical method to determine $R_{after}$ ........................................... 53
3.18 Illustration of the tag design ................................................................. 55
3.19 A simplified equivalent circuit representation of the tag .......................... 56
3.20 Simulated directivity pattern of the tag antenna structure (a combination of a loop antenna and a matching network) located in free space, with the plane of the tag in the $xy$-plane ........................................... 59
3.21 Fabricated RFID tag prototype .............................................................. 61
3.22 Different orientations of tag with respect to reader antenna ...................... 62
3.23 Tag encapsulation casing ................................................................. 64
3.24 The available space in a casing base for accommodating an RFID tag ...... 64
3.25 The fabricated RFID tag in preparation for a field trial in a piggery .......... 65
3.26 Fitting and securing a tag firmly onto a base of a tag encapsulation casing 66
3.27 A typical pig feeder in a piggery ............................................................. 68
3.28 A protective casing to contain the trial equipment .................................. 69
3.29 Illustration of a complete setup for the field trial .................................. 70
3.30 Tagged pigs in the field trial ................................................................. 70
3.31 Monitoring of pigs during the trial .......................................................... 72

4.1 Structure of the RFID tag with a rectangular loop antenna ..................... 77
4.2 Model used for conversion of the width $W_{rec}$ of the wide metallic strip to its equivalent wire radius $r$ ......................................................... 79
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.3</td>
<td>Simulated directivity pattern of tag antenna with dimensions $L_{rec} = 25$ mm, $H_{rec} = 10$ mm and $W_{rec} = 5$ mm located in free space</td>
<td>82</td>
</tr>
<tr>
<td>4.4</td>
<td>Simulation model of tag above a metallic plane</td>
<td>83</td>
</tr>
<tr>
<td>4.5</td>
<td>Cross-sectional view of tag encapsulated in protective casing</td>
<td>84</td>
</tr>
<tr>
<td>4.6</td>
<td>Simulated directivity pattern of tag antenna with dimensions $L_{rec} = 25$ mm, $H_{rec} = 10$ mm and $W_{rec} = 5$ mm located 3 mm above a $1.5\lambda \times 1.5\lambda$ aluminium metallic plane</td>
<td>85</td>
</tr>
<tr>
<td>4.7</td>
<td>Fabricated RFID tag</td>
<td>86</td>
</tr>
<tr>
<td>4.8</td>
<td>Investigation of tag resonant frequency</td>
<td>87</td>
</tr>
<tr>
<td>4.9</td>
<td>Plot of return loss curve from the network analyser</td>
<td>88</td>
</tr>
<tr>
<td>4.10</td>
<td>Simulated directivity pattern of tag antenna with dimensions $L_{rec} = 25$ mm, $H_{rec} = 10$ mm and $W_{rec} = 15$ mm located in free space</td>
<td>90</td>
</tr>
<tr>
<td>4.11</td>
<td>Simulated directivity pattern of tag antenna with dimensions $L_{rec} = 25$ mm, $H_{rec} = 10$ mm and $W_{rec} = 15$ mm located 3 mm above a $1.5\lambda \times 1.5\lambda$ aluminium metallic plane</td>
<td>91</td>
</tr>
<tr>
<td>4.12</td>
<td>Fabricated RFID tag with revised dimensions</td>
<td>91</td>
</tr>
<tr>
<td>4.13</td>
<td>Plot of return loss curve from the network analyser corresponding to the tag with revised dimensions of $L_{rec} = 25$ mm, $H_{rec} = 10$ mm and $W_{rec} = 15$ mm</td>
<td>92</td>
</tr>
<tr>
<td>4.14</td>
<td>Read range measured over a frequency range</td>
<td>93</td>
</tr>
<tr>
<td>4.15</td>
<td>Read range measured over a frequency range for tag above metallic planes of different materials</td>
<td>95</td>
</tr>
<tr>
<td>4.16</td>
<td>Improved version of the tag</td>
<td>96</td>
</tr>
<tr>
<td>4.17</td>
<td>Plot of return loss curve from the network analyser corresponding to the tag with improved fabrication</td>
<td>97</td>
</tr>
<tr>
<td>4.18</td>
<td>Plot of the simulated tag antenna resistance with respect to the change in the tag antenna width</td>
<td>98</td>
</tr>
<tr>
<td>4.19</td>
<td>Plot of the simulated tag antenna reactance with respect to the change in the tag antenna width</td>
<td>99</td>
</tr>
</tbody>
</table>
List of Figures

4.20 Plot of the simulated tag antenna gain with respect to the change in the tag antenna width ........................................... 99
4.21 Plot of the antenna coupling volume $V_{cv}$ with respect to the tag antenna width $W_{rec}$ .................................................. 103
4.22 Plot of the antenna coupling volume $V_{cv}$ with respect to the equivalent square loop antenna side length $S$ ..................... 103

5.1 A modified antenna feeding method based on a coaxial probe feed method ................................................................. 110
5.2 Structure of the RFID tag antenna ................................................................. 112
5.3 A Smith chart visualisation of the concept on using an inset microstrip line feed for matching the patch antenna and RFID tag chip impedances 113
5.4 Simulation model of the tag antenna without an inset and a microstrip line (Top view) ....................................................... 117
5.5 Simulated impedance of the tag antenna without an inset and a microstrip line ............................................................. 118
5.6 Simulation model of the tag antenna with an inset but without a microstrip line (Top view) .................................................. 118
5.7 Simulated impedance of the tag antenna with an inset but without a microstrip line ......................................................... 119
5.8 Simulation model of the tag antenna with an inset and a microstrip line (Top view) ............................................................. 120
5.9 Simulated impedance of the tag antenna with an inset and a microstrip line ................................................................. 120
5.10 Simulated directivity pattern of the tag antenna (with inset and microstrip line) located in free space ............................... 121
5.11 Simulated directivity pattern of the tag antenna (with inset and microstrip line) located on a $1.5\lambda \times 1.5\lambda$ metallic plane .............. 121
5.12 Fabricated RFID tag .................................................................................... 123
5.13 Simulated impedance plots of the patch antenna with width $W_{patch} = 59$ mm ................................................................. 126
### List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.14</td>
<td>Simulated impedance plots of the patch antenna with width $W_{patch} = 19$ mm</td>
</tr>
<tr>
<td>5.15</td>
<td>Fabricated RFID tags of different sizes</td>
</tr>
<tr>
<td>5.16</td>
<td>Practical read range measurement results</td>
</tr>
<tr>
<td>5.17</td>
<td>Simulated directivity pattern of the tag antenna (with a shortened patch length and a full shorting wall) located in free space</td>
</tr>
<tr>
<td>5.18</td>
<td>Simulated directivity pattern of the tag antenna (with a shortened patch length and a full shorting wall) located on a $1.5\lambda \times 1.5\lambda$ metallic plane</td>
</tr>
<tr>
<td>5.19</td>
<td>Fabricated RFID tag with a shortened patch length and a full shorting wall</td>
</tr>
<tr>
<td>6.1</td>
<td>Possible locations for tag attachment</td>
</tr>
<tr>
<td>6.2</td>
<td>Arrangement of half a dozen of metallic cans (Top view)</td>
</tr>
<tr>
<td>6.3</td>
<td>Bottom section of a metallic can (cross-sectional view)</td>
</tr>
<tr>
<td>6.4</td>
<td>Calculated diameter of the patch element of a basic circular patch antenna</td>
</tr>
<tr>
<td>6.5</td>
<td>Simulation model of circular patch antenna with reduced size</td>
</tr>
<tr>
<td>6.6</td>
<td>Plot of simulated impedance of the circular patch antenna with reduced size</td>
</tr>
<tr>
<td>6.7</td>
<td>Initial concept of an RFID tag antenna for metallic can</td>
</tr>
<tr>
<td>6.8</td>
<td>Location of the RFID tag at the bottom of the metallic can</td>
</tr>
<tr>
<td>6.9</td>
<td>Simulation model of the tag antenna for a metallic can</td>
</tr>
<tr>
<td>6.10</td>
<td>Simulated impedance of the tag antenna for a metallic can</td>
</tr>
<tr>
<td>6.11</td>
<td>Simulated directivity pattern of the tag antenna located in free space</td>
</tr>
<tr>
<td>6.12</td>
<td>Simulated directivity pattern of the tag antenna located on a metallic cylinder to mimic a real-life metallic can</td>
</tr>
<tr>
<td>6.13</td>
<td>A fabricated RFID tag suitable for attachment to the bottom of a metallic can</td>
</tr>
<tr>
<td>6.14</td>
<td>An RFID tag fitted neatly to the bottom of a metallic can</td>
</tr>
<tr>
<td>6.15</td>
<td>Simulated impedance of the tag antenna with slit length $b = 6.4$ mm</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>6.16</td>
<td>Simulated impedance of the tag antenna with slit length $b = 5.9$ mm</td>
</tr>
<tr>
<td>6.17</td>
<td>Tag read range measured from different directions</td>
</tr>
<tr>
<td>6.18</td>
<td>Simulated impedance of the tag antenna made of Rogers RT/duroid 6010 $(h = 1.27$ mm; $\varepsilon_r = 10.2)$</td>
</tr>
<tr>
<td>6.19</td>
<td>Simulated directivity pattern of the tag antenna made of Rogers RT/duroid 6010 $(h = 1.27$ mm; $\varepsilon_r = 10.2)$ located in free space</td>
</tr>
<tr>
<td>6.20</td>
<td>Simulated directivity pattern of the tag antenna made of Rogers RT/duroid 6010 $(h = 1.27$ mm; $\varepsilon_r = 10.2)$ located on a metallic cylinder</td>
</tr>
<tr>
<td>6.21</td>
<td>A fabricated metallic can RFID tag made of Rogers RT/duroid 6010 $(h = 1.27$ mm; $\varepsilon_r = 10.2)$</td>
</tr>
<tr>
<td>6.22</td>
<td>Simulated impedance of the tag antenna made of Rogers RT/duroid 6010 $(h = 0.64$ mm; $\varepsilon_r = 10.8)$</td>
</tr>
<tr>
<td>6.23</td>
<td>Simulated directivity pattern of the tag antenna made of Rogers RT/duroid 6010 $(h = 0.64$ mm; $\varepsilon_r = 10.8)$ located in free space</td>
</tr>
<tr>
<td>6.24</td>
<td>Simulated directivity pattern of the tag antenna made of Rogers RT/duroid 6010 $(h = 0.64$ mm; $\varepsilon_r = 10.8)$ located on a metallic cylinder</td>
</tr>
<tr>
<td>6.25</td>
<td>A fabricated metallic can RFID tag made of Rogers RT/duroid 6010 $(h = 0.64$ mm; $\varepsilon_r = 10.8)$</td>
</tr>
<tr>
<td>7.1</td>
<td>Structure of the RFID tag considered in the analysis</td>
</tr>
<tr>
<td>7.2</td>
<td>Different tag and depression combinations considered</td>
</tr>
<tr>
<td>7.3</td>
<td>Simplified equivalent circuit of the RFID tag</td>
</tr>
<tr>
<td>7.4</td>
<td>Simplified equivalent circuits of tag in two particular cases</td>
</tr>
<tr>
<td>7.5</td>
<td>Simulation model to obtain the simulated magnetic field intensity $</td>
</tr>
<tr>
<td>7.6</td>
<td>Concept flowchart for read range prediction</td>
</tr>
<tr>
<td>7.7</td>
<td>Ratio $(1 - p_{loss,m})/(1 - p_{loss,fs})$ corresponding to a tag in a circular depression</td>
</tr>
<tr>
<td>7.8</td>
<td>Ratio $R_{r,m}/R_{r,fs}$ corresponding to a tag in a circular depression</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>7.9</td>
<td>Ratio $</td>
</tr>
<tr>
<td>7.10</td>
<td>Measurement of $</td>
</tr>
<tr>
<td>7.11</td>
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<td>7.15</td>
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<tr>
<td>7.16</td>
<td>Ratio $r_{\text{max},m}/r_{\text{max,fs}}$ for a tag in a circular metallic depression</td>
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<td>7.17</td>
<td>Ratio $r_{\text{max},m}/r_{\text{max,fs}}$ for a tag in a square metallic depression (Orientation 1)</td>
</tr>
<tr>
<td>7.18</td>
<td>Ratio $r_{\text{max},m}/r_{\text{max,fs}}$ for a tag in a square metallic depression (Orientation 2)</td>
</tr>
<tr>
<td>7.19</td>
<td>Ratio $r_{\text{max},m}/r_{\text{max,fs}}$ for a tag in a rectangular metallic depression (Orientation 1)</td>
</tr>
<tr>
<td>7.20</td>
<td>Ratio $r_{\text{max},m}/r_{\text{max,fs}}$ for a tag in a rectangular metallic depression (Orientation 2)</td>
</tr>
<tr>
<td>7.21</td>
<td>Experiment setup for read range measurement</td>
</tr>
<tr>
<td>7.22</td>
<td>Constructed depression structures</td>
</tr>
<tr>
<td>7.23</td>
<td>Ratio $R_{\text{max},m}/R_{\text{max,fs}}$ for a tag in a circular metallic depression</td>
</tr>
<tr>
<td>7.24</td>
<td>Ratio $R_{\text{max},m}/R_{\text{max,fs}}$ for a tag in a square metallic depression (Orientation 1)</td>
</tr>
<tr>
<td>7.25</td>
<td>Ratio $R_{\text{max},m}/R_{\text{max,fs}}$ for a tag in a square metallic depression (Orientation 2)</td>
</tr>
<tr>
<td>7.26</td>
<td>Ratio $R_{\text{max},m}/R_{\text{max,fs}}$ for a tag in a rectangular metallic depression (Orientation 1)</td>
</tr>
</tbody>
</table>
List of Figures

7.27 Ratio $R_{\text{max, m}} / R_{\text{max, fs}}$ for a tag in a rectangular metallic depression (Orientation 2) .................................................. 193

A.1 PSPICE simulation schematic - Case 1 ............................................. 211
A.2 PSPICE simulation schematic - Case 2 ............................................. 212
A.3 PSPICE simulation schematic - Case 3 ............................................. 212

C.1 Ratio $(1 - p_{\text{loss, m}}) / (1 - p_{\text{loss, fs}})$ corresponding to a tag in a circular depression ........................................................................... 219
C.2 Ratio $(1 - p_{\text{loss, m}}) / (1 - p_{\text{loss, fs}})$ corresponding to a tag in a square depression (Orientation 1) .................................................. 220
C.3 Ratio $(1 - p_{\text{loss, m}}) / (1 - p_{\text{loss, fs}})$ corresponding to a tag in a square depression (Orientation 2) .................................................. 220
C.4 Ratio $(1 - p_{\text{loss, m}}) / (1 - p_{\text{loss, fs}})$ corresponding to a tag in a rectangular depression (Orientation 1) .................................................. 221
C.5 Ratio $(1 - p_{\text{loss, m}}) / (1 - p_{\text{loss, fs}})$ corresponding to a tag in a rectangular depression (Orientation 2) .................................................. 221
C.6 Ratio $R_{r, m} / R_{r, fs}$ corresponding to a tag in a circular depression ...... 222
C.7 Ratio $R_{r, m} / R_{r, fs}$ corresponding to a tag in a square depression (Orientation 1) .......................................................... 222
C.8 Ratio $R_{r, m} / R_{r, fs}$ corresponding to a tag in a square depression (Orientation 2) .......................................................... 223
C.9 Ratio $R_{r, m} / R_{r, fs}$ corresponding to a tag in a rectangular depression (Orientation 1) .......................................................... 223
C.10 Ratio $R_{r, m} / R_{r, fs}$ corresponding to a tag in a rectangular depression (Orientation 2) .......................................................... 224
List of Figures
C.11

Ratio |H|min,m /|H|min, f s corresponding to a tag in a circular depression . 224

C.12

Ratio |H|min,m /|H|min, f s corresponding to a tag in a square depression
(Orientation 1) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 225

C.13

Ratio |H|min,m /|H|min, f s corresponding to a tag in a square depression
(Orientation 2) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 225

C.14

Ratio |H|min,m /|H|min, f s corresponding to a tag in a rectangular depression (Orientation 1) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 226

C.15

Ratio |H|min,m /|H|min, f s corresponding to a tag in a rectangular depression (Orientation 2) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 226

Page xxxi


List of Tables

2.1 Spectrum usage for UHF RFID according to regulations .......................... 16
2.2 Size and free space read range of the five commercial tags considered ..... 26
3.1 Measured maximum read range results of 30 tags ................................. 67
3.2 Record of RFID tags assigned to each of the pigs .................................. 71
4.1 Summary of simulation results for a tag with antenna dimensions \( L_{\text{rec}} = 25 \text{ mm}, \ H_{\text{rec}} = 10 \text{ mm and } W_{\text{rec}} = 5 \text{ mm} \) ........................................ 86
4.2 Summary of simulation results for a tag with antenna dimensions \( L_{\text{rec}} = 25 \text{ mm}, \ H_{\text{rec}} = 10 \text{ mm and } W_{\text{rec}} = 15 \text{ mm} \) ............... 90
4.3 Calculated coupling volume values \( V_{\text{cv}} \) corresponding to the tag antenna with fixed loop area ........................................ 102
4.4 Calculated coupling volume values \( V_{\text{cv}} \) corresponding to the tag antenna with fixed wide strip loop width \( W_{\text{rec}} \) .................. 104
6.1 Read range measurement results for a number of metallic can tags in free space .............................................................. 153
6.2 Read range measurement results for a number of metallic can tags attached to the bottom of a metallic can ............................... 155
B.1 Summary of simulation results for tags each with a half wavelength patch antenna of different width \( W_{\text{patch}} \) ................................. 215
B.2 Summary of simulation results for tags each with a half wavelength patch antenna of different width \( W_{\text{patch}} \) ................................. 216
Chapter 1

Introduction and Motivation

This chapter presents some brief information on RFID, its common applications, and challenges in pursuing those applications. The chapter also provides a summary of the organisation of this thesis and the contributions of the research work presented.
1.1 Area of Research

The research work presented in this thesis is in the area of Radio Frequency Identification (RFID). RFID is an emerging technology used for object identification by means of radio waves. An RFID system consists of 3 major parts: a tag, associated with the object to be identified; a reader, used to extract the object’s unique identifier from the tag; and an application system possibly in the form of a network [3]. The tags and readers enable the automated identification of tagged objects, and the application system performs important tasks using this captured information.

Figure 1.1 shows the components of a basic RFID system. RFID tags are attached to objects that are to be identified. Each of the tags has a tiny chip (integrated circuit) that has memory and is capable of containing information. The Auto-ID Center has introduced an Electronic Product Code (EPC) concept where each tag chip contains a 96-bit unique identity code [4]. When EPC tags are attached to objects, they are able to give each of the tagged objects a unique identity. Further information on a tagged object can be stored in a database elsewhere and the unique identity code contained in the tag attached to the object can then point to this information.

![An overview of a basic RFID system.](image)

The major components of the system are reader (with reader antenna), tags (attached to objects) and a host computer (connected to the reader for data management). The host computer can be connected to the internet or a network consisting other computers for data sharing purposes.

The type of RFID tags considered in this research are passive Ultra High Frequency (UHF) tags operating within the frequency 860 - 960 MHz in the far-field region with
respect to the RFID reader antenna. For a passive tag, electromagnetic fields from a reader antenna are required to power up the tag. If the tag is successfully detected (interrogated) by the reader, information of the tag received by the reader will be passed on to application systems in a host computer (connected to the reader) for further data and information processing.

More detailed discussion of RFID will follow in Chapter 2.

1.2 Motivation

RFID is a technology that has existed for many years, but it is only recently that it has experienced the rapid growth that has arisen from application of this technology in various supply chains. The catalyst to the growth of RFID came after the introduction of the Electronic Product Code (EPC) concept whereby each tagged object can have its information stored in a database elsewhere instead of in the tags attached to them. With each of the tagged objects having a unique identity (due to the unique EPC in each tag) and having its information stored in a database, information associated with each of the physical objects can be accessed and updated any time and anywhere, hence allowing easy track and trace of physical objects throughout supply chains. In addition, since large memories are not required to store object information, the cost of tags will be lower. All these factors open the possibility of wide implementation of RFID technology by tagging and identifying every single physical object (or product) in supply chains for total visibility within those supply chains. Hence, there is a vision to extend the RFID technology to item level tagging (other than pallet and case level tagging), to give each specific item level object a unique identity [5].

From inventory management to theft detection, RFID has been applied in many areas such as in the automotive industry and logistics, as well as in warehouses and retail stores [6] [7] [8] [9] [10]. Potential has also been seen for the application of RFID in capital asset management applications such as keeping track of maintenance tools in the aircraft maintenance sector [11]. Wal-Mart, a large American retail chain, has mandated that its top 100 suppliers employ RFID tagging on the goods delivered to
1.2 Motivation

them [12]. The United States Department of Defense (DoD) has also issued a policy on RFID implementation in its supply chain for improved and more efficient military logistics [13] [14].

Although RFID brings forward the benefit of efficient supply chain management, the increasing implementation of the RFID technology in supply chains has posed many challenges. Among the major challenges are:

- Degradation of RFID system performance and reliability due to the presence of complex materials
- RFID tagging costs
- Tagging smaller objects at item level
- Electromagnetic compatibility issues
- Privacy and security concerns of RFID users
- Management of the mass data associated to tagged objects

Overview discussions on RFID challenges can be found in the literature such as in [15] and [16].

To allow a thorough and full deployment of RFID, and to bring into realisation the vision of tagging objects down to item level, feasible solutions must be drawn to meet these RFID challenges from all aspects. In this research, the main focus is on tackling the first challenge listed above, with the complex material of concern being metallic objects and structures. One of the biggest RFID implementation problem is the degradation of the RFID system performance when tagging metallic objects or operating in an environment containing metallic structures. The tagging of objects at pallet, case, and even item levels will most likely involve metallic objects. For example, in the automotive industry, when RFID is used for part tracking, a majority of the parts are made of metal [17].

While tackling the first challenge, this research also places emphasis on meeting the second and third challenges listed above (concerning cost and size respectively), which
become especially important when item level tagging is involved. This means designed tags must be restricted to being made from inexpensive tag material and must consist of simple to manufacture small tag antennas. However, the ohmic losses of an antenna will increase as the size of the antenna gets smaller [18], and hence the antenna efficiency will decrease. Small antennas will have a radiation power factor much less than the loss power factor [19]. Therefore, maintaining a balance between the tag size, cost and performance will be a challenging task.

1.3 Original Contributions

Following the discussions in the previous section, the major aims of this research are to tackle the challenge of metallic object identifications in a passive UHF RFID implementation, and at the same time, to draw solutions that maintain a balance between cost, size and performance. In addition, this research also aims at creating a better understanding of the possible effects of metallic structures on the performance of an RFID system.

In the early stage of this research, work began with the measurement of read range performances of several commercial or conventional passive UHF flexible adhesive label RFID tags when the tags were placed on or near metallic surfaces. The results of these measurements added to the findings in then existing published work to confirm and strengthen knowledge of the severity of the degradation of read range performances when conventional tags are used on or near metallic surfaces.

As a second stage, for evaluation of one of the steps involved in producing an RFID tag prototype from scratch, a series of experiments to measure the resistance of a z-axis conductive tape commonly used for attaching tag chips to tag antenna prototypes was designed and performed. From these experiments it was shown that for the small amount of z-axis conductive tape required for a tag chip attachment, the additional resistance introduced by the tape is small and is expected not to affect the tag performance.
The main objective of this research is to achieve the aims stated above by designing low cost and small size passive UHF RFID tags suitable for metallic object identification. As a start, since this research work places emphasis on the size and cost factors, and before the development of tags that are specific for metallic objects, a novel low cost and small size general passive UHF RFID tag was designed. This tag was able to provide a good free space read range performance despite its small size. This tag was later put into the application of animal identification as part of the study of the feasibility of using passive UHF RFID for animal identification in place of the current passive low frequency (LF) RFID technology used. A real-life field trial was planned and carried out, and results from the trial show that the tag design is reliable and can provide a good performance for animal identification. This trial of using passive UHF RFID tags for animal identification was the first in Australia. In addition, an important aspect of this part of the research is that the work has illustrated the entire process from designing and developing a tag to a successful RFID deployment for real-life applications.

Most of the currently existing RFID tags suitable for metallic objects use patch antennas since patch antennas have a ground plane as part of their structure and hence will be minimally affected when placed on metallic surfaces. Instead of being just limited to patch antennas, this research looks into a wider scope by exploring the use of tag antennas that are based on different concepts of operation and are able to operate on metallic surfaces. Hence, a tag prototype consisting a wide strip loop antenna suitable for metallic object identification was designed. This tag operates by utilising the magnetic fields near a metallic surface. Analysis and measurement results have shown that this tag has provided a promising read range performance. Most importantly, the tag size is small and is of low cost to manufacture.

Since patch antennas are common antenna choices for tags suitable for metallic objects, this research also covers the design and analysis of tags consisting of patch antennas. There has been a number of published results by other researchers on small size patch antenna designs for RFID tags with rather good performance. However, it is very often that the small size and good performance comes with the trade-off of a more complex antenna construction and the use of more expensive antenna material. Hence in this research, instead of complex patch antenna designs, the potential of using a basic patch
antenna for a tag suitable for metallic objects has been examined. A simple RFID tag with a rectangular patch antenna was designed. Measurement results showed that even with a simple low cost tag design, a satisfactory tag read range performance can be achieved. Methods used for reducing the size of the tag, without adding complexity to the tag design and using expensive antenna material, are presented. Results on the tag read range performance as the tag size was reduced are shown.

To further draw solutions to meet the challenge of tagging small metallic objects at item level, a novel compact and low cost RFID tag for common metallic beverage cans was designed, fabricated and tested. This is believed to be the first ever RFID tag designed to be placed at the bottom of metallic beverage cans. Measurement results have shown that the read range performance of the tag is sufficient to meet the requirement of item level tagging.

To tackle the challenge of metallic object identification, in addition to the designing of RFID tags suitable for metallic objects, understanding the general effects of metallic structures on tag read range performance, plays an important part. Hence, in this research, work has been done on studying and analysing the effects of metallic depressions of various shapes and sizes on tag read range performance. A theoretical model has been developed to predict the read range performance of a tag located in a metallic depression. Real-life practical measurements were also carried out. Good agreement between the measured and predicted read range results was achieved. Results from this work have shown that, unless a metallic depression is quite deep and has only a small opening, a reasonable tag read range performance can actually be obtained if the tag is required to operate in a metallic depression.

The original contributions resulting from the work of this research encourage a widespread RFID implementation, particularly involving metallic objects. Most importantly, the work of this research adds confidence to item level tagging.

1.4 Thesis Organisation

A flowchart illustrating the structure of this thesis is as shown in Figure 1.2.
1.4 Thesis Organisation

Figure 1.2. Structure of thesis. The main body of the thesis can be grouped into three parts. The first part of the thesis body consists mainly of review work and also novel results from foundational research work done. The second part of the thesis body presents novel results from the design and analysis of RFID tags for metallic objects. The third part of the thesis body presents novel results from the analysis of the effects of metallic structures on an RFID system performance.
Chapter 1 provides a brief introduction to Radio Frequency Identification (RFID). It also discusses the original contributions of the research work done in this research and the motivation behind them.

Chapters 2 and 3 cover the foundational studies and research work done that have mostly taken place at the earlier stage of this research.

Chapter 2 provides a more detailed introduction to RFID with more emphasis on passive UHF RFID systems. It also discusses related topics, and reviews the existing RFID research work on metallic object identifications. Read range measurement results obtained in this research on conventional passive UHF RFID tags placed on metallic surfaces are shown.

Chapter 3 presents the steps or processes involved in producing an RFID tag from start to finish. Methods and results from the series of experiments performed to determine the amount of resistance introduced by a z-axis conductive tape when used for attaching a tag chip to a tag antenna are shown. The theoretical calculation, simulation and fabrication steps involved in designing a novel small passive UHF RFID tag in this research are presented. Details on the deployment of the designed tag for a practical application follow.

Chapters 4, 5 and 6 present novel RFID tag designs produced in this research for the purpose of metallic object identifications. Chapter 4 contains details of an RFID tag design consisting of a wide strip loop antenna. Chapter 5 covers work on the design and size reduction of an RFID tag consisting a patch antenna. Chapter 6 presents an RFID tag designed specifically for small metallic beverage cans. In all these three chapters, design concepts and steps taken to achieve the final tag prototypes are described. Significant calculation, simulation and measurement results are shown.

Chapter 7 presents the work on analysing the effects of metallic depressions of various sizes and shapes on the read range performance of an RFID tag. Both predicted and measured read range results corresponding to a tag placed in various depressions are shown.
1.4 Thesis Organisation

Chapter 8 concludes this thesis with a summary of the work done and the resulting contributions to knowledge. Recommendations on possible work to extend this research in the future are given.
Chapter 2

RFID: Background and Operation with Metallic Objects

This chapter provides a further and more detailed introduction to Radio Frequency Identification (RFID) technology and concepts than was provided in the brief discussion in Chapter 1. This chapter also looks into the application of RFID in contexts involving metallic objects, which is the main focus of the research presented in this thesis.
2.1 Introduction

This chapter contains two major parts. For the completeness of this thesis, the first part provides an introduction to Radio Frequency Identification (RFID) technology and concepts, focusing particularly on passive Ultra High Frequency (UHF) RFID. The history and the types of RFID are presented, followed by standards and regulations and the operating principles of far-field passive UHF RFID. As the main focus of this thesis is on metallic object identifications using RFID, the second part of this chapter covers the topic of RFID involving metallic objects. Some theoretical background of electromagnetic waves near metallic surfaces and the effects of metallic surfaces on RFID tag antennas are discussed. The discussions also look into some of the current RFID research in the area of metallic object identifications.

2.2 Introduction to RFID

2.2.1 History of RFID

Although Radio Frequency Identification (RFID) only became known to many in recent years due to the widening of its applications, the concept of RFID has actually existed decades ago. It can be traced back to as early as around the World War II era. Listed below, in chronological order, are significant events that led up to the RFID of today:

- In 1935, Sir Robert Alexander Watson-Watt led to the development of an “Identify Friend or Foe (IFF)” system using radar. The IFF system was used in World War II to detect and differentiate between friendly and enemy aircraft. Friendly aircraft would transmit a signal back upon receiving a signal from a ground radar station for identification. This radar concept is very closely related to the RFID concept. [20]

- In the 1960s, electronic article surveillance (EAS) systems were developed and commercialised for merchandise anti-theft purposes [21]. EAS tags are 1-bit tags that can be in either an “on” or “off” state. When attached to merchandise, they
can indicate whether an item of merchandise has been legitimately sold. A deacti-
vated (“off” state) EAS tag can pass through an EAS tag reader without triggering
an alarm. [20] (Further details on EAS can be found in [22].)

• In the 1970s, more development work on RFID started to take place. Scientists
from the Los Alamos Scientific Laboratory released their results on their research
titled “Short-Range Radio-Telemetry for Electronic Identification Using Modu-
lated Backscatter”. Developments were aimed at applications such as animal
and vehicle tracking. [21]

• In the 1980s, full implementation of RFID systems for various applications took
place. Due to the advancement of CMOS integrated circuit technology, smaller
RFID tags with more functionalities were able to be produced. The RFID tags at
that time were made of a combination of CMOS circuits and discrete components.
[21]

• In the 1990s, further advancement of technology allowed RFID tags consisting a
single CMOS integrated circuit and without discrete components to be produced.
The RFID technology was widely applied to motor vehicle toll collection. [21]

• In 1999, an organisation called the Auto-ID Center at Massachusetts Institute of
Technology was established. The organisation introduced the vision and idea of
using RFID to track and identify every object in supply chains down to an item
level. To allow this, the cost of the tag should be minimal. Hence, the concept of
each tag having a unique ID called the Electronic Product Code (EPC) stored in
the RFID integrated circuit or chip of the tag was introduced. Instead of requiring
a large memory to store huge amount of data related to an object, the tag chip is
only required to have enough memory to store the EPC, which points to more
information of a particular object stored elsewhere in a database. [20]
This concept encourages massive deployment of low cost RFID systems in supply
chains.

• In 2003, after much preliminary research and development to achieve its vision,
the Auto-ID Center passed on its work and responsibilities to two newly founded
2.2 Introduction to RFID

organisations, the Auto-ID Labs and EPCglobal. The purpose of the Auto-ID Labs [23] are to continue the technical research and development aspects of the RFID technology, while EPCglobal [24] aims to develop RFID standards for seamless global deployment of RFID systems. At the same time, RFID related standards are also being developed by another organisation called International Organization for Standardization (ISO) [25].

2.2.2 RFID Types and Frequencies

There are several types of RFID systems that operate on different frequencies. Some of the common frequencies of operation are 125 kHz (Low Frequency, LF), 13.56 MHz (High Frequency, HF), 860-960 MHz (Ultra High Frequency, UHF) and 2.45 GHz (microwave). Some other existing frequencies of operations can be found in RFID references such as [22] and [26].

The operating principle of both LF and HF RFID systems is based on near-field coupling. For higher frequency systems such as the UHF and microwave RFID systems, a far-field radiation concept is employed. From the electromagnetic theory point of view, the field regions of an antenna can be separated into near-field and far-field. According to [27], the near-field and far-field regions can be approximately separated by a radian sphere with radius of \( r = \frac{\lambda}{2\pi} \), where \( \lambda \) is the free space wavelength that depends on the operating frequency. The region within the radian sphere will be a near-field region, while the region beyond the radian sphere will be a far-field region. For a near-field coupling RFID system, RFID tags operate within the near-field region of an RFID reader antenna. On the other hand, for a far-field radiation RFID system, RFID tags can operate in the radiation or propagation zone of the fields from an RFID reader antenna. Further discussions of far-field tag-reader operating principles will continue later in this chapter.

Due to the operating principle that requires the tags to operate within the near-field region of a reader antenna, LF and HF RFID systems operating by means of near-field coupling are limited in terms of maximum read range (maximum distance between the tag and reader antenna before the tag fails to be detected) [28]. As LF and HF RFID
systems operate at lower frequencies when compared with UHF and microwave RFID systems, their data transfer rates are also low [29]. However, they are less susceptible to environmental changes. For example, an HF RFID tag can operate when attached to objects with liquid contents, but this is not so for a UHF RFID tag where the tag may be totally unreadable or the read range is significantly reduced [30]. However, though this is the case, both HF and UHF RFID systems suffer serious performance degradation when tagging of metallic objects is involved [30]. Further discussions on the effects of metallic surfaces on conventional passive UHF RFID tags are presented later in this chapter.

In addition to the discussions above, RFID tags can be in general classified into two major categories: passive or active. According to the definition in the standard “ISO/IEC 19762-3” [31], a passive tag is defined as “RFID device which reflects and modulates a carrier signal received from an interrogator”. Also in “ISO/IEC 19762-3”, an active tag is defined as “RFID device having the ability of producing a radio signal”. A passive tag depends on the fields from a reader antenna to obtain sufficient energy to power it up and operate. Hence, passive tags usually offer a shorter read range compared with active tags. Active tags can also have more tag functionalities, but their tag costs are higher and they may require periodic maintenance [32].

### 2.2.3 Regulations and Standards

Since the research work presented in this thesis involves UHF RFID systems, the discussion on regulations and standards in this section will be focused on the significant ones related to UHF RFID.

Regulations are required for proper spectrum usage such as operating an RF device in an allocated frequency band with an allowed radiated power and with a specified frequency channel selection technique so that the RF device will not interfere with other RF devices. The regulations can be different from one country to another, and depend on the regulatory body of a country. For UHF RFID devices, there are a few common regulations. For example, “Title 47 CFR Part 15.247” [33] is used in the United States of
2.2 Introduction to RFID

America. This is specified by the Federal Communications Commission (FCC). In European countries, “EN 302 208-1 (Version 1.1.1)” [34] that is specified by the European Telecommunications Standards Institute (ETSI) is used.

A study of the various spectrum regulations in different countries will show that the operating frequency for UHF RFID systems spans from 860-960 MHz. Referring to [35], a few examples of frequency bands (corresponding to different countries) allowed for the operation of UHF RFID systems are listed in Table 2.1.

Table 2.1. Spectrum usage for UHF RFID according to regulations. The allocated bandwidth and the maximum allowed radiated power for UHF RFID can vary between countries. The data in the table is obtained from [35]. Power is expressed with respect to EIRP (equivalent isotropic radiated power) or ERP (equivalent radiated power).

<table>
<thead>
<tr>
<th>Country</th>
<th>Allocated bandwidth</th>
<th>Maximum allowed radiated power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>920-926 MHz</td>
<td>4 W EIRP (license required)</td>
</tr>
<tr>
<td>United States</td>
<td>902-928 MHz</td>
<td>4 W EIRP</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>865.6-867.6 MHz</td>
<td>2 W ERP</td>
</tr>
<tr>
<td>Japan</td>
<td>952-954 MHz</td>
<td>4 W EIRP (license required)</td>
</tr>
<tr>
<td>New Zealand</td>
<td>864-868 MHz</td>
<td>4 W EIRP</td>
</tr>
</tbody>
</table>

There is also a maximum allowed radiated power limit, which can vary between countries. The radiated power limit is usually expressed in terms of “EIRP” or “ERP”. For EIRP (equivalent isotropic radiated power), the radiated power from an antenna is expressed with respect to the power accepted by the antenna and the gain of the antenna based on an isotropic antenna. For ERP (equivalent radiated power), the radiated power from an antenna is expressed with respect to the power accepted by the antenna and the gain of the antenna based on a dipole antenna. The power in terms of EIRP and ERP can be related by [22]:

\[ P_{EIRP} = 1.64 \times P_{ERP}. \]  

(2.1)

The maximum allowed radiated power limits for RFID operations in the UHF band in several countries around the world are shown in Table 2.1.
The frequency channel selection techniques employed for RFID operations will depend on the regulations in a particular country. The most common techniques are (or were) the Frequency Hopping Spread Spectrum (FHSS) and Listen Before Talk (LBT). FHSS is used in the United States of America and LBT was once used in European countries.

The purpose of having RFID standards is to allow seamless and wide deployment of RFID systems. For instance, RFID components such as the readers and tags can be produced by different manufacturers, and standards will ensure that RFID devices can be used together even though they may be of a different make as long as they conform to the same standards. Standards can also allow efficient sharing (when permitted) of data associated with tagged objects contained in the database of one company with another company. This is particularly important when data flow is required in a supply chain and different companies are involved along the chain.

Among a number of standards, a common one is a standard on the tag-reader communications. There are two documents on this by two separate standardisation bodies. They are:

- Class-1 Generation-2 UHF RFID Protocol for Communications at 860 MHz-960 MHz (Version 1.1.0) by EPCglobal [36]

- ISO/IEC 18000: Information technology - Radio frequency identification for item management, Part 6: Parameters for air interface communications at 860 MHz to 960 MHz by International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC) [37].

As mentioned in Section 2.2.1, the Auto-ID Center has previously introduced the EPC concept. In support of this concept, the EPCglobal has also developed a number of other standards besides the one stated above on tag-reader communications. Some examples of the developed standards are:

- Tag Data Standards (Version 1.3.1) [38]: Defines the data format of an EPC tag.

- Reader Protocol Standard (Version 1.1) [39]: Defines the interface for the interactions between a reader and the software applications in a host computer.
2.2 Introduction to RFID

- EPC Information Services (EPCIS) (Version 1.0.1) [40]: Defines how EPC related data is shared either internally within a company or externally between companies.

More standards developed by the EPCglobal can be obtained through [41] and more detailed discussions on standards can be found in [42]. RFID standards are still currently being improved from time to time. Existing standards may be revised, hence the version of the standards listed above may be subject to changes in the future. New standards may also be developed in the future.

2.2.4 Far-Field Tag-Reader Operating Principles

The research work presented in this thesis involves passive UHF RFID systems operating by far-field radiation. Hence, the discussions in this section focusses on the relationship between an RFID reader antenna and a passive RFID tag.

As mentioned earlier in this chapter, for a far-field radiation RFID system, a tag is located in the far-field region with respect to a reader antenna. For a passive tag, it has no internal energy source. Hence, a passive tag can only be powered-up when there is sufficient field from an RFID reader antenna reaching the tag and hence providing enough power for the tag chip. The amount of power received by a tag from a reader antenna can be approximated using the Friis equation. Considering a free space far-field propagation from a reader antenna to a tag and using the basic Friis equation, the amount of power $P_{\text{tag}}$ received by a tag from a reader antenna and available to the tag chip can be written as:

\[
P_{\text{tag}} = g_{\text{tag}}g_{\text{reader}}P_{\text{reader}} \left( \frac{\lambda}{4\pi r} \right)^2
\]

(2.2)

where $g_{\text{tag}}$ is the gain of the tag antenna, $g_{\text{reader}}$ is the gain of the reader antenna, $P_{\text{reader}}$ is the accepted input power to the reader antenna, $\lambda$ is the free space wavelength and $r$ is the distance between the reader antenna and the tag.

As can be seen from (2.2), the amount of available received power to a tag chip is influenced by the gains of the reader and tag antennas respectively, the amount of
power provided to the reader antenna and the distance separating the reader and tag antennas. Note that the product $g_{\text{reader}}P_{\text{reader}}$ is the EIRP from the reader antenna, and has a maximum limit specified by regulations (More on regulations can be found in Section 2.2.3). For a far-field propagation and from (2.2), the radiated power density will diminish in proportion to $\frac{1}{r^2}$ upon reaching a tag.

There may be cases where both the reader and tag antennas are linearly polarised, and the relative orientation between the reader and tag antennas is in a way that a polarisation mismatch occurs. Depending on the degree of polarisation mismatch, the power received by a tag from a reader antenna can be significantly reduced. More detailed discussions on antenna polarisations, particularly from an RFID perspective, can be found in [43]. In the research work presented in this thesis, the reader antennas used are all circularly polarised. By using a circularly polarised reader antenna, polarisation mismatch can be avoided. However, a circularly polarised antenna may incur additional loss [44], but regulations normally allow a greater power input to the antenna, which increase will compensate for that loss.

The amount of power delivered to a tag chip may not necessarily be the maximum amount of available received power from the tag antenna. If there is a mismatch between the tag antenna and chip impedances, part of the originally available received power will be reflected and only a smaller portion of this power will be delivered to the tag chip.

If the polarisation and impedance mismatches are taken into account, (2.2) can be in general further written as [44]:

$$P_{\text{tag}} = pqg_{\text{tag}}g_{\text{reader}}P_{\text{reader}} \left(\frac{\lambda}{4\pi r}\right)^2$$

(2.3)

where $p$ is a coefficient representing the fraction of remaining power after an impedance mismatch and $q$ is a coefficient representing the fraction of remaining power after a polarisation mismatch.

In a passive backscatter RFID system, a portion of power obtained through the electromagnetic fields from a reader antenna and the amount that becomes available to a tag chip is used for powering-up the tag chip. With the power delivered to the tag
chip, a DC voltage is generated using a rectifier circuit in the tag chip. The amount of DC voltage is then increased using a voltage multiplier for the operation of the tag chip [45]. For a successful tag-reader communication, the tag chip will modulate the signal from the reader antenna by changing its impedance state (Following the EPC-global standard [36], for an EPC tag, the signal can either be Amplitude Shift Keying (ASK) or Phase Shift Keying (PSK) modulated.). The modulated signal will then be backscattered to the reader antenna. The backscattered signal will once again experience propagation loss, where it will diminish over the distance from the tag to the reader antenna. Hence, the amount of power delivered to the tag chip should be sufficient for all the operations above including the backscattering of the signal. An expression for estimating the amount of power received by a reader antenna from a tag backscattered signal has been derived in [46].

In [44], analysis results have shown that the limiting factor to the maximum read range between a reader antenna and a tag is the forward link (from reader to tag) and not the backward link (from tag to reader). This is because the sensitivity of an RFID reader is usually high and should be sufficient to allow the detection of a backscattered signal from a tag. On the other hand, a tag chip will require more power for its operation. In [44], it has been stated as an example that a tag chip has a threshold value of -10 dBm as compared with -80 dBm for an RFID reader. Even for a good performance tag chip such as the one presented in [47], a threshold value of about -17 dBm is still required by the tag chip. If \( P_{th} \) is the threshold power required for the RFID tag chip to operate, and using (2.3), the maximum read range \( r_{max} \) achievable can then be expressed as:

\[
    r_{max} = \frac{\lambda}{4\pi} \sqrt{\frac{p_{tag} g_{tag} g_{reader} P_{reader}}{P_{th}}}. \tag{2.4}
\]

## 2.3 RFID for Metallic Objects

Sections 2.3.1 and 2.3.2 are based on a published book chapter [48], in which the main author is the author of this thesis.
2.3.1 Electromagnetic Waves Near Metallic Surfaces

The knowledge of the behaviour or characteristics of electromagnetic waves near metallic surfaces is an important part of understanding the operation of RFID systems involving metallic structures or objects. Hence, in this section, a brief introduction to the theory of electromagnetic boundary conditions with particular application of this theory to metallic boundaries is presented.

For a boundary that lies between two media in space with medium 1 characterised by dielectric permittivity $\varepsilon_1$, magnetic permeability $\mu_1$ and electric conductivity $\sigma_1$, and medium 2 characterised by $\varepsilon_2$, $\mu_2$ and $\sigma_2$, the electromagnetic boundary conditions for a general case can be expressed (in vector form for time-varying fields) as follow:

\begin{align}
\hat{n} \times (\mathbf{E}_2 - \mathbf{E}_1) &= 0 \\
\hat{n} \cdot (\mathbf{D}_2 - \mathbf{D}_1) &= \rho_s \\
\hat{n} \times (\mathbf{H}_2 - \mathbf{H}_1) &= \mathbf{J}_s \\
\hat{n} \cdot (\mathbf{B}_2 - \mathbf{B}_1) &= 0
\end{align}

(2.5) (2.6) (2.7) (2.8)

where $\hat{n}$ is the unit normal vector to the boundary directed from medium 1 to medium 2, $\mathbf{E}$ and $\mathbf{H}$ are the electric and magnetic field intensities respectively, $\mathbf{D}$ and $\mathbf{B}$ are the electric and magnetic flux densities respectively, and $\rho_s$ and $\mathbf{J}_s$ are the surface charge density and surface current density respectively that may exist at the boundary.

If medium 1 is a metallic medium and is assumed a perfect electric conductor with infinite conductivity ($\sigma_1 \to \infty$), there will be no electric field in this medium (i.e. $\mathbf{E}_1 = 0$). Consequently, $\mathbf{D}_1 = 0, \mathbf{B}_1 = 0$ and $\mathbf{H}_1 = 0$. Hence, for this case, the boundary conditions become:

\begin{align}
\hat{n} \times \mathbf{E}_2 &= 0 \\
\hat{n} \cdot \mathbf{D}_2 &= \rho_s \\
\hat{n} \times \mathbf{H}_2 &= \mathbf{J}_s \\
\hat{n} \cdot \mathbf{B}_2 &= 0
\end{align}

(2.9) (2.10) (2.11) (2.12)
Since $\hat{n}$ is the unit normal vector to the boundary, the “cross” products in (2.9) and (2.11) will respectively result in a tangential component, while the “dot” products in (2.10) and (2.12) will respectively result in a normal component.

From here, it can be seen that there are only perpendicular (normal) components of the electric field to the surface of a perfect electric conductor. There are no tangential components of the electric field directly next to a perfect electric conductor. On the other hand, there are only tangential components of the magnetic field directly next to a perfect electric conductor. There are no normal components of the magnetic field to the surface of a perfect electric conductor. Hence, not all components of electromagnetic fields are available near a perfect electric conductor. Figure 2.1 shows simplified illustrations of electric fields and magnetic fields near a metallic surface. The relation of these results to RFID will be discussed further in the following section. Also, the knowledge of these results serves as a preliminary design consideration for one of the RFID tags that is presented in this thesis. Note that only the main expressions for the boundary conditions have been shown above. Detailed derivations of these expressions can be found in literatures such as [49] and [50].

Before proceeding to the next section, another part of the electromagnetic theory that is related to the presence of metallic media in the environment should be mentioned. For a uniform plane electromagnetic wave directed at normal incidence to a boundary formed by having a perfect electric conductor on one side, a phase reversal of the field
occurs at the boundary. Consequently, the total of the incident and reflected electric fields at the boundary will be zero. Also, the total of the incident and reflected magnetic fields at the boundary will be double that of the incident magnetic field. It can be observed that these results satisfy the boundary conditions discussed above.

2.3.2 Effects of Metallic Surfaces on RFID Tag Antennas

Passive UHF RFID tags are able to provide good read ranges for object identification when compared with LF or HF RFID tags, and they are also seen as potentially low cost. However, conventional planar passive UHF RFID tags will suffer a degradation in performance when attached to metallic objects or structures. A number of commercially available planar and label-like passive UHF RFID tags have been tested against a large aluminium plane [51]. Results from the testing have shown that as the tags were brought closer to the aluminium plane, the read range decreased. It is also shown that the read range approached zero when the tags were less than 2 mm from the aluminium plane.

Passive RFID tags obtain their energy from the interrogation fields from an RFID reader antenna. The energy obtained is then converted to electrical energy within the tag for powering up of the tag chip [18]. If there is insufficient interrogation field from the RFID reader antenna reaching the tags, the tags will not be readable. In the presence of a metallic structure, not all electromagnetic field components are present near the surface of the metallic structure. This result is part of the theory of boundary conditions involving metallic boundaries discussed in the previous section. There are only the normal component of the electric field, and tangential component of the magnetic field, to the metallic surface. Hence, any RFID tag that depends either the tangential component of the electric field or the normal component of the magnetic field to operate will suffer from serious performance degradation when attached directly to or extremely close to metallic surfaces.

Another issue of placing the RFID tag near a metallic surface is the change of the tag antenna parameters such as the input impedance, directivity, radiation pattern and also the efficiency. Antennas, such as electric dipoles, will suffer a significant change
2.3 RFID for Metallic Objects

in their impedance when placed near a metallic surface. Plots of impedance change for a basic half wavelength dipole antenna as well as a basic circular loop antenna placed horizontally and located at different distance above a metallic or conducting surface can be found in [52]. Studies of impedance changes of a folded dipole antenna corresponding to different distances of the antenna from a metallic plate are also presented in [53] and [54]. The change of the tag antenna impedance will then lead to two issues. First is the deviation of the resonant frequency of the tag. The resonant frequency of a tuned circuit can be expressed as

\[ f_r = \frac{1}{2\pi \sqrt{LC}} \]  

(2.13)

where \( L \) and \( C \) are the inductance and capacitance of the circuit respectively. This expression shows that the change of the reactive part of the antenna impedance will lead to the change of the resonant frequency. Hence, when the tag is brought close to a metallic surface, the tag antenna impedance will change, which then affects the resonant frequency. This means detuning will occur and the read range (between the RFID tag and the RFID reader antenna) will degrade. The seriousness of the read range performance degradation will of course depend on the amount of the resonant frequency deviation.

The second issue caused by the change in the tag antenna impedance is impedance mismatch. The tag antenna is usually designed to have an impedance that matches as closely as possible to the RFID tag chip impedance. A match between the tag antenna and chip impedances means that one of the impedances is the complex conjugate of the other and hence in theory, a maximum power transfer will occur. When the tag antenna impedance is affected by the presence of metallic structures, the impedance matching will be affected. Hence, the amount of power transfer from the antenna to the tag chip will also change which will in turn affect the read range performance. In addition, the change of the tag antenna impedance may also affect the bandwidth.

Beside the input impedance, the presence of metallic structures may also cause changes to other antenna parameters such as the directivity and the radiation pattern. Antennas such as an electric dipole with an omnidirectional radiation pattern in the equatorial plane may become unidirectional when placed close to a metallic surface. The
reflections caused by the metallic surface may change the concentration of the electromagnetic fields near the antenna and hence, will lead to the change of directivity. Measurements have shown that when an omnidirectional antenna was placed near a cylindrical metallic can at a separation of approximately 50 mm, the antenna gain suffered a reduction of as much as 20 dB (in the direction of the antenna nearer to the metallic can) compared to the gain when the antenna was in free space [55]. The changes in the directivity and radiation pattern will of course depend on the shape and size of the metallic structure and also the separation distance of the antenna from the structure. These have been studied for a folded dipole antenna in [53].

Discussed above are some of the most common effects the metallic structure can possibly cause to RFID tags. Although they are negative effects and make tagging metallic objects seem impossible, it is actually not as difficult as it seems. One obvious solution for metallic object tagging is to use antennas, such as patch antennas, that require a ground plane to operate. Since the ground plane is a part of the antenna design, this type of antenna will not be affected too much when attached to metallic objects. Another solution is to use a tag antenna design that is able to utilise the electromagnetic fields that are present near the metallic surface to operate. An increase in the antenna directivity due to the metallic surface may also be obtained. Tag designs corresponding to both solutions above will be discussed further in this thesis.

### 2.3.3 Conventional RFID Tags Near Metal

As mentioned in Section 2.3.2, some measurement results on a number of commercially available conventional planar label-like passive UHF RFID tags placed against a large aluminium plane have been presented in [51]. Since the research area of this thesis focusses mainly on metallic object identification, measurements similar to those in [51] (but using other varieties of commercial tags) were also carried out as part of the research work. This work serves as a foundation to the understanding of the possible effects of metallic surfaces on RFID tag performances, and adds to published findings such as those in [51].
2.3 RFID for Metallic Objects

Table 2.2. Size and free space read range of the five commercial tags considered. The commercial tags are labelled “1” to “5”. Size is the overall length and width of a tag. The read range was measured in a large office environment with any possible obstructing object located far away, hence the read range was assumed a free space read range.

<table>
<thead>
<tr>
<th>Commercial tag</th>
<th>Size (Length (mm) × Width (mm))</th>
<th>Free space read range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>149 × 10</td>
<td>1.44</td>
</tr>
<tr>
<td>2</td>
<td>95 × 8</td>
<td>0.79</td>
</tr>
<tr>
<td>3</td>
<td>96 × 8.5</td>
<td>1.95</td>
</tr>
<tr>
<td>4</td>
<td>91.5 × 24</td>
<td>1.48</td>
</tr>
<tr>
<td>5</td>
<td>89 × 25</td>
<td>1.57</td>
</tr>
</tbody>
</table>

Five commercial label-like passive UHF RFID tags were considered in the measurements. For the privacy of the tag manufacturer, the model of the tags will not be disclosed here. Hence, the tags will be labelled with the number from “1” up to “5”. Commercial tags 1 and 2 are based on the Class 1 Generation 1 (C1G1) protocol, while commercial tags 3 to 5 are based on the Class 1 Generation 2 (C1G2) protocol. All five tags consist of electric dipole like antennas with some impedance matching network. Due to the electric dipole like antennas, the tags have quite a large size. The overall sizes of the tags are listed in Table 2.2.

First, the read range of each commercial tag was measured without the presence of a metallic plane. The measurement took place in a large office environment with any possible obstructing object located far away from the measurement location. Although the environment is not a vacuum, the read range measured for each tag without the presence of a metallic plane will be considered here as a free space read range for simplicity. The RFID reader (Model ALR-9780-EA) and a 6 dBi gain circularly polarised reader antenna (Model ALR-9610-BC) both manufactured by Alien Technology and suitable for operation in Australia were used. The equivalent isotropic radiated power (EIRP) from the reader antenna is 4W. The results obtained from the read range measurements corresponding to each of the tags are shown in Table 2.2.
With the free space read range of the tags measured, the next step was to measure the read range when the tags were placed against a metallic plane. An aluminium metallic plane was used in the measurement. Each of the tags was placed at varying distances from the aluminium metallic plane. To separate a tag a distance away from the aluminium metallic plane, a spacer made of cardboard material was used. The cardboard spacer was expected to have a relative dielectric permittivity low enough not to affect the performance of the tags. A layer of the cardboard spacer is 0.8 mm thick, hence when a larger separation distance between a tag and the aluminium metallic plane was required, the number of layers of cardboard spacer was increased. The measurement began with the case of having the tag placed directly on the aluminium metallic plane (without any cardboard spacer). The separation distance between a tag and the metallic plane was then slowly increased by adding a layer of the cardboard spacer one at a time until 10 layers of cardboard spacer were added. The measured read range results obtained corresponding to the five commercial tags considered are normalised with the free space read range of each respective tags. They are plotted and shown in Figure 2.2.

As can be seen from Figure 2.2, the read range performance of all the tags had been seriously degraded with the presence of the aluminium metallic plane. The closer a tag was located to the metallic plane, the worse the tag read range performance became. The results obtained are consistent to those reported in [51] where the read range values of the tags were said to have approached zero when the tags were less than 2 mm from the metallic plane. Though a different variety of tags compared with that in [51] was considered here, the measured results here have also shown that when the tags were separated from the metallic plane a distance of 1.6 mm (2 layers of cardboard spacer) or lesser, the tags could not be read at all. The results here have hence shown that commercial label-like passive UHF RFID tags are unsuitable for metallic object identification.
2.3 RFID for Metallic Objects

Figure 2.2. Read range results of commercial label-like passive UHF RFID tags placed against a metal surface. An aluminium metallic plane of size $1.5\lambda \times 1.5\lambda$ was used in the measurement. The read range of five commercial tags (labelled “1” to “5”) placed at different spacings from the metallic plane were measured. The spacings are in terms of the number of layers of cardboard spacers used. Each cardboard spacer is approximately 0.8 mm. The read range results for each of the tags shown in the plot above are normalised with the free space read range corresponding to the respective tags.

2.3.4 Research on RFID Involving Metallic Objects

The research on RFID tags suitable for metallic object identification and the analysis of metallic structures on the performance of an RFID implementation are still in an infancy stage. However, due to the widening of the applications of the RFID technology in supply chains in recent years, the importance of being able to tag and identify any type of object (including metallic objects) using RFID became obvious. Hence, during the research duration (spanning the past few years) of the author of this thesis on the topic of metallic object identifications, there has been increasing concurrent work by other researchers on designing RFID tags suitable for metallic object identification.
As mentioned previously, one of the solutions to designing RFID tags for metallic objects is to use tag antennas with a ground plane of their own. As patch antennas have this feature, they become a valid and quite a common choice. One of the earlier published tag design with a patch antenna can be found in [56], with further analysis of this tag presented in [57]. In [56], a patch antenna with an Electromagnetic Band Gap (EBG) ground plane for surface wave suppression is used in the tag design. Patch tag antenna designs employing various antenna feeding methods can also be found in [58], [59] and [60]. In [58] and [59], an inductively-coupled feed method is used, with the patch antenna fabricated on a layer of FR4 dielectric substrate and separated from the antenna ground plane with an additional foam layer for both tag designs. In [60], a proximity-coupled feed method is used, with the feeding structure made on a dielectric substrate material and placed in between the patch element and the ground plane of the tag antenna.

There have also been a number of reported tag designs using inverted-F antennas such as [61], [62] and [63]. These tags have also a ground plane as part of the tag antenna structure. The tag antenna shown in [61] consists of a protruding F-shaped structure from a ground plane. In [62] and [63], the inverted-F antenna is made planar for low antenna profile purposes. In both tag designs, the tag consists of double dielectric layers. Beside the tag designs mentioned above, some other design examples can be found in publications such as [64], [65], [66], [67] and [68].

Existing RFID tags suitable for metallic objects, some discussed above, vary in terms of tag construction, size, cost and read range performance. As tagging objects, for example in a supply chain, may involve small metallic objects at individual item level, maintaining a balance between the tag size, tag cost and a feasible tag read range performance is essential. While a few of the existing or reported tag designs can be seen to be approaching towards these criteria, many are still not. Those tag designs that do not meet these criteria have at least one or more of the following attributes:

- Large tag dimensions (difficult or even impossible to attach the tag to smaller metallic objects)
- Use of low loss and high relative dielectric permittivity but expensive substrate(s)
2.3 RFID for Metallic Objects

- Use of multiple dielectric substrate layers
- Use of too many shorting pins or vias
- Overall tag structure is too complex for construction in a large tag quantity

Hence, much research is still needed on the area of RFID involving metallic object identification.

The major aims and challenges of the research work presented in this thesis are not only to design RFID tags suitable for metallic object identifications, but also to develop tags that are balanced in terms of the size and cost, and of feasible read range performance when attached to metallic objects. For example, in some cases of the research work presented in this thesis, low cost materials but with higher loss were used for the tag as a compromise even though this may cause a reduced tag read range performance. Moreover, the research here aims to explore tag antenna designs that are based on concepts of operation that are sometimes different from and sometimes the same as those commonly adopted such as the use of patch antennas. The research here also strives to reach the aim of tagging small metallic objects at item level. As there is a lack of research into the effects of metallic structures on an RFID implementation, the research here has also covered an analysis on the effects of metallic structures on the performance of an RFID tag, as well as on designing tags suitable for metallic objects.
In this chapter, the standard design process for a basic passive UHF RFID tag, and work related to this process, are presented. These form a basis for designing RFID tags for metallic item identification presented in later chapters in this thesis. This chapter also presents a simple RFID tag design for application in livestock identification as an illustration of the tag design process.
3.1 Introduction

The RFID tags designed in this research are based on somewhat diverse design ideas and concepts. Though this is the case, they share a common design process in general. As this research involves extensive tag design work, by adhering to systematic guidelines, the tag design work in this research was approached in a more efficient way. Hence, the tag design process adopted in this research is outlined in this chapter.

Design simulations play an important role in the tag design process. By itself, there are a standard set of steps required to set up a proper simulation environment. Therefore, these steps are discussed in this chapter.

As electrically conductive adhesive transfer tape is frequently used for the attachment of RFID tag chips on tag antenna structures, results from studies performed on this tape are shown.

In the early stage of this research, a basic RFID tag was developed to gain familiarity with the fundamentals of tag design. This work is presented in this chapter, and serves as an illustration of the tag design process. As the research progressed, that basic tag designed was used as part of an RFID deployment in a piggery. Details on this deployment are also presented.

All the work and discussions covered in this chapter form a basis for designing RFID tags for metallic objects in the later part of this research.

3.2 Tag Design Process

In [69], a discussion of a design process for a conventional RFID tag is presented. The tag design process adhered to in this research has close similarity to that presented in [69]. Based on [69], a flow chart of the tag design process adopted and simplified to suit the work in this research is shown in Figure 3.1.

Referring to Figure 3.1, the first stage to designing a tag is to evaluate the tag applications and requirements in order to generate an adequate set of design considerations. The tags designed in this research stressed the requirements of minimal tag size and
cost. In addition, all the tags, except for the one presented later in this chapter, must be suitable for applications involving metallic surfaces or objects. The design concepts, though rather different for each of the tags, and the decisions on the tag material to be used were greatly influenced by this set of design considerations.

With a conceptual idea of the tag design in mind, the next two stages are to perform theoretical calculations and simulations. Theoretical calculations were carried out in some of the tag design work presented in this thesis to determine the approximate tag antenna dimensions required before simulations were performed. However, the theoretical calculations for some tag designs were too complex and hence, they were omitted. In this case, the tag design process proceeded directly to the simulations. The simulations themselves involve a set of procedures for a proper setup of the simulation environment. This aspect will be discussed in the next section.

A basic passive RFID tag consists of an antenna and an RFID tag chip attached across the antenna feed terminal. To have a good match between the tag antenna and chip impedances for maximum power transfer, an impedance matching network can be
3.2 Tag Design Process

added and integrated, if possible, as part of the tag antenna design. However, for some of the tag designs presented here in this thesis, it was too difficult and complex to include an impedance matching network. In order to have at least a tag resonance at the desired frequency of operation of the tag, the tag antenna must provide sufficient inductive reactance to complement the capacitive reactance of the tag chip. Hence, whether or not an impedance matching network is added, the tag chip impedance has to be considered in most of the theoretical calculations and simulations. As the RFID tag chips used may be from different manufacturers or batches, their equivalent chip impedances may vary (though often not too much). In the case where the exact equivalent impedance of a tag chip is not known, it is common to assume an equivalent chip impedance that corresponds to having a resistor with resistance 1 kΩ and capacitor with capacitance 1 pF in parallel for theoretical calculations and simulations purposes.

Results from design simulations serve as a prediction of tag characteristics. After obtaining satisfactory simulation results, the next stage is to fabricate the tag. For most of the tag prototypes in this research, low-cost double-sided copper clad FR4 board was used. Some of the prototypes were hand made, or for most cases, they were fabricated using a milling machine. To have a fully operational tag, an RFID tag chip is attached across the feed terminal of the tag antenna structure. For most of the tags presented in this thesis, an electrically conductive adhesive transfer tape (3M 9703 [70]) was used for the tag chip attachment. Additional studies on this tape are presented later in this chapter.

The final stage of the tag design process is the read range performance measurements of the tag. To perform read range measurements, an RFID reader and reader antenna set is required. Shown in Figure 3.2 are examples of some of the RFID reader and reader antenna sets (with required accessories) that have been used in the measurement work in this research. The tag read range is the maximum distance between the tag under measurement and the reader antenna before the tag fails to be detected.

Discussed above is just a simplified tag design process. For some tag designs, fine tuning can be included in the tag design process to achieve a better tag performance.
Figure 3.2. **RFID reader and reader antenna sets.** Shown are reader and reader antenna sets from different manufacturers, with the accompanying accessories required.

### 3.3 HFSS Simulations

As discussed in the previous section, simulation work is an important part of a tag design process and is used to predict the characteristics of a tag before proceeding to the fabrication stage. For the research work presented in this thesis, simulations were performed using a software called High Frequency Structure Simulator (HFSS) by Ansoft Corporation. In HFSS, solutions are computed using the Finite Element
3.3 HFSS Simulations

Method (FEM), which is a type of computational electromagnetic method. Study of computational electromagnetic methods is a large subject and is not within the scope of this thesis. Further information on this can be obtained from literature such as [71]. The scope of this section is to outline the general steps employed for simulating, using HFSS, the RFID tag designs presented in this thesis. Additional details on HFSS and guidelines on how it can be used for a broad range of other applications can be found in [72].

Shown in Figure 3.3 is a flow chart of the steps used for simulating the RFID tag designs presented in this thesis. Referring to this flow chart, to begin the simulation work, some preliminary setups are required. They include inserting a new design file, and setting the solution type and the geometrical unit for the design model. For the simulation work shown in this thesis, the geometrical unit was set to “mm” (millimetres) since the simulation structures involved corresponded to rather small tag designs. There are three available solution types to choose from in HFSS and the solution type chosen will determine the options available later in the simulation setup process. According to HFSS, the three solution types are described as:

**Driven Modal**

For calculating the mode-based S-parameters of passive, high-frequency structures such as microstrips, waveguides, and transmission lines, which are driven by a source.

**Driven Terminal**

For calculating the terminal-based S-parameters of passive, high-frequency structures with multi-conductor transmission line ports, which are driven by a source.

**Eigenmode**

For calculating the eigenmodes, or resonances, of a structure.

“Driven Modal” is by experience the most suitable solution type for the tag design simulation work presented in this thesis, hence it was chosen.

The next stage in the simulation setup is design modelling. In this stage, simulation structures are drawn and modelled in HFSS according to desired design concepts and
theoretically calculated design dimensions. Appropriate materials are assigned to the simulation structures drawn in order to mimic a real life implementation of a design. For example, for a simple tag made of a single layer of double-sided copper clad FR4 board, the simulation structure will comprise of three attached layers. Copper material will be assigned to the top and bottom layers, and FR4 material to the middle layer.

After a design is modelled, a simulation problem region (a space containing the simulation structure) is set and a boundary type is assigned to the edges of this problem region. For tag design simulations, there are two boundary types that can be used. They are the “Radiation Boundary” and ”Perfectly Matched Layer (PML) Boundary”. According to HFSS, they are described as:

Figure 3.3. HFSS simulation steps. These are the general steps adopted for the simulation work presented in this thesis.
3.3 HFSS Simulations

Radiation Boundary:
Represents an open surface from which energy can radiate.

Perfectly Matched Layer (PML) Boundary:
Represents several layers of specialized materials that absorb outgoing waves.

For the simulation work presented in this thesis, the “Perfectly Matched Layer (PML) Boundary” was chosen (with the free space termination option selected). It has been noted in HFSS that for “Radiation Boundary”, the surface of the boundary has to be convex with respect to the source of the radiation (for example an antenna) and it should be located at least a quarter wavelength away from the source of radiation. On the other hand, for the “PML Boundary”, the surface of the boundary can be located closer to the source of radiation. This can reduce the size of the problem region required for a more efficient simulation.

The next step is to assign an excitation to the simulation structure. For the case of a tag design simulation, the excitation will act as a source to the tag antenna structure when placed across the feed terminal of the tag antenna structure. The “Wave Port” and Lumped Port excitation types are the most common for the simulation of antennas. They are described in HFSS as:

Wave Port:
Represents the surface through which a signal enters or exits the geometry.

Lumped Port:
Represents an internal surface through which a signal enters or exits the geometry.

For small tag antenna structures with a feed terminal designed for the attachment of an RFID tag chip, the “Lumped Port” is more feasible and flexible to be used.

The final step before running the simulation is to specify how the simulation solutions are to be computed by HFSS (or, in short, to perform the analysis setup). In this stage, the target frequency which HFSS will use when computing the simulation solutions is
specified. In addition, it is also at this stage that the desired accuracy of the simulation solutions or results is stated. Higher solution accuracy can be obtained by specifying a higher number of simulation iterations and setting a lower error margin. However, by doing so, high simulation resources will be required and this may lead to an inefficient simulation time span. Hence, a good balance between the simulation accuracy and the time taken to complete a simulation should be maintained. A frequency sweep can be added if the simulation solutions are required to be computed at a number of frequencies.

With all the steps above performed, the simulation can then be run and the computation of simulation solutions takes place. The simulation will complete once its solutions converge to meet the accuracy criteria set previously. After the completion of the simulation, the simulation results can be viewed and plotted. For the simulation of a tag design, the results of interest are usually the impedance, gain and directivity of the tag antenna structure.

In the work presented in this thesis, beside using HFSS for tag design simulations, HFSS was also used for simulations involving the prediction of electromagnetic field concentrations near metallic structures (the work presented in Chapter 7 of this thesis). The steps outlined in Figure 3.3 can also be applied for this type of simulation work.

### 3.4 Electrically Conductive Adhesive Transfer Tape

As mentioned earlier in this chapter in Section 3.2, an electrically conductive adhesive transfer tape was used for tag chip attachments across the feed terminals of tag antenna structures during the tag fabrication process. A tape manufactured by 3M (Model number 9703 [70]) was used. This tape has the ability to conduct in the z-axis direction, hence it will be called a z-axis conductive tape in the discussions here. Using this tape is likely to introduce additional resistance to the tag. Hence, a series of three experiments were performed to determine the amount of possible additional resistance that the tape would introduce when the tape was used for tag chip attachments. The three experiments performed were: (a) Four-terminal DC (direct current); (b) short circuit; and (c) microstrip line coupling measurements.
3.4 Electrically Conductive Adhesive Transfer Tape

3.4.1 Four-Terminal DC Measurement

The first experiment performed involved a four-terminal DC measurement. In this experiment, first a short track of a microstrip line with width of approximately 3 mm was made on a standard FR4 dielectric substrate material. This is shown in Figure 3.4(a). Both ends of the short microstrip line track were connected to a DC power supply and a constant current was applied. Referring to Figure 3.4(a), a pair of multimeter probes were placed on two points (each probe on one point) on the microstrip line to measure the voltage across the two points. The constant current applied started from 0.1 A and was increased in steps of 0.1 A up to 1 A. With each increment of the current, the voltage across the two points on the microstrip line was measured. Shown in Figure 3.5 is the plot of the measured results. As can be seen, using Ohm’s Law, the gradient or slope of the plotted line is the approximate resistance of the microstrip line track between the two points of probing. The resistance was found to be around 4 mΩ.

In the next part of this experiment, a small part of the microstrip line track was removed, leaving a gap. The disconnected microstrip line tracks were reconnected by attaching a copper strip (of similar width with the microstrip line) across the gap using a z-axis conductive tape. This is illustrated in Figure 3.4(b). The size of the copper strip and the amount of area where the z-axis conductive tape was applied was determined in a way that it mimics the situation where an RFID tag chip was attached across a feed terminal of a tag antenna. Similar to the first part of this experiment, a constant current was applied and the voltage across two points on the microstrip line track was measured. The measurement results are shown in Figure 3.6. Looking at the gradient of the plotted line, the resistance of the microstrip line track between the two probing points was found to be around 332 mΩ.

Comparing the results between the first and second parts of this experiment, it can be observed that the resistance value obtained had increased in the latter case. This is most likely caused by the z-axis conductive tape. Although the z-axis conductive tape had introduced additional resistance, the amount added is still quite small.

It has to be noted that, for this experiment, the constant current applied to the microstrip line should not be too high. If the current is too high, the microstrip line track
Figure 3.4. **Four-terminal DC measurement.** A short track of a microstrip line with width of approximately 3 mm was made on a standard FR4 dielectric substrate material. (a) Before and (b) after part of the microstrip line track was removed.

will begin to get quite warm and this will likely cause an inconsistency in the measurement results.

### 3.4.2 Short Circuit Measurement

DC measurements were performed in the previous experiment to estimate the resistance introduced by the z-axis conductive tape. In this experiment, the aim was to estimate the tape resistance at a high frequency case. A short circuit structure shown in Figure 3.7(a) was used in this experiment. Similar to the four-terminal DC experiment presented previously, a short track of a microstrip line with width of approximately 3 mm was made on a standard FR4 dielectric substrate material. However, for this
3.4 Electrically Conductive Adhesive Transfer Tape

![Graph](image1)

**Figure 3.5.** Results from the four-terminal DC measurement before using the z-axis conductive tape. With the constant current applied and the voltage measured, the resistance of the microstrip line track between the two points of probing was found through the slope of the plotted line above to be around 4 mΩ.

![Graph](image2)

**Figure 3.6.** Results from the four-terminal DC measurement after using the z-axis conductive tape. With the constant current applied and the voltage measured, the resistance of the microstrip line track between the two points of probing was found through the slope of the plotted line above to be around 332 mΩ.

Experiment, one end of the microstrip line track was shorted to the copper layer at the bottom of the substrate layer, and another was connected to the centre pin of an SMA connector. This created a form of a short circuit.
Figure 3.7. Short circuit measurement. A short track of a microstrip line with width of approximately 3 mm was made on a standard FR4 dielectric substrate material. This track was shorted to the copper layer at the bottom at one end and connected to a SMA connector on the other end. (a) Before and (b) after part of the microstrip line track was removed.

The entire structure was connected to a network analyser (Model HP 8714C) through the SMA connector. With the structure connected, the network analyser was then calibrated and normalised to a short circuit. The Smith Chart plot observed on the network analyser corresponding to this step is shown in Figure 3.8. As can be seen, the plot markings on the Smith Chart are located on a typical short circuit position. At this position, the resistance recorded are shown to be almost zero.

Next, the structure was disconnected from the network analyser with the network analyser settings remained unchanged. A small part of the microstrip line track was removed, leaving a gap. The disconnected microstrip line tracks were reconnected by
3.4 Electrically Conductive Adhesive Transfer Tape

Figure 3.8. Smith Chart plot on the network analyser after normalisation to a short circuit.

Normalisation was performed with the short circuit structure shown in Figure 3.7(a) connected to the network analyser.

attaching a copper strip, with width similar to that of the microstrip line, across the gap using a z-axis conductive tape. The entire structure was then connected to the network analyser once again and the Smith Chart plot was observed. This observation is shown in Figure 3.9. The measurement was performed twice to ensure a consistency in the observation. Hence, two Smith Chart plots corresponding to the first and second measurements are shown in Figure 3.9.

Comparing the Smith Chart plots in Figures 3.8 and 3.9, it can be seen that after the addition of the z-axis conductive tape to the short circuit structure, a higher resistance was recorded. This is as expected. Averaging the resistance shown in both plots in Figure 3.9, the resistance is approximately 329 mΩ. This resistance value is very close to that obtained in the four-terminal DC experiment presented previously.

3.4.3 Microstrip Line Coupling Measurement

In the short circuit experiment just presented, the Smith chart plots were all located near the periphery of the chart. Although modern network analyser normalisation software has made working near the periphery, particularly at a single frequency, a lesser problem than in the past, a measurement method that brings the significant
points of observation closer to the centre of the Smith chart, was thought to be worth investigating. The experiment reported below was designed to estimate the resistance introduced by the z-axis conductive tape, at a high frequency, by using a microstrip line coupling method so that the relevant parts of the Smith chart plot from which measurements would be taken, would be located away from the periphery. This work was done in collaboration with Prof. Peter H. Cole, the research supervisor of the author of this thesis.

In the method, first a half wavelength microstrip line resonator with characteristic impedance of 50 Ω was made on a standard FR4 dielectric substrate material as shown in Figure 3.10. Based on the frequency of 923 MHz, and with a substrate relative dielectric permittivity of 4.4 and thickness 1.6 mm, the microstrip line of characteristic impedance 50 Ω had a width of 3 mm. Both ends of the track of this microstrip line were shorted to the copper layer at the bottom of the FR4 substrate. Next, referring to Figure 3.10, an additional short length of microstrip line of similar width was made, with one end of the track of this microstrip line connected to an SMA connector and another end located very close to the track of the half wavelength microstrip line made
3.4 Electrically Conductive Adhesive Transfer Tape

previously. For simplicity, from now on, the half wavelength microstrip line will be referred to as the main line, and the short length microstrip line (with the extended track to allow coupling) will be referred to as the side line.

![Diagram of microstrip line coupling measurement](image)

**Figure 3.10. Structure for microstrip line coupling measurement.** Both microstrip line tracks have a width of approximately 3 mm. They were made on a standard FR4 dielectric substrate material. The longer track corresponds to a half wavelength microstrip line.

The structure in Figure 3.10 was then connected to a network analyser (Model HP 8714C) through the SMA connector attached to the structure. The network analyser was calibrated and normalised to an open circuit. This means the reference plane of measurement of the network analyser had shifted from the SMA connector end of the microstrip line track to the other end of the track (the end closer to the half wavelength microstrip line track) and, in addition, the effect of losses in the side line and coupling cable are removed. The Smith Chart plot observed on the network analyser corresponding to this step is shown in Figure 3.11.

Next, to allow the coupling of the short length microstrip line with the half wavelength microstrip line, the track of the short length microstrip line was slowly extended until sufficient coupling was obtained. The slight extension of the track length was done using an additional copper strip. Sufficient coupling in fact occurred when there was a non-conducting overlap between the side line and the main line. Although the extension of the track would transform the measured impedance, it would be possible during the analysis and calculation stage that will be discussed later to allow for it, at least approximately, by a change of reference plane. The structure with the short length microstrip line coupled to the half wavelength microstrip line is as shown in
Figure 3.11. Smith Chart plot on the network analyser after normalisation to an open circuit.

Normalisation was performed with respect to the structure in Figure 3.10.

Figure 3.12(a). To avoid the side line from making a direct connection to the main line, a plastic adhesive tape was used to separate both lines at the area where they overlapped.

The concept of the structure in Figure 3.12(a) is that the main line acts as a form of a resonant structure. With an appropriate amount of capacitive coupling between the main and side lines, a significant curve that passes near the centre point of the Smith chart may be observed. After the slight extension of the side line mentioned above, the Smith chart plots as shown in Figure 3.13 were observed. The measurement was performed twice to ensure consistency in the observation. As can be observed in the Smith chart plots, a near critical coupling was achieved. The arcs of the plots were not symmetrical about the horizontal axis but were rotated in the clockwise direction. This was caused by the additional (and potentially lossy) capacitance provided by the slight extension of the track of the side line. A change of reference plane could rotate the plots so that they become symmetrical about the horizontal axis.

Near one of the two ends of the main line, part of the main line track was removed. The disconnected tracks were then reconnected by attaching a copper strip across the gap using a z-axis conductive tape. The modified structure is shown in Figure 3.12(b). The structure was then measured using the network analyser and the Smith Chart plots shown in Figure 3.14 were observed (measurements performed twice).
Figure 3.12. Structure for microstrip line coupling measurement, with the short length microstrip line coupled to the half wavelength microstrip line. (a) Before and (b) after part of the half wavelength microstrip line track was removed.

The next step was to calculate the \( z \)-axis tape resistance \( R_z \). As mentioned before, the reference plane of measurement of the network analyser was shifted from the SMA connector end of the side line to the other end closer to the main line. However, the side line was then extended slightly to achieve a coupling with the main line, which caused the measured results on the Smith chart (both before and after the addition of the \( z \)-axis conductive tape) to be slightly rotated in the clockwise direction. To compensate for this, and referring to a simplified illustration in Figure 3.15, a diameter can be drawn for the Locus Y from points B to C so that when point C is rotated along Locus P (a circle of constant radius centred at the origin O) to point E located on the horizontal axis of the Smith chart, the Locus Y will be rotated counter-clockwise. This rotation will cause a change in reference plane and so the relocated Locus Y will be symmetrical along the
Figure 3.13. Smith Chart plots on the network analyser showing a near critical coupling of the microstrip lines of the structure in Figure 3.12(a). The same measurement was performed twice. The plots from the first and second measurements are shown.

Figure 3.14. Smith Chart plots on the network analyser after the addition of z-axis conductive tape to the microstrip line coupling structure. The same measurement was performed twice. The plots from the first and second measurements are shown.

horizontal axis of the Smith chart with its detuned open position close to the infinite impedance point F.

The side line was coupled to the main line via a capacitance $C_{couple}$ which came from the overlap of the side and main lines. The overlapping area $A$ between the main and
3.4 Electrically Conductive Adhesive Transfer Tape

![Graphical representation of Locus Y and Locus P](image)

**Figure 3.15.** Graphical concept to determine the resistance of the z-axis conductive tape using the measured results on a Smith chart. Locus P shown above was used to transform the measured impedance from point C to point E at which the impedance seen looking into the coupling capacitor becomes real.

Side lines was 3 (mm)$^2$. The adhesive tape was used to prevent the main and side lines from making direct contact at the overlapping area had a thickness $d$ of about 0.06 mm. The adhesive tape was plastic and is assumed for the purpose of this calculation to be made of polyethylene with relative dielectric permittivity $\varepsilon_r$ of 2.25, although later investigations called this assumption into question. Using the expression $C_{\text{couple}} = \frac{\varepsilon_0 \varepsilon_r A}{d}$, where $\varepsilon_0$ is the free space permittivity, $C_{\text{couple}}$ was found to be about 1 pF. This gave a capacitive reactance of $X_c = 188$ $\Omega$ at the frequency 850 MHz (The frequency 850 MHz was chosen because point C on the Locus Y corresponded to this frequency).

The method of calculation to determine $R_z$ is based on:

- Representing the impedance at the centre of the main line, without the effect of $R_z$, by a parallel resonant circuit in which the conductance $G_L$ represents the losses, believed to be mainly caused by the dielectric loss, of that line.

- Representing the effect of the loss resistance $R_z$ by an additional loss conductance $G_z$ where $G_z Z_0^2 = R_z$, and $Z_0$ is the characteristic impedance of the main line.
• Representing the sum of the losses on the main line by a conductance
\[ G = G_L + G_z. \]

• Recognising that the real part \( R \) of the impedance seen looking into the coupling capacitance \( C_{couple} \), after the parallel tuned circuit has provided sufficient inductance to tune the reactance \( X_c \) of \( C_{couple} \), can be expressed as \( R \) where \( \frac{R}{X_c^2} = G \).

Figure 3.16 and Figure 3.17 show at point E the real parts \( R_{before} \) and \( R_{after} \) the impedance seen looking into the coupling capacitor \( C_{couple} \) before and after the resistance \( R_z \) was inserted. We define the change in resistance as \( \Delta R = R_{after} - R_{before} \). From these figures we derive \( \Delta R = 8 \Omega \).

Applying all these concepts, the resistance introduced by the z-axis conductive tape can be found using:

\[ R_z = \frac{Z_0^2}{X_c^2} \Delta R. \quad (3.1) \]

The result is \( R_z = 566 \, m\Omega \).

The results from the three experiments have shown that the z-axis conductive tape can possibly introduce an additional resistance. The four-terminal DC and the short circuit experiments gave resistance values in the range of about 300 - 400 m\( \Omega \). The microstrip line coupling experiment gave a higher value at 566 m\( \Omega \).

The higher value obtained in the microstrip line coupling experiment may be caused by the inaccuracies introduced by making approximations in deriving equation 3.1, and some of the estimations made during the analysis. For instance, the coupling capacitance \( C_{couple} \) was estimated with respect to the overlapping area between the main and side lines without taking into account fringing effects. When estimating \( C_{couple} \), the distance separating the main and side lines in the overlapping area was assumed to be contributed just by the thickness of the adhesive tape. Moreover, the adhesive tape was assumed to be made of polyethylene, but in actual fact, the tape was made of one layer of plastic material combined with a layer of adhesive material. Despite many searches, the thicknesses of the individual layers (plastic and adhesive) of the
tape could not be found, and it was thought impractical to continue the search. All these may have led to either an overestimation or underestimation of $C_{\text{couple}}$. In the analysis, an assumption was also made that the slightly extended track of the side line was lossless. However, in practice, there may be a small loss that made the measured result (Locus Y) to be slightly shifted. All the inaccuracies, though identified and mentioned here, are rather difficult to analyse further and to correct, but even with the inaccuracies, the resistance value estimated for the $z$-axis conductive tape is in general still quite small. Hence, it can be concluded from all three experiments that the small amount of $z$-axis conductive tape usually used for attaching a tag chip to a tag antenna will most likely not affect the performance of a tag.
It has to be noted that there is a life span to the optimum performance of a z-axis conductive tape. The recommended shelf-life of the tape is 24 months from the date the tape is manufactured. Hence, it is good when used for tag prototypes for short term testing and measurement, but is not recommended for long term commercial purposes.

### 3.5 A Small Passive UHF RFID Tag Design

As an illustration of the tag design process presented earlier in this chapter in Section 3.2, a novel RFID tag design is presented in this section. The design work of this RFID tag served as an early familiarisation with the general ideas and skills required
in designing an RFID tag, which ideas later became the basis of designing RFID tags for metallic objects in this research.

While the tag design presented can also be suitable for general RFID applications, except for those involving difficult objects such as metallic items, the tag was designed specially for livestock identification purposes. Implementation of RFID for livestock identification can allow better management in the farming industry, for example in terms of animal food consumption monitoring, disease control and breeding management [73] [22] [74] [75]. The tag is to be attached on the ears of livestock such as pigs, cattle and sheep.

The RFID tag design presented in this section is a collaborative work between the author of this thesis with Mr. David Malcolm Hall and Mr. Kin Seong Leong. The content of this section is based on a published paper with joint authorship [76].

3.5.1 Tag Design Considerations and Concepts

The first step was to determine the type of tag antenna to be used and a magnetic dipole antenna or, in a more common term, loop antenna was chosen. Among different possible loop antenna shapes, a circular loop antenna was chosen considering that it does not have sharp edges and can be fitted on an animal’s ear relatively easily as compared with a rectangular or square loop antenna.

As mentioned previously, the RFID tag is to be attached to animal ears. Hence, having a small tag size is essential. However, having a small tag size means that the loop antenna also has to be small. A small loop antenna typically exhibits the characteristic of low radiation resistance. Although a small loop antenna may still be able to provide sufficient inductance to tune with the capacitance of the tag chip for the tag to resonate at the desired frequency, the overall antenna impedance will most likely not be matched to the tag chip impedance. While the tag may still be able to operate if properly tuned to the desired frequency, it is best that a matching network can be added, if possible, to the tag design. This way, the tag antenna and tag chip impedances can
be matched for maximum power transfer and hence a better tag performance can be achieved.

With tag size and cost limitations, it was a rather difficult task to implement a feasible impedance matching network in the tag design. First, due to the size constraint, there was only very little area for the matching network implementation. Secondly, the matching network implementation must be as simple as possible so as not to increase the complexity of the tag design and hence the cost. Despite these constraints, a simple and feasible impedance matching network implementation based on [77] was able to be employed in the tag design here. This implementation consists of a two-element matching network (a parallel capacitance and a series capacitance). With this matching network implementation and with the circular loop antenna, the illustration of the tag design concept is as shown in Figure 3.18. Low cost double-sided copper clad FR4 material was chosen for the tag material.

![Figure 3.18. Illustration of the tag design.](image)

The front and back of the tag design are shown: (a) Front of the tag with a planar circular loop antenna; and (b) back of the tag with a series capacitance and a parallel capacitance corresponding to the impedance matching network implementation. $D_{\text{max}}$ is the overall (or maximum) diameter of the tag. $w_1$ is the width of the copper track corresponding to the circular loop antenna. $w_2$ is the width of the copper tracks corresponding to both the series and parallel capacitances respectively of the impedance matching network implementation.

As can be seen from Figure 3.18, the circular loop antenna is located on one side of the dielectric substrate (Figure 3.18(a)), and both the matching network elements are located on the other (Figure 3.18(b)). The circular loop antenna was made planar with
3.5 A Small Passive UHF RFID Tag Design

the plane of the dielectric substrate instead of a conventional wire-type loop antenna. Two small gaps were created to break the loop antenna. One of these gaps serves as the loop antenna feed terminal to cater for an RFID tag chip attachment across the gap. The other gap, together with the copper strip across it at its back on the other side of the dielectric substrate, allows the implementation of a series capacitance for the matching network. The copper strip lying across the loop antenna feed terminal at the back on the other side of the dielectric substrate functions as a parallel capacitance for the matching network. Assuming the loop antenna is lossless and has radiation resistance $R_r$ and inductance $L_a$, the tag chip has an equivalent resistance $R_c$ and capacitance $C_c$, and assuming that the matching network is purely consisting of just a simple series capacitance $C_1$ and a parallel capacitance $C_2$ without any loss and stray capacitance introduced by the matching network implementation method, a simplified equivalent circuit of the tag is shown in Figure 3.19.

![Figure 3.19. A simplified equivalent circuit representation of the tag. $R_r$ and $L_a$ are the radiation resistance and inductance respectively of the circular loop antenna (assuming lossless). $R_c$ and $C_c$ are the equivalent RFID tag chip resistance and capacitance respectively. $C_1$ and $C_2$ are the series capacitance and parallel capacitance respectively of the impedance matching network (assuming lossless and no stray capacitance).](image)

3.5.2 Tag Design Calculations

Calculations were performed to estimate the amount of series and parallel capacitances required for the impedance matching network. This is to ensure that the capacitance values required are not too high or low and are hence suitable for the impedance
matching network implementation method used in the tag design. The simplified equivalent tag circuit shown in Figure 3.19 was used for the calculations. This means a lossless loop antenna and an ideal impedance matching network containing a simple series capacitance and a parallel capacitance were assumed. As only approximate capacitance values for the impedance matching network were required, these assumptions were reasonable to maintain the simplicity of the calculations.

The equivalent impedance values for the circular loop antenna and the RFID tag chip were required for the calculations of the capacitance values $C_1$ and $C_2$ in Figure 3.19. Hence, to begin, the loop antenna impedance $Z_a$ was first calculated. Referring to the tag design shown in Figure 3.18, the width of the circular loop antenna track was fixed to $w_1 = 2$ mm and the outer diameter of the loop antenna was fixed to $D_{\text{max}} = 24$ mm. This means the average diameter of the loop antenna was $D = 22$ mm (or average radius $R = 11$ mm. Since the tag design consisted of a planar circular loop antenna, the width $w_1$ of the loop antenna was converted to an equivalent circular wire radius $r$ for calculation purpose. Following the relation $r = 0.25w_1$ [52], $w_1 = 2$ mm gave $r = 0.5$ mm.

From [52], for an electrically small circular wire loop antenna, the radiation resistance and inductance can be calculated using

\[
R_r = 20\pi^2(\beta R)^4\Omega
\]

\[
L_a = \mu_0 R \left[\ln \left(\frac{8R}{r}\right) - 2\right]
\]

where $\beta = \frac{2\pi}{\lambda}$ is the free space propagation constant with wavelength $\lambda$, and $\mu_0 = 4\pi \times 10^{-7} \text{ Hm}^{-1}$ is the free space permeability. Using these expressions and the dimensions specified above, the antenna radiation resistance and inductance were calculated to be $R_r = 0.39$ $\Omega$ and $L_a = 44$ nH respectively. The tag was designed for operation in the UHF RFID band at around the frequency 915 MHz. With this frequency, the loop antenna impedance was calculated to be $Z_a = 0.39 + j252$ $\Omega$.

Next in the calculations was to determine the equivalent RFID tag chip impedance. A tag chip can be represented by a resistor $R_c$ and a capacitor $C_c$ in parallel as shown in part of the circuit in Figure 3.19. For the tag chip used here, $R_c = 1.3$ k$\Omega$ and $C_c =$
3.5 A Small Passive UHF RFID Tag Design

1.15 pF. At the frequency 915 MHz, the equivalent tag chip impedance was calculated to be $Z_c = 17 - j149 \, \Omega$.

With the antenna and tag chip impedances known, the capacitance values $C_1$ and $C_2$ of the impedance matching network could then be determined. The values could be found either graphically using a Smith chart or by theoretical derivations. The latter method was used and it was calculated that $C_1 = 0.63$ pF and $C_2 = 6.50$ pF.

The $C_1$ and $C_2$ values are not overly low or high, hence it is feasible to employ the impedance matching network implementation method shown in Figure 3.18(b), as long as the dielectric substrate used is not excessively thick. The capacitance values calculated were just an approximate guideline for implementation feasibility study. Due to the impedance matching network implementation method used, there may be additional stray capacitances present in the non-ideal case, which were too complex to be included into the calculations. Hence, the dimensions of the copper tracks corresponding to the series and parallel capacitances shown in Figure 3.18(b) were determined through simulations, and later finalised by fine-tuning after the tag was fabricated.

3.5.3 Simulations

Ansoft HFSS simulation software was used for the tag design simulations. The dimensions of the copper tracks corresponding to the series and parallel capacitances of the impedance matching network shown in Figure 3.18(b) were adjusted through simulations such that the entire simulation structure (loop antenna together with the impedance matching network) would provide a total impedance conjugate to the tag chip impedance.

Double-sided copper clad FR4 substrate was used as the tag antenna material. The dielectric substrate had a relative dielectric permittivity $\varepsilon_r = 4.4$ and thickness $h = 0.36$ mm. The width $w_2$ for both the copper tracks corresponding to the series and parallel capacitances was set to 1 mm to begin with. With the copper tracks having a width $w_2 = 1$ mm and lying along the arc corresponding to the average loop antenna radius, this means the copper tracks were located at an inset of 0.5 mm from the edge.
of the substrate. As the equivalent tag chip impedance was calculated previously to be \(Z_c = 17 - j149\ \Omega\), the angle subtended by the copper tracks (or in other words, the lengths of the tracks) were adjusted in order for the entire simulation structure to reach a total impedance as close as possible to \(17 + j149\ \Omega\).

After some adjustments, it was found that with track arc angles \(\theta_1 = 115^\circ\) and \(\theta_2 = 155^\circ\), the structure had a simulated total impedance of \(17 + j142\ \Omega\) at 915 MHz. The simulation also gave a simulated peak directivity and peak gain of 1.53 and 0.13 respectively. The directivity pattern of this tag antenna structure is shown in various forms in Figure 3.20. As can be seen, the shape of the directivity pattern is similar to that of a conventional loop antenna. This means the implementation of the impedance matching network did not affect the radiation pattern of the loop antenna much.

For the RFID tag chip used, although the equivalent chip impedance is \(17 - j149\ \Omega\) based on the specified parallel chip resistance and capacitance values, experience has
shown that the real part of the equivalent impedance of this chip may be lower. To also consider this case beside the original case above, the length of the copper tracks corresponding to the impedance matching network were adjusted and the tag antenna structure (loop antenna plus matching network) was simulated to achieve a total impedance with a lower real-part. With track arc angles $\theta_1 = 140^\circ$ and $\theta_2 = 55^\circ$, the simulation gave a total impedance of $7 + j143$ $\Omega$. The simulated peak directivity and peak gain of the structure were given as 1.61 and 0.14. The radiation pattern of this structure is very similar to that in the original case above (Figure 3.20) and hence will not be shown here.

It can be observed from the simulation results above that the peak gain is much less than the peak directivity. This is possibly caused by the losses introduced by the dielectric substrate and the copper material used for the tag. An analysis was performed to estimate the losses and it was shown that the main contributor to the losses was the dielectric substrate. The analysis can be found in Appendix A of this thesis.

### 3.5.4 Tag Fabrication and Read Range Measurement

The next stage was to fabricate the tag. Shown in Figure 3.21 is the fabricated tag, which was hand-made. Double-sided copper clad FR4 material (with specifications consistent with those used in the simulation stage) was used as the tag material. The RFID tag chip used was a Class 1 Generation 1 (C1G1) chip and it was attached across the tag antenna feed terminal using a $z$-axis conductive tape.

The copper tracks corresponding to the series and parallel capacitances of the impedance matching network implementation located at the back of the tag were at first intentionally made longer in order to allow trimming and fine-tuning. A network analyser (Model HP 8714C) was set to couple by means of a small un-tuned loop to the tag, and to measure the reflection from that loop over a set frequency range. The small un-tuned loop used had a diameter of 7 mm and was made from the centre conductor at one end of a short length of the coaxial cable. The lengths of the copper tracks at the back of the tag were slowly adjusted by trimming the ends of the tracks until the frequency point at which the return loss curve had the deepest dip was located close to 915 MHz. After
the trimming and fine-tuning of the tag, the respective angles subtended by each of the copper tracks were measured to be approximately $\theta_1 = 164^\circ$ and $\theta_2 = 76^\circ$.

The next step was to measure the read range of the tag (maximum distance between the reader antenna and the tag before the reader fails to detect the tag). An RFID reader and reader antenna were set up for the measurement. The reader antenna used was circularly polarised and it gave a total equivalent isotropic radiated power (EIRP) of approximately 4 W. The tag was read in the orientations shown in Figure 3.22. The distance between the tag and the reader antenna was varied to find the maximum read range of the tag. When the sheep tag was placed horizontally, the read range was about 1 m. When the orientation of the tag was changed to vertical, but the reader remained in the equatorial plane of the tag, the read range fell to slightly less than 1 m. The reason that the vertical orientation was not as good was that the reader antenna was not perfectly circularly polarised (it was slightly elliptically polarised). However, as predicted by the radiation pattern, when the tag was aligned with its axis parallel with that of the interrogator antenna, the reading distance was only a few centimetres.
3.6 Application for Pigs Identification

![Diagram of reader antenna and tag in three orientations](image)

**Figure 3.22. Different orientations of tag with respect to reader antenna.** Tag was read at three different orientations: (a) horizontal; (b) vertical; and (c) parallel.

### 3.6 Application for Pigs Identification

The identification of pigs is mandated by Livestock Disease Control Act 1994 Australia to prevent disease spreading and to maintain consumer confidence in the quality of Australian pork. Current RFID technology used in animal identification, such as cattle and sheep, is the Low Frequency (LF) system, which based on ISO 11785 and operates within the frequency band 125 - 134 kHz. However, it does not offer an anti-collision capability. Tagging small piglets may mean that more than one animal may be present in the RF field at the same time and anti-collision is recommended. In this research, the use of HF (13.56 MHz) and UHF (920 - 926 MHz) RFID tags for pig tagging in Australia was investigated. HF and UHF RFID tags can offer an anti-collision capability, and those designed and used in the investigation were required to be passive, reusable and their size must be small enough for easy fitting to the ears of the pigs.

As the focus of this thesis is on passive UHF RFID systems, the HF part of this investigation will not be discussed here and further information on the HF tags can be found in [78] and [79]. For the UHF part, the tag used in the investigation was based on the
tag design presented in Section 3.5. The investigation involved the monitoring of RFID tagged pigs feeding on food at a pig feeder.

The content of this section is partially based on published papers [78] and [79], which are co-authored by the author of this thesis joint research. This work is supported by Pork CRC Australia.

3.6.1 Stage 1: Preparation of RFID Tags

In the investigation or case study on pigs identification, the first stage was to prepare sufficient RFID tags for use in a field trial in the final stage of the study. The aim was to prepare at least 10 UHF RFID tags for tagging on a small population of 10 pigs. However, in the tag preparation stage, the requirement was increased to produce at least 30 tags, so that the best 10 tags could be chosen for the field trial later and the remaining tags could be kept as back-up substitutions for any failed tags.

The tags were required to fit into tag encapsulation casings in order to protect them from harsh environments in the piggery. The tag encapsulation casings provide tamper proof and water proof abilities. Shown in Figure 3.23 is a tag encapsulation casing (from Leader Products Pty Ltd, Australia) consisting of two parts: a cap and a base. Each tag was required to fit within the available space of the casing base. Figure 3.24 shows the casing base with a highlighted area indicating the available space for the tag. Referring to Figure 3.24, \( D_{\text{inner}} \approx 15 \text{ mm} \) and \( D_{\text{outer}} \approx 28 \text{ mm} \). To fit within the casing base, tags similar to that presented in Section 3.5 but with a hole of diameter 15 mm in the tag substrate were made. The tag was also made slightly larger with maximum diameter \( D_{\text{max}} = 25 \text{ mm} \).

The tag design presented in Section 3.5 has the flexibility of fine tuning by trimming the ends of the copper tracks (corresponding to an impedance matching network) at the back of the tag. This feature has, by experience, allowed the tag to be able to operate with RFID tag chips of different manufacturer and production batches, as long as proper fine-tuning is performed. For the 30 RFID tags made for a field trial in a piggery, the RFID tag chips used were Class 1 Generation 2 (C1G2) UHF RFID tag chips.
3.6 Application for Pigs Identification

Figure 3.23. Tag encapsulation casing. This casing was provided by Leader Products Pty Ltd, Australia. The casing consists of two parts: a cap and a base.

Figure 3.24. The available space in a casing base for accommodating an RFID tag. The available space is highlighted in orange. This space has a circular area with diameter \(D_{\text{outer}}\) minus a circular area with diameter \(D_{\text{inner}}\).

by Texas Instruments. With a different tag chip used and also with a slightly larger tag dimension and a hole in the tag substrate compared with the tag in Section 3.5, the copper tracks at the back of the tags were intentionally made longer and then slowly trimmed to fine tune the tags. Shown in Figure 3.25 are the front and back views of the RFID tag after fine tuning was performed. The material used for the tag was double-sided copper clad FR4 substrate with relative dielectric permittivity \(\varepsilon_r = 4.4\) and thickness \(h = 0.2\) mm.

After the tags were made, tag read range performance measurements were performed. An RFID reader together with a circularly polarised reader antenna that gave a total equivalent isotropic radiated power (EIRP) of approximately 4 W were used for the read range measurements. The tags were first measured in free space before they were
Encapsulated by the tag casings. To encapsulate the tags, first each of the tags was placed on the casing base and a glue-like epoxy resin was poured over the tag (and filled the casing base) in order to keep the tag firmly in place. This is shown in Figure 3.26. A casing cap was then placed over the tag and casing base combination, and the casing was sealed using an ultrasonic vibration process. With the addition of the epoxy resin and a casing around each of the tags, experience had shown that there would be a slight detuning where the resonant frequency of the tags was reduced. Hence, each tag had been fine tuned earlier on to operate slightly higher than the desired frequency of operation. After the tags were encapsulated, the tags read range performance were measured in both free space and when placed on a palm of a human hand. The reason to placing the encapsulated tags on a palm of a human hand was to mimic the situation where the tags were attached to the ears of pigs.

The results for the maximum read range measured for the tags before and after the encapsulation stage are shown in Table 3.1. As can be seen, the read range performances are not totally consistent for some of the tags. The reason to this is most likely because the tags were each fine tuned by hand manually. Nevertheless, there are a few things that are as expected and can be observed from the results in general. First, since each
of the tags was fine tuned to have a slightly higher tag resonant frequency to take into account of the tag detuning caused by the tag encapsulation, the free space read range performances of the tags are better after the encapsulation than before. Secondly, the presence of a hand near the tags had caused a reduction in the read range of the tags, which is as expected. Although there was a reduction in read range when the tags were placed on the palm of a hand, the amount of read range recorded for each tag on average was still sufficient for the intended investigation on pig identification. In fact, for the monitoring of pig feeding on food at the pig feeder, the tag read range should not be too high so that pigs that are not feeding on food and are standing at a distance away from the pig feeder will not be identified unintentionally, giving a false record.

3.6.2 Stage 2: Trial Setup

With the RFID tags made and prepared, the next stage in preparation for the field trial was to set up the required equipment (such as the RFID reader and reader antennas) in a way suitable for deployment of an RFID system in a piggery. Due to the harsh and
Table 3.1. Measured maximum read range results of 30 tags. The read range of each tag was measured in free space before and after the tag was encapsulated. The read range of each encapsulated tag was also measured when the tag was placed on a palm of a human hand to mimic the situation of the tag attached to a pig’s ear.

<table>
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<th>Before Encapsulation</th>
<th>After Encapsulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Free space (m)</td>
<td>Free space (m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>On palm (m)</td>
</tr>
<tr>
<td>C1</td>
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<td>0.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.34</td>
</tr>
<tr>
<td>C2</td>
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</tr>
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</tr>
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</tr>
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</tr>
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<td>0.36</td>
</tr>
<tr>
<td></td>
<td></td>
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<tr>
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<td>0.43</td>
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<td>1.09</td>
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</tr>
<tr>
<td>E10</td>
<td>0.21</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>0.30</td>
</tr>
</tbody>
</table>
3.6 Application for Pigs Identification

often wet environment in a piggery, all the equipment was required to be protected from any form of potential damage.

A typical or conventional pig feeder is as shown in Figure 3.27. The feeder has a width, height and depth of approximately 0.5 m, 0.9 m and 0.4 m respectively. It is made entirely of metallic plates except for the side plates, which are made of a high density plastic material. To allow the monitoring of pig feedings, it was required to mount one RFID reader antenna on each of the two sides of the pig feeder. A modification to the conventional pig feeder was required to protect the two reader antennas. The two plastic side plates of the original feeder were removed (all the metallic parts of the feeder retained) and were replaced by two box-like structures made of 20 mm thick high density polyethylene plastic material. The box-like structures were hollow inside in order to contain the reader antenna and parts of the reader antenna coaxial cables.

Figure 3.27. A typical pig feeder in a piggery. This feeder is made entirely of metallic plates except for the sides (in black), which are made of high density plastic material.

To protect the RFID reader, and also the power supply adapter and parts of the cables connected to the RFID reader, a waterproof protection casing was used to contain the RFID reader and the components connected to the reader (except for the reader antennas which were already contained in box-like structures made of thick high density polyethylene plastic material at the sides of the pig feeder). An illustration of the
arrangements and cabling of equipment in the protective casing is as shown in Figure 3.28, and is further illustrated in Figure 3.31.

Figure 3.28. A protective casing to contain the trial equipment. Labeled A is the RFID reader. Labeled B is the power supply adapter. Labeled C, D and E are glands for various cables. The approximate width and length of the protective casing is shown.

Figure 3.29 shows a complete setup for the trial consisting of all the equipment and the pig feeder. As both the reader antennas were located at the sides of the pig feeder, they were positioned in a way to have minimal obstructions by the metallic parts of the pig feeder. Hence, as can be seen in Figure 3.29(b) showing one side of the pig feeder, the reader antenna was tilted in order to avoid the metallic parts of the pig feeder. Due to the tilting of the reader antennas, the plastic box-like structures containing the reader antennas were made larger, projecting approximately 0.25 m out the front of the pig feeder adding to the original depth of the pig feeder.

### 3.6.3 Stage 3: Field Trial

As mentioned previously, a total of 30 RFID tags were prepared. Only a small population of 10 pigs were involved in the field trial. Hence, 10 good tags were chosen from the 30 tags available. The pigs were numbered 1 to 10 and each of the pigs was tagged on its left ear on 24th September 2007. Shown in Figure 3.30 is a close view picture of some of the tagged pigs and Table 3.2 shows a record of the 10 RFID tags chosen and the respective pigs assigned to each of them.

The pigs were monitored and observed from 25th to 27th September 2007 when they were feeding on food at the pig feeder (Figure 3.31). During the trial, any occurrence
3.6 Application for Pigs Identification

Figure 3.29. Illustration of a complete setup for the field trial. Different views of the setup shown: (a) Front, and (b) side. The reader antennas (on both sides of the pig feeder) were tilted to avoid the metallic parts of the pig feeder.

Figure 3.30. Tagged pigs in the field trial. The pigs were tagged on their left ears for the UHF RFID tags (HF RFID tags on their right ears).
Table 3.2. Record of RFID tags assigned to each of the pigs. 10 RFID tags were chosen from the 30 available tags made earlier. Pigs were numbered from 1 to 10.

<table>
<thead>
<tr>
<th>Pig Number</th>
<th>Tag Label</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C1</td>
</tr>
<tr>
<td>2</td>
<td>D3</td>
</tr>
<tr>
<td>3</td>
<td>D8</td>
</tr>
<tr>
<td>4</td>
<td>D7</td>
</tr>
<tr>
<td>5</td>
<td>D1</td>
</tr>
<tr>
<td>6</td>
<td>C6</td>
</tr>
<tr>
<td>7</td>
<td>D10</td>
</tr>
<tr>
<td>8</td>
<td>E7</td>
</tr>
<tr>
<td>9</td>
<td>C4</td>
</tr>
<tr>
<td>10</td>
<td>C10</td>
</tr>
</tbody>
</table>

of “missed read”, “ghost read” and “out-of-zone read” were particularly noted. A “missed read” occurs when a pig enters the zone of the pig feeder (near the food outlet) to consume food but not detected by the RFID reader. A “ghost read” occurs when a tag (not from the group of chosen tags) with unknown tag number is recorded. An “out-of-zone read” occurs when the tag on a pig that is not at the feeding zone and at a distance away from the pig feeder is detected by the RFID reader. “Missed reads” and “out-of-zone reads” were detected by continuously visually monitoring the pig movements and the reader output.

Based on the observations from 25th to 27th September 2007, the UHF RFID implementation in the piggery went well. On 25th September 2007, there was one “ghost read” recorded. The source of the problem was unknown. Other than that, there was no occurrence of any other type of unwanted reads stated above on this day and the remaining days of the trial. The trial for the implementation of the UHF RFID system was carried out in parallel with the HF RFID system. Results from this trial have
3.6 Application for Pigs Identification

Figure 3.31. Monitoring of pigs during the trial. Shown are some of the pigs feeding on food at the pig feeder.

shown that there was quite a number of “missed read” and “out-of-zone read” occurrences for the HF RFID implementation. This indicates that a UHF RFID system may be a better candidate over a HF RFID system for the application investigated here.

After 27th September 2007, the trial continued but the data collected was monitored remotely. As the pigs could not be observed in person, any occurrences of unwanted reads were unable to be recorded. However, the continuation of this trial would show the reliability of the tags and whether the tags would continue to function for a long period of time. Results have shown that 7 days after the pigs were tagged, the data from the tag on pig 8 stopped. It was later discovered that the tag on pig 8 was dropped from the pig’s ear, hence providing no data. Other than that, the rest of the tags were still attached to the pigs, and were functioning well.
3.7 Conclusion

In this chapter, the process employed in designing tags presented in this thesis has been systematically outlined. Work related to the tag design process has also been presented. This includes the discussion on the simulation steps used for simulating a tag design, with the major simulation setup options clearly shown. Also, since $z$-axis conductive tapes were used in tag fabrications, results from the investigation of the possible additional resistance introduced by the $z$-axis conductive tape have been presented. The additional resistance caused by the $z$-axis conductive tape was found to be minimal and was expected not to give significant effects.

In the second part of this chapter, a small passive UHF RFID tag design was presented. The work has illustrated the adoption of the tag design process discussed earlier in this chapter. Even though the tag has a small size, a good read range performance was achieved with the tag design presented. This tag was later applied for pig identifications. Field testings in a real-life piggery were designed and performed. Successful field testing results were obtained, proving the reliability and good performance of the tag.

The work presented in this chapter forms a foundation or basis for designing RFID tags for metallic objects in this research.
A small passive UHF RFID tag containing a loop antenna and designed specifically for attaching to metallic objects is presented in this chapter. Theoretical design steps for this tag design, as well as significant simulation results are included. The results for practical read range performance measurements of this tag are also presented.
4.1 Introduction

When designing an RFID tag suitable for attaching to metallic objects, the first point to be considered is the behaviour of the interrogation fields (from the RFID reader antenna) near a metallic surface. According to the theory of boundary conditions, for magnetic field, there are only tangential components and no normal components of this field at the metallic surface [80]. In addition, for a uniform plane electromagnetic wave, the magnetic field (tangential component) will be doubled when it is very near the metallic surface. All these have been discussed in more detail in Chapter 2.

The RFID tag design presented here in this chapter exploits both facts above by having a loop antenna oriented such that the plane of the loop is perpendicular to the plane of the metallic surface where the RFID tag will be attached to. With this orientation, the idea is to have the rich concentration of magnetic fields near the metallic surface to couple to the loop antenna of the RFID tag.

In the next section, the preliminary design considerations of the tag are discussed. This is then followed by presentations of results on design calculations, simulations and measurements, along with tag design fine-tuning steps. In the later part of this chapter, additional measurement results as well as analyses related to the tag are presented.

This chapter is based on a published paper [81], in which the main author is the author of this thesis.

4.2 Design Considerations

Besides having the tag loop antenna oriented in a way that the plane of the loop is perpendicular to the plane of the metallic surface the tag is attached to (as mentioned in the previous section), the tag design has a few other criteria. These criteria are: the tag must be small, easy for attachment to metallic surfaces and low in cost.

Many different types of loop antenna could be considered for the tag antenna. The circular loop antenna is the most common among all loop antennas, however this antenna will occupy too much height if it is to have an adequate area and is oriented in
Figure 4.1. Structure of the RFID tag with a rectangular loop antenna. The rectangular loop antenna is constructed with a wide metallic strip. It has a length, height and width denoted by $L_{rec}$, $H_{rec}$ and $W_{rec}$ respectively. The feed point terminals are separated by a gap $g$ and the tag chip is placed across the gap.

a way that the plane of the loop is perpendicular to the plane of the metallic surface. Hence, a rectangular loop antenna was chosen.

The first idea was to have a semi-loop antenna mounted on a piece of metallic plate (as a ground plane), with one end of the semi-loop connected directly and the other end through a tag chip to the metallic plate. The plane of the semi-loop would be perpendicular to that of the metallic plate. However, having a metallic plate as part of the tag will increase the overall size of the tag and hence, potentially restrict the tag from being able to attach to smaller size metallic objects or surfaces. Therefore, the idea of having a metallic plate was rejected. Instead, a full loop antenna was considered. The idea was to have the full loop antenna located above any metallic surface that the tag would be attached to, with the antenna very close to but separated from the metallic surface by a small gap. The planes of the full loop antenna and the metallic surface would still be perpendicular to each other. This way, the tag will be compactly in the form of just the loop antenna itself, able to attach to any metallic surfaces with ease, and yet still able to benefit from the rich concentration of magnetic fields when attached to metallic surfaces.

Figure 4.1 shows the structure of the RFID tag design that consists of a rectangular loop antenna and an RFID tag chip. As can be observed, the rectangular loop antenna is not a regular planar loop antenna constructed with circular wire. Instead, it is made of a wide metallic strip of width $W_{rec}$. The reason for this is that, by having a certain width,
the antenna will provide a better coupling volume. The concept of coupling volume will be analysed and discussed later in this chapter.

4.3 Theoretical Calculations

The calculations for this loop antenna are the same as the calculations for regular loop antennas made of circular wire, except that the tag antenna width $W_{rec}$ (width of the wide metallic strip) was converted to its equivalent circular wire radius $r$ before calculations were performed. In [52], a number of models for conversion to equivalent radii each corresponding to a different structure type have been shown. The most appropriate model suited for the tag antenna structure here was chosen for the radius conversion. Referring to [52], the illustration of the chosen model is as shown in Figure 4.2, where the expression for the equivalent radius conversion is

$$r \simeq 0.2(a + b).$$  \hspace{1cm} (4.1)

Referring to the axis on Figure 4.2, it is believed that this model can be applied to loops with a majority of the conducting surface of width $b$ and parallel to the $z$-axis but which has an orthogonal segment of width $a$ lying on the $xy$-plane. To make this relevant to the work here, this chosen model in Figure 4.2 was related to the tag antenna structure by having $a \simeq 0$ and $b \simeq W_{rec}$. The dimension $a$ was approximated to zero because the thickness of the wide metallic strip was assumed negligible compared to the width of the strip. Hence, the equivalent wire radius $r$ corresponding to the wide metallic strip of width $W_{rec}$ is

$$r \simeq 0.2W_{rec}.$$  \hspace{1cm} (4.2)

The rectangular loop antenna with the structure presented here could be approximately represented by a resistor with radiation resistance $R_{r}$ and an inductor with inductance $L_{a}$ in series (assuming it to be lossless, electrically small and of negligible self-capacitance). Small loop antennas with the same loop area carrying a uniform current have the same radiation resistance. The radiation resistance and inductance of the rectangular loop antenna were determined using the expressions found in [52]
that correspond to a small circular loop antenna with loop radius $R$ and circular wire radius $r$. The expressions used were [52]

$$R_r = 20\pi^2(\beta R)^4\Omega$$  \hspace{1cm} (4.3)

$$L_a = \mu_0 R \left[ \ln \left( \frac{8R}{r} \right) - 2 \right]$$  \hspace{1cm} (4.4)

where $\beta = \frac{2\pi}{\lambda}$ is the free space propagation constant with wavelength $\lambda$, and $\mu_0 = 4\pi \times 10^{-7}$ Hm$^{-1}$ is the free space permeability.

The RFID tag chip used in this design could be represented by a resistor with resistance $R_c$ and a capacitor with capacitance $C_c$ in parallel. For a start, the values of $R_c = 1.5$ k$\Omega$ and $C_c = 1.15$ pF were used in the design. The RFID tag was designed to operate in the UHF band at around the frequency of 915 MHz. For this frequency, the equivalent impedance of the chip $Z_c$ was calculated to be $15 - j150$ $\Omega$.

It is known that the maximum power transfer will occur when the tag antenna impedance is equal to the conjugate of the tag chip impedance. To achieve this, it is usual to include an impedance matching network to the tag design. However, the antenna structure of the tag design considered here made the implementation of an impedance matching network difficult. Hence, an impedance matching network was not included in the tag design. Even in the case when the tag antenna and chip impedances are not matched, the tag antenna inductance and chip capacitance will still need to be tuned.
4.3 Theoretical Calculations

with each other in order for the tag to resonate at the desired frequency. Therefore in the tag design here, the physical dimension of the rectangular loop antenna was adjusted to provide sufficient inductance to be tuned with by the capacitance of the tag chip. The trade-off of this method is that the small rectangular loop antenna will be able to provide sufficient inductance but not the resistance that corresponds to the tag chip impedance, since it is a characteristic of small loop antennas to have low radiation resistance. However, this method was still used in order to maintain the simplicity and low cost of the design.

As the rectangular loop antenna width $W_{rec}$ was chosen to be the varying parameter to obtain the desired inductance, the height $H_{rec}$ and length $L_{rec}$ of the rectangular loop antenna were fixed to 10 mm and 25 mm respectively. This height and length gave a rectangular loop circumference of approximately $\frac{\lambda}{5}$. Although it is usual to classify (such as in [52] and [82]) that only loop antennas with perimeter less than $\frac{\lambda}{10}$ are considered to be electrically small, the tag antenna here still had a reasonably small perimeter close to this common defining limit. Hence, the tag antenna was assumed to have an electrically small size.

By having

$$\pi R^2 = L_{rec}H_{rec}, \quad (4.5)$$

a circular loop with an equal area to the rectangular loop with dimensions stated above was calculated to have a loop radius of $R = 9$ mm. Note again that since $H_{rec}$ and $L_{rec}$ were fixed, the only variable was the width $W_{rec}$ of the rectangular loop antenna. As mentioned previously, the tag chip was found to have an equivalent impedance with a capacitive reactance of $-150$ $\Omega$. Hence, for the tag antenna to tune with the tag chip for tag resonance at 915 MHz, the tag antenna was required to have an inductive reactance of 150 $\Omega$ at 915 MHz. To achieve this, the loop antenna was required to have an inductance of $L_a = 26$ nH. Using (4.4) with $R = 9$ mm and $L_a = 26$ nH, the antenna circular wire radius $r$ was calculated to be 1 mm. Then with (4.2), the rectangular loop antenna width that corresponded to $r = 1$ mm was found to be $W_{rec} = 5$ mm. In addition, using (4.3), the antenna was expected to have $R_r \simeq 0.17$ $\Omega$ in free space.
It has to be noted that the values calculated above served as an approximation since the calculations were made based on the assumption that the tag antenna was ideal, electrically small and lossless.

### 4.4 Simulations

With the rectangular loop antenna dimensions $W_{\text{rec}} = 5 \text{ mm}$ (calculated theoretically), $H_{\text{rec}} = 10 \text{ mm}$ and $L_{\text{rec}} = 25 \text{ mm}$, the RFID tag design was modelled and simulated using Ansoft HFSS. In addition, a gap of $g = 3 \text{ mm}$ was allocated between the feed point terminals. Two different cases were considered: (1) RFID tag in free space; and (2) RFID tag positioned above a metallic surface. The latter case aims to predict the effect of the metallic surface towards the characteristics of the RFID tag antenna.

#### 4.4.1 Tag in Free Space

As the tag antenna would be fabricated using thin metallic strips of thickness 0.04 mm in the tag implementation stage later, the metallic strip thickness of the tag antenna in the HFSS simulation model was set to 0.04 mm to maintain a consistency. A perfect electric conductor (pec) material was assigned as the tag antenna material.

For the case with the RFID tag in free space, the simulation results have shown that the rectangular loop antenna had an impedance of $Z_a = 0.278 + j162 \Omega$ at the frequency 915 MHz, which is quite close to the theoretically calculated values. The peak directivity and peak gain of the tag antenna were given by the simulation as 1.29 and 1.20 respectively. (Notice that the peak directivity and peak gain values are different even though a perfect electric conductor material was used. When a perfect electric conductor is used, there should be no loss and the gain should have the same value as the directivity. However, in HFSS simulations, the computed radiated power of the antenna may deviate slightly from the actual value depending on the accuracy of the electromagnetic fields on the absorbing boundary set up in the simulation that encompass the antenna structure. Since gain is related to directivity through radiation efficiency, the simulated gain value here is slightly different from the directivity value.)
4.4 Simulations

However, in a real-life implementation, a perfect electric conductor material does not exist. Copper strips of thickness 0.04 mm was chosen for the tag implementation in the later stage. Hence, the tag antenna above was re-simulated, but this time with the tag antenna material changed to copper. The simulation results gave a tag antenna impedance of $Z_a = 0.488 + j161$ Ω at the frequency 915 MHz. The directivity pattern of this antenna in the $yz$-plane is as shown in Figure 4.3(a). Also shown in Figure 4.3(b) is the three dimensional polar plot of the pattern. Since this antenna is a loop antenna, the directivity pattern of this antenna is very similar to that of conventional small circular wire loop antennas in free space, which is as expected. The peak directivity obtained from the simulation is 1.28 and the peak gain is 0.66.

![Simulated directivity pattern of tag antenna with dimensions $L_{rec} = 25$ mm, $H_{rec} = 10$ mm and $W_{rec} = 5$ mm located in free space. Directivity pattern was plotted in the form of: (a)$yz$-plane plot (Radial scale markings are in dB.), and (b) three dimensional polar plot (The reference direction for the "Theta", $\theta$ coordinate is the $z$-axis and the reference direction for the "Phi", $\phi$ coordinate is the $x$-axis.).](image)

4.4.2 Tag Above Metallic Surface

In the second simulation case, the RFID tag was positioned above a metallic plane, with the plane of the rectangular loop antenna perpendicular to the metallic plane.
The simulation model is shown in Figure 4.4. Aluminium material was assigned to the metallic plane and a plane size of $1.5\lambda \times 1.5\lambda$ and thickness 2 mm were set for the simulation in order to be consistent with the aluminium plane that would be used later in the practical measurement stage. The tag antenna in the simulation model was built with copper material and with the same dimensions as described previously.

![Simulation model of tag above a metallic plane.](image)

**Figure 4.4. Simulation model of tag above a metallic plane.** The tag has dimensions $L_{rec} = 25$ mm, $H_{rec} = 10$ mm and $W_{rec} = 5$ mm. The metallic plane (shown above in green colour) is aluminium with size $1.5\lambda \times 1.5\lambda$ and thickness 2 mm. The transparent box encompassing the tag and the metallic plane structures shown above is a PML boundary that is required as a part of the simulation setup.

In the simulation, the antenna and the metallic plane was separated by a small gap of 3 mm. This is to prevent the antenna from having a direct short-circuit to the metallic plane. In addition, in the implementation of this RFID tag design for real-life usage in different applications, adhesives will most likely be inserted within this gap to allow the attachment of the tag to metallic items, with possibly a protective casing such as that shown in Figure 4.5 also added to increase the durability of the tag.

The simulation for the second case was performed and the results gave a rectangular loop antenna impedance of $Z_a = 0.733 + j159 \ \Omega$ at the frequency 915 MHz. Comparing with the first case (tag in free space where $Z_a = 0.488 + j161 \ \Omega$), it can be observed that the reactance of the antenna did not change much when the RFID tag was above
a metallic surface. Only the resistance changed, with the second case having almost 1.5 times the resistance in the first case. The directivity pattern of the antenna in the $yz$-plane corresponding to the second case is as shown in Figure 4.6(a). It can be seen in Figure 4.6(a) that the antenna pattern was significantly changed with the presence of a metallic plane near it as compared to that of the free space case. Also shown is the directivity pattern of the antenna in a three dimensional polar plot form in Figure 4.6(b). The peak directivity obtained from the simulation is 4.14 and the peak gain is 3.31, which are much higher than in the free space case.

The simulation results presented above have shown that, for this RFID tag design, the presence of a metallic plane does not affect the reactive impedance of the antenna. Hence, this tag will most likely not suffer from detuning of the resonant frequency when it is attached near a metallic surface, making it a suitable tag for metallic objects. In addition, the presence of a metallic plane has also enhanced the directivity of the antenna.

The simulation results for both cases (tag in free space and tag above metallic surface) are summarised in Table 4.1.
Figure 4.6. Simulated directivity pattern of tag antenna with dimensions $L_{\text{rec}} = 25$ mm, $H_{\text{rec}} = 10$ mm and $W_{\text{rec}} = 5$ mm located 3 mm above a $1.5\lambda$ × $1.5\lambda$ aluminium metallic plane. Directivity pattern was plotted in the form of: (a) $yz$-plane plot (Radial scale markings are in dB.), and (b) three dimensional polar plot (The reference direction for the "Theta", $\theta$ coordinate is the $z$-axis and the reference direction for the "Phi", $\phi$ coordinate is the $x$-axis.).

### 4.5.1 Tag Fabrication and Measurement

The tag design was implemented according to the illustration in Figure 4.1 with dimensions $L_{\text{rec}} = 25$ mm, $H_{\text{rec}} = 10$ mm and $W_{\text{rec}} = 5$ mm. The material used for making the wide strip rectangular loop antenna of the tag was a copper foil tape with non-conductive adhesive (3M 1194 [83]). The tape has a thickness of 0.04 mm.

As the copper foil tape is very thin, it was difficult to maintain the overall rectangular shape of the loop antenna. Hence, an ABS (acrylonitrile butadiene styrene) plastic block was added to the empty or hollow area of the loop to maintain the shape and durability of the rectangular loop antenna. ABS plastic material was chosen because it is easy to handle, light weight and physically strong. In addition, it has quite a low relative dielectric permittivity and hence, it was expected not to perturb the electromagnetic fields too much. To see the effect of the ABS plastic material, the tag antenna was simulated in free space with a material block of relative dielectric permittivity.
4.5 Design Implementation and Fine-Tuning

Table 4.1. Summary of simulation results for a tag with antenna dimensions $L_{rec} = 25$ mm, $H_{rec} = 10$ mm and $W_{rec} = 5$ mm. Two cases were considered. In the first case, the tag was simulated in free space. In the second case, the tag was simulated above a $1.5\lambda \times 1.5\lambda$ aluminium metallic plane of thickness 2 mm.

<table>
<thead>
<tr>
<th>Tag location</th>
<th>Antenna impedance, $Z_a$</th>
<th>Peak directivity</th>
<th>Peak gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free space</td>
<td>$0.488 + j161\ \Omega$</td>
<td>1.28</td>
<td>0.66</td>
</tr>
<tr>
<td>Above metallic surface</td>
<td>$0.733 + j159\ \Omega$</td>
<td>4.14</td>
<td>3.31</td>
</tr>
</tbody>
</table>

of 2.8 (to resemble an ABS plastic material). The material was inserted into the hollow area of the loop antenna and simulation results gave an antenna impedance of $Z_a = 0.519 + j177\ \Omega$, which is quite close to the simulated antenna impedance in the case without the ABS plastic material. The slight effect caused by the ABS plastic material could be easily compensated in the tag dimension fine-tuning in the later stage.

Figure 4.7. Fabricated RFID tag. The tag has dimensions $L_{rec} = 25$ mm, $H_{rec} = 10$ mm and $W_{rec} = 5$ mm. A Class 1 Generation 1 (C1G1) tag chip was used.

A Class 1 Generation 1 (C1G1) tag chip by Alien Technology was used for the tag. Figure 4.7 shows the fabricated tag. As this is a tag prototype, it was hand-made. Moreover, due to the unavailability of a z-axis conductive tape at the time when the
tag was made, two short metal pins (one soldered on each side of the gap g) were used to connect and hold the tag chip in place across the feed terminals of the tag antenna.

![Image of a tag antenna with a small un-tuned loop](image)

**Figure 4.8. Investigation of tag resonant frequency.** A small un-tuned loop was brought near to the tag antenna for coupling.

For investigation of the tag resonant frequency, a network analyser (Model HP 8714C) was set to couple by means of a small un-tuned loop to the tag, and to measure the reflection from that loop over a set frequency range. The small un-tuned loop used had a diameter of 7 mm and was made from the centre conductor at one end of a short length of the coaxial cable. Figure 4.8 shows the small un-tuned loop brought near to the tag for coupling.

At the tag’s resonance, the tag will couple better to the field generated by the small un-tuned loop. When this happens, a greater amount of energy will be drawn from the small un-tuned loop. Hence, a dip will be observed on the return loss curve of the small un-tuned loop on the network analyser at the resonant point of the tag. By locating the frequency point at which the return loss curve had the deepest dip, the approximate resonant frequency of the tag was found to be 650 MHz. The plot of the return loss curve obtained from the network analyser is shown in Figure 4.9. However, this resonant frequency was much lower than expected. This may be caused by the variation of the actual tag chip capacitance in practice from the chip capacitance assumed during theoretical calculations, or by additional self-capacitance of the tag loop.
4.5 Design Implementation and Fine-Tuning

Figure 4.9. Plot of return loss curve from the network analyser. By observing the return loss curve, the tag resonant frequency was approximated to be around 650 MHz.

antenna. In addition, the two metallic pins used to connect and hold the tag chip across the tag antenna feed terminals, although short in length, had most likely contributed to additional tag antenna inductance which would then lower the tag resonant frequency. The use of ABS plastic material to support the structure of the fabricated tag may also have a minor contribution to a somewhat higher tag antenna effective inductance.

4.5.2 Tag Dimension Adjustment

The tag resonant frequency was found to be much lower than expected as mentioned previously. Therefore, revision to the dimension of the tag antenna was required to push the tag resonant frequency higher. Since the tag antenna length $L_{\text{rec}}$ and height $H_{\text{rec}}$ were fixed, the only dimension that could be varied was the tag antenna width $W_{\text{rec}}$. The variation of $W_{\text{rec}}$ should be in a way that the tag antenna inductance would be lowered in order to increase the tag resonant frequency.
Chapter 4  
Tags with Wide Strip Loop Antennas

To readjust the antenna width $W_{rec}$, first it was required to estimate the equivalent total capacitance (which consisted of tag chip capacitance and possibly some antenna self-capacitance) that had tuned with the inductance of the rectangular loop antenna. To do this, the following expression was used

$$f_r = \frac{1}{2\pi \sqrt{LC}} \quad (4.6)$$

where $f_r$ is the resonant frequency, and L and C are the inductance and capacitance of an inductor and capacitor in the circuit respectively. It was known from earlier theoretical calculations that the rectangular loop antenna with dimensions $H_{rec} = 10$ mm, $L_{rec} = 25$ mm and $W_{rec} = 5$ mm had an estimated inductance of $L_a = 26$ nH. Although the pair of short metallic pins to hold the tag chip and the use of ABS plastic material could contribute to some additional tag antenna inductance, the effects were assumed here to be minimal. Hence using (4.6), and with $L_a = 26$ nH and the approximate measured $f_r = 650$ MHz, the total resonating capacitance was estimated to be 2.3 pF.

Using the newly estimated capacitance value and using (4.6) again, in order for the antenna to resonate at around the desired frequency of 915 MHz, it was calculated that an inductance of $L_a = 13$ nH was required. Hence, to obtain this antenna inductance, using calculations methods similar to those presented in Section 4.3, it was found that a rectangular loop antenna width of $W_{rec} = 15$ mm was needed, with $L_{rec}$ and $H_{rec}$ remained the same. Note that the tag antenna with the revised width had a lower inductance when compared with the original tag antenna.

4.5.3 Re-simulation and Re-measurement

The tag design with the new dimensions was simulated using HFSS. As previously, two cases were considered. For the first case, the tag was modeled in free space and for the second case, the tag was modeled above a metallic plane. The same simulation settings as previously used were employed for both cases. The only difference in the simulation here was the dimensions of the tag antenna, where the antenna width $W_{rec}$ was increased to 15 mm. The simulation results for both cases considered are as shown in Table 4.2. Comparing both cases, once again it can be observed that the tag antenna


4.5 Design Implementation and Fine-Tuning

Table 4.2. Summary of simulation results for a tag with antenna dimensions $L_{rec} = 25$ mm, $H_{rec} = 10$ mm and $W_{rec} = 15$ mm. Two cases were considered. In the first case, the tag was simulated in free space. In the second case, the tag was simulated above a $1.5\lambda \times 1.5\lambda$ aluminium metallic plane of thickness 2 mm.

<table>
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<th>Tag location</th>
<th>Antenna impedance, $Z_a$</th>
<th>Peak directivity</th>
<th>Peak gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free space</td>
<td>0.343 + j98.1 Ω</td>
<td>1.36</td>
<td>1.10</td>
</tr>
<tr>
<td>Above metallic surface</td>
<td>0.636 + j95.6 Ω</td>
<td>4.18</td>
<td>3.94</td>
</tr>
</tbody>
</table>

reactance has remained almost unchanged. Also, the resistance increased for the second case where the tag was located above a metallic plane (about double the resistance in the free space case). The directivity patterns of the tag antenna in the $yz$-plane and in the form of a three dimensional polar plot corresponding to the first and second cases are as shown in Figure 4.10 and Figure 4.11 respectively.

[Figure 4.10] Simulated directivity pattern of tag antenna with dimensions $L_{rec} = 25$ mm, $H_{rec} = 10$ mm and $W_{rec} = 15$ mm located in free space. Directivity pattern was plotted in the form of: (a) $yz$-plane plot (Radial scale markings are in dB.), and (b) three dimensional polar plot (The reference direction for the "Theta", $\theta$ coordinate is the $z$-axis and the reference direction for the "Phi", $\phi$ coordinate is the $x$-axis.).
Figure 4.11. Simulated directivity pattern of tag antenna with dimensions $L_{rec} = 25$ mm, $H_{rec} = 10$ mm and $W_{rec} = 15$ mm located 3 mm above a $1.5\lambda \times 1.5\lambda$ aluminium metallic plane. Directivity pattern was plotted in the form of: (a) $yz$-plane plot (Radial scale markings are in dB.), and (b) three dimensional polar plot (The reference direction for the "Theta", $\theta$ coordinate is the $z$-axis and the reference direction for the "Phi", $\phi$ coordinate is the $x$-axis.).

Figure 4.12. Fabricated RFID tag with revised dimensions. The tag has dimensions $L_{rec} = 25$ mm, $H_{rec} = 10$ mm and $W_{rec} = 15$ mm. A Class 1 Generation 1 (C1G1) tag chip was used.
4.6 Read Range Measurements

The tag design with the new dimensions was fabricated (Figure 4.12). The approximate resonant frequency of the tag was then measured using the small un-tuned loop mentioned previously. A resonant frequency of 897 MHz was measured. The return loss curve from the network analyser corresponding to the small un-tuned loop used for coupling to the tag antenna is as shown in Figure 4.13. The tag resonant frequency is much closer to the expected value compared to the earlier case after the dimension adjustment.

![Graph](attachment:image.png)

**Figure 4.13.** Plot of return loss curve from the network analyser corresponding to the tag with revised dimensions of $L_{rec} = 25$ mm, $H_{rec} = 10$ mm and $W_{rec} = 15$ mm. By observing the return loss curve, the tag resonant frequency was approximated to be around 897 MHz. The small un-tuned loop of Figure 4.8 was again used.

4.6 Read Range Measurements

The next step was to perform read range measurements on the RFID tag (with revised dimensions of $L_{rec} = 25$ mm, $H_{rec} = 10$ mm and $W_{rec} = 15$ mm after the tag design fine-tuning process). An RFID reader (developed by Dr. Behnam Jamali of the Adelaide Auto-ID Laboratory) which has the ability to operate over the band 900 MHz...
to 940 MHz was set up to measure the read range performance of the RFID tag. The reader was set to have an output peak power of approximately 250 mW. Taking into consideration of the 8 dBi gain circularly polarised reader antenna used, the total equivalent isotropic radiated power (EIRP) was approximately 1.6 W.

The RFID tag was placed 3 mm above a $1.5\lambda \times 1.5\lambda$ aluminium metallic plane of thickness 2 mm. With the reader antenna radiated at normal incidence to the metallic plane, the read range was measured at a number of frequencies within 900 MHz to 940 MHz. The measurement results is as shown in Figure 4.14.

![Figure 4.14. Read range measured over a frequency range.](image)

Although read range values were obtained at a number of frequencies within 900 MHz to 940 MHz, the read range value at the desired frequency of operation of 915 MHz was of particular interest. As can be seen in Figure 4.14, a read range value of approximately 0.83 m was achieved at 915 MHz for the above specified total transmit power of the RFID reader. The read range performance of the RFID tag in free space at the frequency of 915 MHz was also measured and was found to be approximately 0.5 m. For a total transmit power of 4 W EIRP (e.g. in the United States of America), the read range is expected to increase by approximately 1.6 times. A second RFID tag with the same dimension was made and the measured read range was found to be consistent and close to that of the first RFID tag. Overall, the read range performance of this RFID tag is promising, with good read range values achieved over a wide frequency range.
4.7 Variation in Metallic Surfaces

The reason for this is that the RFID tag antenna performance is, as shown in the simulation, enhanced when it is near a metallic surface as compared with when the tag is in free space. In addition, the structure of this antenna allowed good coupling to the magnetic components of the interrogation fields from the RFID reader antenna near the metallic surface.

4.7 Variation in Metallic Surfaces

In real-life applications, the metallic surfaces that the tag will attach to are not just limited to aluminium materials. Hence, further practical read range measurements were performed on the RFID tag by replacing the initial aluminium metallic plane with other metallic planes of the same size (that is, $1.5\lambda \times 1.5\lambda$) but of different materials. Two materials, stainless steel and copper, were chosen.

The same experimental setups as in the aluminium metallic plane case in Section 4.6 were used. The read range results at a number of frequencies within 900 MHz and 940 MHz corresponding to the stainless steel and copper cases are shown in Figure 4.15. From the measurement results, it can be observed that the read range performances of the tag above a stainless steel metallic plane and a copper metallic plane are very close to that of the aluminium metallic plane case. This is a fortunate result as the tag read range performance is good and consistent with respect to a variety of metallic materials.

4.8 Tag Fabrication Improvement

In the earlier tag fabrications, as mentioned previously, a pair of metallic pins had been used to hold and connect the tag chip across the feed terminals of the tag antenna. This was because conductive tapes that could be used to adhere the tag chip to the tag antenna was not available at the time the tag was fabricated. In the later stage of the research on this tag, an electrically conductive adhesive transfer tape (3M 9703 [70]) became available. This tape is able to conduct in the z-axis, that is, the direction normal
Chapter 4  
Tags with Wide Strip Loop Antennas

Figure 4.15. Read range measured over a frequency range for tag above metallic planes of different materials. Stainless steel and copper metallic planes, both of size $1.5\lambda \times 1.5\lambda$, were considered. The RFID tag was placed 3 mm above the metallic plane for each case.

to the plane of the tape. The tape was used to attach the tag chip across the feed terminals of the tag loop antenna, replacing the pair of metallic pins.

The tag chip was also changed to a newer model. The initial tag chip used in both tags mentioned earlier in this chapter was a Class 1 Generation 1 (C1G1) tag chip. In the improved version of the tag, Class 1 Generation 2 (C1G2) tag chip was used instead. Figure 4.16 shows the improved version of the tag.

A new set of commercial RFID reader (Model ID ISC.LRU2000) and an RFID reader antenna (Model ID ISC.ANT.U250/250) both manufactured by Feig Electronic were used in the read range measurement. The reason for the change was because the customised reader used in the previous read range measurements was only suitable for measuring tags with C1G1 tag chips. The new reader was set such that, with the reader antenna, it gave a total equivalent isotropic radiated power (EIRP) of 3.7 W. The reader operated within the Australian RFID bandwidth of 920 MHz to 926 MHz.

Although the previous tags discussed in this chapter were designed for the frequency 915 MHz (centre of the RFID band in the United States of America spanning from 902 MHz to 928 MHz), which is not within the Australian RFID band, Sections 4.6
4.8 Tag Fabrication Improvement

Figure 4.16. Improved version of the tag. The tag has dimensions \( L_{rec} = 25 \text{ mm}, H_{rec} = 10 \text{ mm} \) and \( W_{rec} = 15 \text{ mm} \). A Class 1 Generation 2 (C1G2) tag chip was used.

and 4.7 have shown that the tag had good read range performance over a wide frequency range that also covered the Australian RFID band. The middle frequency of the Australian RFID band is 923 MHz and to ensure that the tag antenna parameters remained almost the same at this frequency, the tag (with dimensions \( L_{rec} = 25 \text{ mm}, \ H_{rec} = 10 \text{ mm} \) and \( W_{rec} = 15 \text{ mm} \)) was re-simulated in HFSS by setting the simulation solution frequency to 923 MHz. For the tag in free space, the simulation results gave a tag antenna impedance of \( 0.351 + j \times 99.3 \, \Omega \), a peak directivity of 1.36 and peak gain of 1.11. For the tag located 3 mm above an aluminium metallic plane of thickness 2 mm, a simulated tag antenna impedance of \( 0.636 + j \times 97.0 \, \Omega \), a peak directivity of 4.52 and peak gain of 4.26 were obtained. These results have shown that the tag parameters did not change much compared to the previous case when the tag was simulated with the solution frequency set to 915 MHz.

Before read range measurements were performed, a small un-tuned loop was used to couple to the fabricated tag to check the resonant frequency of the tag. The result is as shown in Figure 4.17 where the resonant frequency was approximated to be around 933 MHz. This is a promising value as it is very close to 923 MHz.

The read range measurements using the new commercial reader mentioned above gave a read range value of 1.23 m in free space. When the tag was placed 3 mm above a
Figure 4.17. Plot of return loss curve from the network analyser corresponding to the tag with improved fabrication. By observing the return loss curve, the tag resonant frequency was approximated to be around 933 MHz.

1.5λ × 1.5λ aluminium metallic plane of thickness 2 mm, and with the reader antenna radiated at normal incidence to the metallic plane, a read range value of 2.04 m was achieved.

## 4.9 Effects of the Change in Antenna Width, $W_{rec}$

Since the work had involved varying the width $W_{rec}$ of the tag antenna (while maintaining the same length $L_{rec}$ and height $H_{rec}$), the effects that resulted from changing $W_{rec}$ was studied and are discussed in this section.

### 4.9.1 Tag Antenna Parameters

First, the effects of varying the antenna width $W_{rec}$ on the tag antenna parameters were examined. This was done by simulating the tag antenna in HFSS such that the length
4.9 Effects of the Change in Antenna Width, $W_{rec}$

and height of the tag antenna remained as before (i.e. $L_{rec} = 25$ mm and $H_{rec} = 10$ mm) and the width $W_{rec}$ was varied from 5 mm to 25 mm in incrementing steps of 5 mm. The antenna parameters observed were the impedance (resistance and reactance) and also the gain. For every variation of the tag antenna width, the tag was first simulated in free space and then 3 mm above a $1.5\lambda \times 1.5\lambda$ aluminium metallic plane of thickness 2 mm. The simulated results were obtained at the frequency 923 MHz. Shown in Figures 4.18, 4.19 and 4.20 are the plots of the tag antenna resistance, reactance and gain respectively.

![Plot of the simulated tag antenna resistance with respect to the change in the tag antenna width.](image)

**Figure 4.18.** Plot of the simulated tag antenna resistance with respect to the change in the tag antenna width. The tag antenna width $W_{rec}$ was varied from 5 mm to 25 mm in incrementing steps of 5 mm. The tag was simulated both in free space and above a $1.5\lambda \times 1.5\lambda$ aluminium metallic plane. The simulation was performed at the frequency 923 MHz.

From Figure 4.18, it can be observed that in general, the tag antenna resistance corresponding to the tag above a metallic plane is about 1.5 to 2 times compared to that of the tag in free space, independently of the change in tag antenna width. Also, the change of the tag antenna resistance within each of the cases (tag in free space and tag above metallic plane) seems quite minimal with respect to the variation of the tag antenna width.
Figure 4.19. Plot of the simulated tag antenna reactance with respect to the change in the tag antenna width. The tag antenna width $W_{rec}$ was varied from 5 mm to 25 mm in incrementing steps of 5 mm. The tag was simulated both in free space and above a $1.5\lambda \times 1.5\lambda$ aluminium metallic plane. The simulation was performed at the frequency 923 MHz.

Figure 4.20. Plot of the simulated tag antenna gain with respect to the change in the tag antenna width. The tag antenna width $W_{rec}$ was varied from 5 mm to 25 mm in incrementing steps of 5 mm. The tag was simulated both in free space and above a $1.5\lambda \times 1.5\lambda$ aluminium metallic plane. The simulation was performed at the frequency 923 MHz.
4.9 Effects of the Change in Antenna Width, $W_{rec}$

However, it can be seen in Figure 4.19 that the tag antenna reactance has experienced quite a significant change with respect to the variation of the tag antenna width. This applies for both cases of whether the tag is in free space or located above a metallic plane. The results have shown that as the tag antenna width increases, the tag antenna reactance decreases. Another observation from Figure 4.19 is that, unlike the tag antenna resistance, the reactance values are almost the same for both when the tag is in free space and tag is located above a metallic plane.

Next, observing Figure 4.20, the gain can be seen to have slightly increased when the tag antenna width is increased for both cases when the tag is in free space and the tag is above a metallic plane. The antenna gain of the tag above a metallic plane can be observed to be overall about 3.5 to 4 times that when the tag is in free space.

The results of the increase in radiation resistance are in accord with a simple theory that assumes that for a tag close to but not on the ground plane, the radiated fields of the tag and its image below the ground plane are substantially in phase. The results of the antenna reactance remaining unchanged are consistent with the fact that the self-inductance of the structure in free space is significantly greater than a mutual inductance between the tag antenna and its image below the ground plane.

4.9.2 Effective Volume and Coupling Volume

This part discusses the possible effect of the tag antenna width $W_{rec}$ on the read range performance of the RFID tag. It will be shown that an increased antenna width $W_{rec}$ is theoretically beneficial to the performance of the tag. However, it must be noted though that in real-life applications, an increased antenna width does not always guarantee a better performance, as the performance of the tag is not solely based on the width of the antenna but also on several other factors, such as the matching between the tag antenna and chip impedances and also the antenna gain. Two apparently similar but different literatures were studied to explain the effect of the antenna width on the performance of the RFID tag presented in this chapter.
The first approach uses the concept of effective volume, which was presented in [19]. According to this concept, the effective volume is proportional to the radiation efficiency of an antenna. Discussed as an example in [19], it was concluded that a thin wire square loop antenna has slightly less effective volume when compared with that of a wide strip square loop antenna, as long as the loop areas of both square loop antennas remain the same.

The second approach is based on the concept of coupling volume theory, which was introduced in [84]. Coupling volume is a figure of merit on the possible performance of tag antennas. A higher coupling volume value for a tag antenna will normally result in a better tag read range performance when compared with another tag antenna with a lower coupling volume value, provided these two antennas under comparison both have the same impedance matchings to their respective tag chips attached to them.

From [84], the coupling volume for a square wire coil with wire radius $r$ is given by

$$V_{cv} = X_{cv} S^3 \quad (4.7)$$

where $S$ is the length of one side of the square loop, and $X_{cv}$ is calculated using

$$X_{cv} = \frac{\pi}{2 \left[ \ln \left( \frac{4S}{r} \right) + \frac{r}{S} - 2.16 \right]} \quad (4.8)$$

Since the tag antenna that is of concern here is a rectangular loop while the coupling volume model above is based on a square loop, an approximation was made by equating the rectangular loop area of the tag antenna to the area of a square to compute the size of the equivalent square loop. That is, $S^2 = L_{rec} H_{rec}$. The tag antenna has dimensions of $L_{rec} = 25$ mm, $H_{rec} = 10$ mm and $W_{rec} = 15$ mm. Hence, the area of the rectangular loop was calculated to be 250 (mm)$^2$. For a square loop to have this same area, a square loop side length $S = 15.8$ mm was required. In addition, it was discussed earlier in this chapter that the wire radius $r$ can be related to the width $W_{rec}$ of the tag antenna using (4.2). Table 4.3 shows the computation of coupling volume based on (4.7) and (4.8), with the tag antenna width $W_{rec}$ varied from 1 mm to 20 mm in incrementing steps of 1 mm. The calculated values for the coupling volume $V_{cv}$ was plotted and the plot is as shown in Figure 4.21.
4.9 Effects of the Change in Antenna Width, $W_{rec}$

Table 4.3. Calculated coupling volume values $V_{cv}$ corresponding to the tag antenna with fixed loop area. The loop area was fixed to 250 (mm)$^2$, giving an equivalent square loop side length of $S = 15.8$ mm. $W_{rec}$ is the width of the wide strip loop and it was varied from 1 mm to 20 mm. The equivalent wire radius $r$ corresponding to each of the $W_{rec}$ values is also shown in the table.

<table>
<thead>
<tr>
<th>$W_{rec}$ (mm)</th>
<th>$r$ (mm)</th>
<th>$S$ (mm)</th>
<th>$X_{cv}$</th>
<th>$V_{cv}$ (mm)$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
<td>15.8</td>
<td>0.435</td>
<td>1717</td>
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<td>2</td>
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<td>0.6</td>
<td>15.8</td>
<td>0.620</td>
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</tr>
<tr>
<td>4</td>
<td>0.8</td>
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<td>0.695</td>
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<tr>
<td>5</td>
<td>1</td>
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<td>0.766</td>
<td>3023</td>
</tr>
<tr>
<td>6</td>
<td>1.2</td>
<td>15.8</td>
<td>0.836</td>
<td>3296</td>
</tr>
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<td>7</td>
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<tr>
<td>8</td>
<td>1.6</td>
<td>15.8</td>
<td>0.971</td>
<td>3830</td>
</tr>
<tr>
<td>9</td>
<td>1.8</td>
<td>15.8</td>
<td>1.039</td>
<td>4096</td>
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<tr>
<td>10</td>
<td>2</td>
<td>15.8</td>
<td>1.106</td>
<td>4364</td>
</tr>
<tr>
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<td>2.2</td>
<td>15.8</td>
<td>1.175</td>
<td>4634</td>
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<td>12</td>
<td>2.4</td>
<td>15.8</td>
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<td>4907</td>
</tr>
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<td>13</td>
<td>2.6</td>
<td>15.8</td>
<td>1.314</td>
<td>5183</td>
</tr>
<tr>
<td>14</td>
<td>2.8</td>
<td>15.8</td>
<td>1.385</td>
<td>5464</td>
</tr>
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<td>16</td>
<td>3.2</td>
<td>15.8</td>
<td>1.531</td>
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<td>17</td>
<td>3.4</td>
<td>15.8</td>
<td>1.607</td>
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<td>3.8</td>
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</tr>
<tr>
<td>20</td>
<td>4</td>
<td>15.8</td>
<td>1.841</td>
<td>7262</td>
</tr>
</tbody>
</table>
As an additional analysis, the tag antenna width was then fixed to \( W_{\text{rec}} = 15 \text{ mm} \) and the square loop side length \( S \) was varied (hence varying the loop area). Table 4.4 shows the computation of coupling volume once again based on (4.7) and (4.8), with \( S \) varied from 1 mm to 20 mm in incrementing steps of 1 mm. The calculated values for the coupling volume \( V_{cv} \) was plotted and the plot is as shown in Figure 4.22.
4.9 Effects of the Change in Antenna Width, $W_{rec}$

Table 4.4. Calculated coupling volume values $V_{cv}$ corresponding to the tag antenna with fixed wide strip loop width $W_{rec}$. $W_{rec}$ was fixed to 15 mm. $S$ is the side length of the square loop and it was varied from 1 mm to 20 mm. The equivalent wire radius $r$ corresponding to the $W_{rec}$ value is also shown in the table.

<table>
<thead>
<tr>
<th>$W_{rec}$ (mm)</th>
<th>$r$ (mm)</th>
<th>$S$ (mm)</th>
<th>$X_{cv}$</th>
<th>$V_{cv}$ (mm$^3$)</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>1.393</td>
<td>1</td>
</tr>
<tr>
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<td>2</td>
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<td>39</td>
</tr>
<tr>
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<td>3</td>
<td>3</td>
<td>6.941</td>
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<td>4</td>
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<td>3</td>
<td>20</td>
<td>1.234</td>
<td>9868</td>
</tr>
</tbody>
</table>
Chapter 4  Tags with Wide Strip Loop Antennas

From Figure 4.21, it can be seen that the increment of $V_{cv}$ is approximately linearly proportional to the increment of $W_{rec}$, while from Figure 4.22, $V_{cv}$ can be seen to be increasing at a faster rate when $S$ was incremented. It has been mentioned in [19] that the effective volume will be affected more by the change of the loop area compared to the change of the width of the wide strip loop. Hence, the calculated values above show that the coupling volume model in [84] is consistent with the effective volume theory in [19].

Although the results show that increasing the loop area will have greater impact on the coupling volume compared to increasing the width of the wide strip loop, nevertheless, the calculations show that the increment of the width is still beneficial to the coupling volume. Hence, a wide strip loop antenna with greater width is possibly a better tag antenna than a loop antenna of similar loop area but with a narrower width. Of course a better way is to increase the area of the loop itself, which unfortunately is always constrained by the availability of space on an object the tag is to be attached to.

4.10 Conclusion

This chapter has presented a small passive UHF RFID tag with a simple rectangular loop antenna design that is suitable for tagging metallic objects. This design had been fine-tuned, implemented and tested, and it was shown to perform well when attached to metallic surfaces. Besides having a good read range performance when attached to metallic surfaces, measurement results have also shown that the tag has an acceptable free space read range. Future work on this RFID tag design can include further analysis on the optimisation of the overall tag antenna dimensions. In Chapter 7 of this thesis, the performance of the tag presented here when the tag is located in metallic depressions of various shapes, sizes and depths is analysed.
Maintaining simplicity in a tag design is always a benefit. In this chapter, a passive UHF RFID tag suitable for metallic object identification that consists of a rectangular patch antenna with a simple impedance matching method to match the tag antenna and chip impedances is presented. It is also a benefit to have a small RFID tag size for the reason of cost reduction and the feasibility of attaching the tag to smaller metallic items. Hence, an analysis of the reduction of the tag antenna size and the possible effect towards the read range performance caused by the size reduction is also presented.
5.1 Introduction

The tag antenna presented previously in Chapter 4 was designed in a way that it utilises the electromagnetic fields present near metallic surfaces in order for the tag to be able to operate well when attached to metallic surfaces. While that is one approach to designing RFID tags for metallic surfaces, a common method often employed is the use of a microstrip patch antenna as the tag antenna. This is because a patch antenna has a ground plane as part of the antenna itself, hence making a tag containing a patch antenna to be less susceptible to the effects caused by placing that tag against a metallic surface.

There have been a few published research efforts on the use of patch antennas for RFID tags for metallic object identification purposes. These have been discussed earlier in this thesis in Section 2.3.4. However, many have used more complex tag designs and expensive materials. It is essential to maintain a low tag cost and also a small tag size. Hence, the first aim of the work here is to design an RFID tag that consists of a very basic microstrip patch antenna with a simple impedance matching method. The tag is to be made of a low cost material. The next aim is to reduce the size of the tag without increasing the complexity of the tag design or changing the original tag material used. The final aim is to investigate the effect of various tag size reductions towards the tag read range performance.

In this chapter, firstly the design of an RFID tag suitable for operation on metallic surfaces and consisting of a full size microstrip patch antenna is presented. Discussion of the design considerations and concepts is included. The results of theoretical calculations, simulations and measurements are shown. A later part of this chapter then presents work on the size minimisation of the tag. Following the tag size reduction efforts, read range measurement results corresponding to tags of different sizes are shown.

This chapter is based on a published paper [85], in which the main author is the author of this thesis.
5.2 A Patch Antenna RFID Tag Design

5.2.1 Design Considerations and Descriptions

There are many types of microstrip patch antennas available. Examples of some of the basic patch antenna shapes are rectangular, square, circular and triangular. More examples, with illustrations, of different types of patch antenna shapes available can be found in references such as [52], [86] and [87]. To demonstrate the use of a basic patch antenna for RFID tags and also to keep a simple tag design, the rectangular patch antenna, which is one of the most common basic patch antenna shapes, was chosen for the work here.

The main criteria for tag designs presented in this thesis so far is to maintain a balance between the cost and the size of the tag, and this remains the same for the work presented in this chapter. Hence, low cost double-sided copper clad FR4 substrate was chosen for the patch antenna material. The substrate used has a thickness $h = 1.6 \text{ mm}$ and relative dielectric permittivity $\varepsilon = 4.4$. Although using substrates with higher relative dielectric permittivity can give a smaller patch antenna size, they were not chosen because these materials are more expensive than a standard FR4 material and hence will increase the tag cost.

The tag was designed to operate in the Australian 4 W EIRP UHF RFID band that spans 920 - 926 MHz. Hence, a target frequency of 923 MHz was used for the design calculations. Although the tag size is an important consideration in the design work here, the first RFID tag presented in this chapter consists of a full size half wavelength rectangular patch antenna. Hence, the tag has a size equal to that of the half wavelength rectangular patch antenna with dimensions calculated based on the frequency 923 MHz and the FR4 parameters stated above. Tag size reductions are described later in this chapter, and the original full size tag serves as a basis for that work.

There are a few common types of feeding methods for microstrip patch antennas, namely the coaxial probe, microstrip line, aperture-coupled and proximity-coupled feeds [52]. To choose a feed type for the rectangular patch antenna, consideration was
given to the appropriateness of a feed in allowing an easy attachment of an RFID tag chip.

The coaxial probe feed is more suitable if the patch antenna is intended for connection to another system with coaxial type feed. It is possible to modify the feed based on the coaxial probe feed idea in order to accommodate an RFID tag chip, but this will increase the complexity of the design and most probably the antenna manufacturing process. Figure 5.1 shows an illustration on the possible use of a modified feed with a rectangular patch antenna. As can be seen, a circular ring area is removed from the ground plane at the bottom of the patch antenna to form a gap between a small circular area with the remaining area of the ground plane. The chip is placed across the gap. The small circular area is connected to the patch element at the top of the antenna through a via. Although this modified feed can accommodate a tag chip, the configuration is rather complex in that the back side of the antenna, which might be placed against a metal surface, is no longer planar, and hence is not preferred. Moreover, it does not provide an adjustment method to obtain the two components of the required antenna impedance, which has both real and imaginary parts.

![Figure 5.1. A modified antenna feeding method based on a coaxial probe feed method.](image)

Aperture and proximity-coupled feeds require two layers of substrate. This will not only increase the tag cost because of more material is required and the difficulty to
construct the tag, it will also increase the thickness of the tag. Therefore, these two feed methods were also eliminated from consideration.

The remaining choice, that is the microstrip line feed, was found to be the most appropriate. This is because it is planar and lies on the same plane and on the same side of the patch antenna as the patch element. In addition, the end of a track of a microstrip line can conveniently allow the attachment of an RFID tag chip. Hence, a microstrip line feed is the most preferred choice.

For an impedance matching between the antenna and the RFID tag chip, a perfect match, and hence maximum power transfer, occurs when the antenna impedance is conjugate to the tag chip impedance. Although sometimes it is not possible to achieve a perfect match for some tag designs (such as the tag presented in Chapter 4), it is of course better to be able to obtain as close as possible to a perfect match. For the tag design here, the impedance matching method used utilises a combination of a microstrip line feed with an inset into the patch element. An illustration of the tag consisting of a rectangular patch antenna with an inset microstrip line feed is as shown in Figure 5.2. Note that the distance $l_{\text{line}} + a$ can be significantly smaller than the distance $x_{\text{in}}$.

The use of a microstrip line feed with an inset into the patch element is quite common for patch antenna designs. The magnitude of the patch antenna impedance is the highest at the radiating edge (along the width of the patch element) and reduces as the inset distance $x_{\text{in}}$ increases, where it becomes zero at the centre of a half wavelength patch. In the usual practice, the impedance that the patch antenna is required to match to is normally real (resistance only). Hence, with the patch antenna reactance very small (almost zero) compared to the resistance at the antenna resonance, the inset distance is usually set to give the antenna resistance required for matching at the inset position, and the small mismatch in reactance is ignored. The feed is later shifted from the inset position to the edge of the patch antenna with a microstrip line of characteristic impedance equal to the target matching resistance in order to allow easy connection of the antenna to another system such as an antenna measurement instrument, or interconnection of several patch antennas, from the front (patch) side.
5.2 A Patch Antenna RFID Tag Design

Figure 5.2. Structure of the RFID tag antenna. Shown is the top view illustration of the rectangular patch antenna with the tag chip located across the gap \( a \) between the small square area and the end of the track of the microstrip line. \( W_{\text{patch}} \) and \( L_{\text{patch}} \) are the width and length of the patch element respectively. \( h \) is the thickness of the dielectric substrate. \( b \) is the separation between the microstrip line and the patch element. \( w \) is the track width of the microstrip line. \( x_{\text{in}} \) is the inset distance from the edge of the patch element. \( l_{\text{line}} \) is the track length of the microstrip line.

However, when it comes to the designing of RFID tags, the case is slightly different. This is because the patch antenna impedance is required to match to the impedance of an RFID tag chip that contains both resistance and reactance. The inset microstrip line feed method was still used in the tag design, but the concept is slightly different from that of the usual practice mentioned above. The idea is to adjust the inset distance \( x_{\text{in}} \) to obtain an impedance value such that when this impedance is transformed using a certain length \( l_{\text{line}} \) of the microstrip line, the transformed impedance corresponds to the conjugate of the tag chip impedance. This idea is visualised using a Smith chart and it is shown in Figure 5.3.

A microstrip line with characteristic impedance of 50 Ω was chosen. The reason is that 50 Ω gives a microstrip line with width \( w \) that is neither too wide nor too thin and hence suitable for attaching the RFID tag chip (Calculation of \( w \) follows in the next section). In addition, 50 Ω is within the valid characteristic impedance range for a microstrip line as discussed in [88]. Referring to Figure 5.3, the values shown at points
Figure 5.3. A Smith chart visualisation of the concept on using an inset microstrip line feed for matching the patch antenna and RFID tag chip impedances. The values shown on the Smith chart are normalised to 50 Ω. As a tag chip impedance of 20 − j141 Ω (equivalent to 0.4 − j2.82 when normalised to 50 Ω) was assumed, the target patch antenna impedance to be achieved is shown as point "B" on the chart. The idea is to have an inset distance $x_{in}$ such that to provide an impedance close to that shown at point "A" on the chart before transforming that impedance using a microstrip line to achieve the impedance at point "B".

"A" and "B" are impedances normalised to 50 Ω. The impedance value shown at point "B", which corresponds to the point of attachment of the chip, is the conjugate of the assumed tag chip impedance of 20 − j141 Ω at 923 MHz, normalised to 50 Ω. The aim is to have an inset distance $x_{in}$ such that the antenna impedance at the inset position is close to the impedance value at point "A", which corresponds approximately to the
impedance at the inset point \( x_{in} \) from the edge of the patch. The approximation made is that the patch antenna impedance behaves as an ideal parallel resonant circuit in which maximum resistance coincides with zero reactance. This approximation allows us to place point "A" on the horizontal axis of the Smith chart of Figure 5.3. The microstrip line then provides impedance transformation (mainly an increase in inductance) and with a certain line length \( l_{line} \), it will transform the impedance from point "A" to point "B" to give an overall antenna impedance close to \( 20 + j141 \Omega \) (0.4 + j2.82 \( \Omega \) when normalised to 50 \( \Omega \)).

Another part of the tag design to be noted is the small square area located at the end of the track of the microstrip line (see Figure 5.2). The small square area is connected to the ground plane through a via. The reason this part of the tag structure was added is to allow an easy attachment of the RFID tag chip on the patch antenna, on the patch element side, where the chip can be placed across the gap between the small square area and the end of the track of the microstrip line.

5.2.2 Theoretical Calculations

In this section, the theoretical calculations to determine some of the tag antenna dimensions are presented. First, the calculation steps to determine the dimensions of the patch element corresponding to a full size half wavelength microstrip patch antenna are shown. This will then be followed by the calculation of the width \( w \) of the microstrip line. The steps and theoretical formulae used for both calculations here are based on [52].

Before calculating the patch element dimensions, besides the desired antenna resonant frequency \( f_r \), the values for the relative dielectric permittivity \( \varepsilon_r \) and thickness \( h \) of the antenna substrate must be known. As mentioned previously, the target design frequency was 923 MHz and a FR4 substrate with \( \varepsilon_r = 4.4 \) and \( h = 1.6 \text{ mm} \) was used.

First, the width \( W_{patch} \) of the patch element was calculated. The expression below was used

\[
W_{patch} = \frac{c}{2f_r} \sqrt{\frac{2}{\varepsilon_r + 1}} \quad (5.1)
\]
where \( c = 3.0 \times 10^8 \text{ ms}^{-1} \) is the free space velocity of light. The calculation gave \( W_{\text{patch}} = 99 \text{ mm} \).

The length \( L_{\text{patch}} \) of the patch element was determined next. The actual physical length \( L_{\text{patch}} \) would be shorter than the required effective length \( L_{\text{eff}} \). This is because the fringing of fields at the radiating edge (along the width) on both sides of the patch element causes the patch length to be electrically longer. If the patch length is electrically longer on each of the both sides of the patch element by \( \Delta L_{\text{patch}} \), then

\[
L_{\text{patch}} = L_{\text{eff}} - 2\Delta L_{\text{patch}}. \tag{5.2}
\]

With the fringing effect, not all fields will be in the substrate and part of it will be in the air. To take into account of this, the calculation of the effective relative dielectric permittivity \( \varepsilon_{\text{reff}} \) was required before \( L_{\text{patch}} \) could be determined. The following expression was used

\[
\varepsilon_{\text{reff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + 12\frac{h}{W_{\text{patch}}} \right]^{-\frac{1}{2}}. \tag{5.3}
\]

This expression is valid for \( \frac{W_{\text{patch}}}{h} > 1 \). The calculation gave \( \varepsilon_{\text{reff}} = 4.26 \).

With \( \varepsilon_{\text{reff}} \) calculated, the effective length \( L_{\text{eff}} \) for a half wavelength patch was determined using

\[
L_{\text{eff}} = \frac{c}{2f_r \sqrt{\varepsilon_{\text{reff}}}}. \tag{5.4}
\]

A value of \( L_{\text{eff}} = 79 \text{ mm} \) was obtained. The length \( \Delta L_{\text{patch}} \) that causes the patch to be electrically longer on each radiating edge was calculated using

\[
\Delta L_{\text{patch}} = 0.412h \left( \frac{\varepsilon_{\text{reff}} + 0.3}{\varepsilon_{\text{reff}} - 0.258} \right) \left( \frac{W_{\text{patch}}}{h} + 0.264 \right) \left( \frac{W_{\text{patch}}}{h} + 0.8 \right). \tag{5.5}
\]

The calculation gave \( \Delta L_{\text{patch}} = 0.7 \text{ mm} \). Hence, referring back to (5.2), the actual physical length of the patch element was found to be \( L_{\text{patch}} = 77.6 \text{ mm} \).

Note that in Figure 5.2, the antenna substrate and ground plane sizes are the same and are both fixed to \( 12h \) larger with respect to the width and length of the patch element. This means they are larger than the patch element by \( 6h = 9.6 \text{ mm} \) on each of the four sides.
5.2 A Patch Antenna RFID Tag Design

To calculate the width $w$ of the microstrip line with characteristic impedance $Z_0$, the following expressions were used:

$$Z_0 = \frac{120\pi \Omega}{\sqrt{\varepsilon_{\text{reff}} \left[ \frac{w}{h} + 1.393 + 0.667 \ln \left( \frac{w}{h} + 1.444 \right) \right]}}$$

(5.6)

where

$$\varepsilon_{\text{reff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + 12 \frac{h}{w} \right]^{-\frac{1}{2}}.$$  (5.7)

(5.6) is only valid for $\frac{w}{h} > 1$. Notice that (5.7) is actually the same expression as (5.3), except that $W_{\text{patch}}$ has been replaced with $w$ here to differentiate the use of this expression for the microstrip line calculations. Using (5.6) and (5.7), to have a microstrip line with characteristic impedance $Z_0 = 50 \Omega$ on the chosen FR4 substrate, the width was found to be approximately $w = 3$ mm.

To be coherent with the width $w$ of the microstrip line, the dimension of the small square area (with a short to the ground through a via) located near the end of the track of the microstrip line was fixed to 3 mm by 3 mm. The gap between the small square area and the microstrip line was fixed to $a = 2$ mm for allocating a space for RFID tag chip attachment. The separation distance $b$ on both sides of the microstrip line with the patch element can affect the antenna impedance. According to [89], it is common to have a spacing equals to the width of the microstrip line. Hence, $b$ was made equal to $w$, which means $b = 3$ mm.

Using the calculation steps above, the dimensions $L_{\text{patch}}$ and $W_{\text{patch}}$ were determined. Because the procedure outlined in Section 5.2.1 contains an approximation in the assumed behaviour of the patch antenna impedance, the inset distance $x_{\text{in}}$ and the length $l_{\text{line}}$ of the microstrip line were instead adjusted by simulations as discussed in the next section.

### 5.2.3 Simulations

Simulations were carried out to determine the distance $x_{\text{in}}$ of the inset from the radiating edge of the patch and the length $l_{\text{line}}$ of the microstrip line. The simulations were done using Ansoft HFSS.
Before $x_{in}$ and $l_{line}$ were determined, the rectangular patch antenna with width and length calculated previously was simulated in the form of a full size half-wavelength patch without the inset and microstrip line. This is to make sure that the patch dimensions calculated previously are correct and that the antenna is displaying an antenna resonance at the desired frequency of 923 MHz.

In the first simulation attempt, a typical impedance plot of a patch antenna as described in [52] was obtained. However, the antenna resonance occurred at 902 MHz, which was close to but lower than the target frequency of 923 MHz. Hence, the patch length $L_{patch}$ was reduced slightly in order to increase the resonant frequency. After this adjustment, $L_{patch} = 76$ mm. Shown in Figure 5.4 is the simulation model of the antenna without the inset and microstrip line. The antenna impedance plot in Figure 5.5 shows that the antenna resonance is at 921 MHz after the patch length adjustment.

![Figure 5.4. Simulation model of the tag antenna without an inset and a microstrip line (Top view). Patch has dimensions: $W_{patch} = 99$ mm and $L_{patch} = 76$ mm.](image-url)

Referring to Figure 5.3, the impedance shown at point "A" normalised to 50 Ω is $0.042 + j0$ (which is equivalent to $2.1 + j0$ Ω). Hence, the inset distance $x_{in}$ was adjusted in the simulations in a way to give an antenna impedance close to $2.1 + j0$ Ω. It was found that when $x_{in} = 32$ mm, the antenna impedance at 923 MHz is $2 + j14$ Ω. The target resistance was reached but it was not possible to obtain a zero reactance. This is because even before having an inset into the patch element, the reactance is low but is...
5.2 A Patch Antenna RFID Tag Design

Figure 5.5. Simulated impedance of the tag antenna without an inset and a microstrip line. The vertical axis markings are in Ω. The blue and red curves correspond to the real and imaginary parts of the antenna impedance respectively. The antenna resonance occurred at around 921 MHz. Not actually zero at the antenna resonant point. The simulation model of the antenna with an inset into the patch element from the radiating edge is shown in Figure 5.6. Figure 5.7 shows the impedance plot of the antenna after having an inset.

Figure 5.6. Simulation model of the tag antenna with an inset but without a microstrip line (Top view). Patch has dimensions: $W_{\text{patch}} = 99$ mm and $L_{\text{patch}} = 76$ mm. Inset distance is $x_{\text{in}} = 32$ mm.
The next addition to the antenna structure was the microstrip line. The microstrip line length $l_{\text{line}}$ was determined in a way that it is sufficient to transform the antenna impedance at the inset point to an impedance that is the conjugate of the tag chip impedance. This has been visualised using a Smith chart earlier in this chapter in Figure 5.3. In the simulations, it could be observed that the antenna impedance was increased with the increment of $l_{\text{line}}$. When $l_{\text{line}} = 32$ mm, an antenna impedance of $60 + j147$ $\Omega$ at 923 MHz was obtained. As the target antenna impedance to achieve is $20 + j141$ $\Omega$, the impedance obtained by having $x_{\text{in}} = 32$ mm and $l_{\text{line}} = 32$ mm has reached the required reactance but not the resistance. The resistance obtained was way too high and hence, further adjustment was required.

After some adjustments through simulations, it was found that with $x_{\text{in}} = 36$ mm and $l_{\text{line}} = 32$ mm, an antenna impedance of $16 + j144$ $\Omega$ at 923 MHz was obtained. This is close enough for a conjugate match with the tag chip impedance of $20 - j141$ $\Omega$. The simulation model of the antenna is shown in Figure 5.8. The impedance plot obtained from the simulation is shown in Figure 5.9. The simulation also gave an antenna peak

**Figure 5.7. Simulated impedance of the tag antenna with an inset but without a microstrip line.** The vertical axis markings are in $\Omega$. The blue and red curves correspond to the real and imaginary parts of the antenna impedance respectively. With inset distance $x_{\text{in}} = 32$ mm, the antenna impedance at 923 MHz is $2 + j14$ $\Omega$. 
5.2 A Patch Antenna RFID Tag Design

directivity and peak gain of 3.55 and 0.48 respectively. Figure 5.10 shows the directivity pattern on the antenna.

Figure 5.8. Simulation model of the tag antenna with an inset and a microstrip line (Top view). Patch has dimensions: $W_{\text{patch}} = 99$ mm and $L_{\text{patch}} = 76$ mm. Inset distance is $x_{\text{in}} = 36$ mm and microstrip line length is $l_{\text{line}} = 32$ mm.

Figure 5.9. Simulated impedance of the tag antenna with an inset and a microstrip line. The vertical axis markings are in $\Omega$. The blue and red curves correspond to the real and imaginary parts of the antenna impedance respectively. With inset distance $x_{\text{in}} = 36$ mm and microstrip line length $l_{\text{line}} = 32$ mm, the antenna impedance at 923 MHz is $16 + j144$ $\Omega$. 

Page 120
Chapter 5  
Tags with Patch Antennas

Figure 5.10. Simulated directivity pattern of the tag antenna (with inset and microstrip line) located in free space. Directivity pattern was plotted in the form of: (a) $yz$-plane plot (Radial scale markings are in dB.), and (b) three dimensional polar plot (The reference direction for the "Theta", $\theta$ coordinate is the $z$-axis and the reference direction for the "Phi", $\phi$ coordinate is the $x$-axis.).

Figure 5.11. Simulated directivity pattern of the tag antenna (with inset and microstrip line) located on a $1.5\lambda \times 1.5\lambda$ metallic plane. Directivity pattern was plotted in the form of: (a) $yz$-plane plot (Radial scale markings are in dB.), and (b) three dimensional polar plot (The reference direction for the "Theta", $\theta$ coordinate is the $z$-axis and the reference direction for the "Phi", $\phi$ coordinate is the $x$-axis.).
5.2 A Patch Antenna RFID Tag Design

The tag antenna structure (with \( x_{in} = 36 \text{ mm} \) and \( l_{line} = 32 \text{ mm} \)) was then simulated on a 1.5\( \lambda \times 1.5\lambda \) aluminium metallic plane. The simulation results showed that the impedance remained almost the same as the case where the antenna was in free space. Hence, the impedance plot corresponding to having the antenna on a metallic plane is not shown here. However, the antenna pattern was found to be slightly different between the antenna in free space and antenna on a metallic plane cases. Shown in Figure 5.11 is the directivity pattern of the antenna plotted in different forms. As can be seen, with the presence of a metallic plane, the antenna pattern has smaller back lobe and the main lobe is fuller at the sides as compared to the free space case. The simulation gave an antenna peak directivity and peak gain of 4.93 and 0.74 respectively. One may also make the observation that the direction of maximum radiation are no longer along the \( z \)-axis, and that two large side lobes in the \( xz \)-plane exist.

5.2.4 Tag Fabrication and Read Range Measurements

The tag antenna was fabricated and is shown in Figure 5.12. Consistent with the simulation stage, the antenna was made using double-sided copper clad FR4 substrate with dimensions \( W_{patch} = 99 \text{ mm} \), \( L_{patch} = 76 \text{ mm} \), \( x_{in} = 36 \text{ mm} \), \( l_{line} = 32 \text{ mm} \), \( w = 3 \text{ mm} \), \( a = 2 \text{ mm} \) and \( b = 3 \text{ mm} \). Although the substrate is copper clad, the patch element shown in Figure 5.12 has a silvery colour appearance due to a thin layer of tin-lead plating (on top of the copper layer), which prevents the copper layer from fast oxidation. The tin-lead plating layer is very thin and was assumed not to affect the electric current flow. The tag antenna was designed for operation with a Class 1 Generation 2 (C1G2) RFID tag chip. However, due to a faulty C1G2 tag chip batch and the unavailability of other good tag chip batches during the period when the tag was made and tested, Class 1 Generation 1 (C1G1) RFID tag chip was used instead. Beside some differences in the chip operation protocol, both the C1G1 and C1G2 tag chips considered have, by experience, impedances very close to each other. Hence, the initial assumed tag chip impedance during the tag design stage is still valid.

An RFID reader (Model ALR-9780-EA) and a reader antenna (Model ALR-9610-BC), both manufactured by Alien Technology, suitable for operation in Australia were used.
for the tag read range measurements. The reader antenna is circularly polarised and has a 6 dBi gain. Hence, with a 1 W input power from the reader, the equivalent isotropic radiated power (EIRP) from the reader antenna is 4 W.

The tag was measured both in free space and on a metallic plane. For both cases, the reader antenna was positioned to radiate towards the tag at normal incidence to the plane of the tag. For the free space case, a read range of 1.39 m was measured. When the tag was placed on a 1.5$\lambda \times 1.5\lambda$ aluminium metallic plane, the read range measured was 1.44 m.

Previously in the simulation stage, the simulated antenna peak gain was 0.48 when the tag antenna was in free space and 0.74 when the tag antenna was located on a metallic plane. Despite the latter case having a peak gain of about 1.5 times higher, the read range measurement results for both cases did not show a significant difference. This is likely caused by the position where the peak gain occurred on the antenna pattern. For the case when the tag antenna was located on a metallic plane, the simulated antenna pattern (Figure 5.11(b)) showed that the peak gain was not located at the top part of the antenna pattern but rather more to the side especially in a direction in the $xz$-plane but rotated towards the $x$-axis. On a second check, it was found that the antenna gain
corresponding to the point at the top part of the antenna pattern (facing the direction of radiation from the RFID reader antenna) was 0.55. Hence, this explains the closeness of the measured tag read range results for both cases.

In all these experiments, we attribute the low values of gain relative to directivity mainly to the poor quality of the dielectric.

### 5.3 Tag Size Reductions

#### 5.3.1 Approach

With a simple RFID tag for metallic surfaces designed and shown in the previous section, the next aim was to reduce the size of the tag antenna to find the smallest possible tag size while still obtaining acceptable tag read range performance. For patch antennas, there are many ways such as those discussed in [90] to reduce the size of the antenna. One example that can possibly be applied is the use of substrate with higher dielectric permittivity. However, this may increase the cost of the RFID tag. Maintaining a low RFID tag cost is desirable so that it is more cost effective to tag objects, especially at item-level, in the supply chain.

An economical way was employed here where the size of the tag was minimised by reducing the patch width $W_{\text{patch}}$ of the tag antenna. The patch length $L_{\text{patch}}$ remains the same and a low-cost FR4 material same as previously was used. $W_{\text{patch}}$ was reduced slowly, at steps of 10 mm, from 99 mm (corresponding to the original full size half wavelength rectangular patch antenna discussed earlier in this chapter) to 19 mm. The antenna ground plane size was reduced accordingly to the patch element size.

The tag antenna corresponding to each size was simulated using HFSS. The simulation results showed that the antenna impedance increased as $W_{\text{patch}}$ was reduced. It was also found from the simulations that the antenna resonant frequency increased slightly as $W_{\text{patch}}$ was reduced. To illustrate these observations, the simulated impedance plots of the antennas with patch width $W_{\text{patch}}$ of 59 mm and 19 mm respectively are shown in Figure 5.13 and Figure 5.14. For each of the antennas, there are two impedance
plots shown, where one corresponds to a plain patch and the other corresponds to a patch with an inset and a microstrip line included. As can be seen, the antenna with $W_{\text{patch}} = 59$ mm has a higher both the impedance and the resonant frequency than the antenna with $W_{\text{patch}} = 99$ mm. The antenna with $W_{\text{patch}} = 19$ mm has the highest impedance and resonant frequency compared to the rest.

It should be noted that although the increase in the antenna resonant frequency can be compensated by increasing the patch length $L_{\text{patch}}$ to shift the antenna resonant frequency back down to the desired frequency, this was not carried out here in order to maintain a consistent $L_{\text{patch}}$ as the original full size patch. The increase in the antenna impedance and shift in the antenna resonance as $W_{\text{patch}}$ was reduced caused the total input impedance of the tag antenna to change. Hence, in order to maintain a total input impedance that is the conjugate of the tag chip impedance, the inset distance $x_{\text{in}}$ and the microstrip line length $l_{\text{line}}$ were adjusted slightly for each antenna case through simulations.

After the adjustment of $x_{\text{in}}$ and $l_{\text{line}}$, the antenna structure was simulated on a $1.5\lambda \times 1.5\lambda$ metallic plane. This was to ensure that the antenna impedance was almost the same as when without the metallic plane.

It was found in the simulations that for both the antenna in free space and on a metallic plane, as the antenna patch width $W_{\text{patch}}$ was reduced, there was a slight decrease in antenna gain in general. For instance, for the original full size antenna with $W_{\text{patch}} = 99$ mm, the antenna peak gains for the antenna in free space and on a metallic plane are 0.48 and 0.74 respectively. For the antenna with $W_{\text{patch}} = 19$ mm, the antenna peak gains for the antenna in free space and on a metallic plane are 0.30 and 0.33 respectively, both of which are lower than for the full size patch.

The simulated values for impedance, peak directivity and peak gain for each of the tag antennas of different sizes can be found in Appendix B.
5.3 Tag Size Reductions

Figure 5.13. Simulated impedance plots of the patch antenna with width $W_{\text{patch}} = 59$ mm. The vertical axis markings are in Ω. The blue and red curves correspond to the real and imaginary parts of the antenna impedance respectively. (a) Impedance plot for a plain patch antenna; and (b) Impedance plot for a patch antenna with an inset and a microstrip line. With inset distance $x_{\text{in}} = 37$ mm and microstrip line length $l_{\text{line}} = 32$ mm, the antenna impedance at 923 MHz is $18 + j147$ Ω.

5.3.2 Read Range Measurements

RFID tags corresponding to different patch widths were fabricated. Figure 5.15 shows the tag with the smallest patch width ($W_{\text{patch}} = 19$ mm) placed next to the original full size tag (with $W_{\text{patch}} = 99$ mm).
Figure 5.14. Simulated impedance plots of the patch antenna with width $W_{\text{patch}} = 19$ mm. The vertical axis markings are in $\Omega$. The blue and red curves correspond to the real and imaginary parts of the antenna impedance respectively. (a) Impedance plot for a plain patch antenna; and (b) Impedance plot for a patch antenna with an inset and a microstrip line. With inset distance $x_{\text{in}} = 30$ mm and microstrip line length $l_{\text{line}} = 29$ mm, the antenna impedance at 923 MHz is $14 + 141 \Omega$.

Read range measurements were performed on all the tags. The same RFID reader and reader antenna as that mentioned in Section 5.2.4 were used. The tags were first measured in free space and later attached to a $1.5\lambda \times 1.5\lambda$ aluminium metallic plane.
5.3 Tag Size Reductions

Figure 5.15. Fabricated RFID tags of different sizes. The large tag has dimensions $W_{\text{patch}} = 99$ mm, $L_{\text{patch}} = 76$ mm, $x_{\text{in}} = 36$ mm, $l_{\text{line}} = 32$ mm, $w = 3$ mm, $a = 2$ mm and $b = 3$ mm. The small tag has dimensions $W_{\text{patch}} = 19$ mm, $L_{\text{patch}} = 76$ mm, $x_{\text{in}} = 30$ mm, $l_{\text{line}} = 29$ mm, $w = 3$ mm, $a = 2$ mm and $b = 3$ mm. Class 1 Generation 1 (C1G1) tag chips were used for both tags.

For both cases, the reader antenna was positioned to radiate towards the tag at normal incidence to the plane of the tag. The plot of the maximum measured read range values versus $W_{\text{patch}}$ is shown in Figure 5.16.

It can be observed from Figure 5.16 a pattern in the reduction of read range as $W_{\text{patch}}$ reduces. This is most likely caused by the drop in gain of the tag antenna when the antenna size becomes smaller. The read range of the smallest size tag (with $W_{\text{patch}} = 19$ mm) is about half that of the full size tag (with $W_{\text{patch}} = 99$ mm). However, despite the read range reduction, the read range for the smallest tag is still acceptable considering the amount of tag size reduction compared with the full size tag. Hence, the smaller tag can be suitable for use in applications that do not require a maximum possible read range but do require a smaller tag size in order to attach the tag to a limited space or area on a metallic object.
Figure 5.16. Practical read range measurement results. Shown are the read range values corresponding to tags with different patch widths $W_{patch}$. For each tag, the read range was measured with the tag located in free space and later attached to an aluminium metallic plane.

5.4 Further Tag Size Reductions

The aim of the work in this section is to investigate the possibility of an even further tag size reduction by reducing the size of the smallest tag (with $W_{patch} = 19$ mm) presented previously in Section 5.3. It is known theoretically that for a half wavelength rectangular patch antenna, the antenna impedance is highest when the feed is at the radiating edge and reduces as the feed moves to the centre of the patch where the impedance is zero. Hence, the patch antenna size can be halved by cutting the antenna across the centre point and shorting the patch element where it is cut to the antenna’s ground plane. This type of antenna is called a quarter wavelength patch antenna. Based on this concept, the tag antenna with patch width $W_{patch} = 19$ mm was cut into half and a full shorting wall was applied across the cutting point to short the patch element to the antenna’s ground plane. The shorting wall had a width similar to $W_{patch}$ that is 19 mm and the patch length $L_{patch}$ was shortened to 38 mm.

The quarter wavelength antenna structure was simulated at a single width of 19 mm. Similarly to the case when the patch antenna size was reduced in Section 5.3, it was observed from simulations that the antenna impedance had increased significantly and
5.5 Conclusion

the antenna resonant frequency had shifted upwards compared with the original full size tag antenna. Hence, the inset distance $x_{in}$ and the microstrip line length $l_{line}$ were adjusted in order to achieve an overall antenna impedance as close as possible to the conjugate of the assumed tag chip impedance. After the adjustments, when the antenna was simulated in free space, an antenna impedance of $20 + 143\, \Omega$ at 923 MHz was obtained. The simulations also gave a peak directivity and a peak gain of 1.51 and 0.057 respectively. When the antenna was simulated on a $1.5\lambda \times 1.5\lambda$ metallic plane, the antenna impedance obtained at 923 MHz was $18 + j135\, \Omega$. A peak directivity and a peak gain of 4.22 and 0.24 respectively were given. These figures show the benefit of reducing the backward radiations by having an adequate ground plane.

The simulated antenna pattern when the tag antenna was located in free space is shown in Figure 5.17 and the simulated antenna pattern when the tag antenna was placed on a metallic plane is shown in Figure 5.18. As can be seen in Figure 5.18, the antenna pattern in the metallic plane case is similar in shape to that of the full size tag antenna shown in Figure 5.11. However, the antenna pattern in the free space case (Figure 5.17) shows that back radiations are quite severe. This is because the antenna has a very small ground plane size.

The tag was fabricated and is shown in Figure 5.19. Using the same set of RFID reader and reader antenna as previously, and with the reader antenna radiated towards the tag at normal incidence to the plane of the tag, the read range of the tag was measured to be 0.06 m when the tag was in free space and 0.17 m when the tag was attached to an aluminium plane of size $1.5\lambda \times 1.5\lambda$. As can be seen, the read range performance of this tag is quite poor. This is as expected for a small size tag. Moreover, the low peak gain values of the antenna of this tag shown in the simulations stage have given a prior indication of this poor performance.

5.5 Conclusion

This chapter has presented a passive RFID tag that consists of a rectangular patch antenna, with a simple impedance matching method, that is suitable for tagging metallic
Figure 5.17. Simulated directivity pattern of the tag antenna (with a shortened patch length and a full shorting wall) located in free space. Directivity pattern was plotted in the form of: (a) $yz$-plane plot (Radial scale markings are in dB.), and (b) three dimensional polar plot (The reference direction for the "Theta", $\theta$ coordinate is the $z$-axis and the reference direction for the "Phi", $\phi$ coordinate is the $x$-axis.).

objects. The tag design was implemented and tested, and a satisfactory read range performance was obtained when the tag was attached to a metallic structure. Analyses on the reduction of the tag antenna size and the effect on the read range performance were also presented. Analysis results have shown that there is a trade-off between having a smaller antenna and the read range performance. The metallic object that the tag is attached to itself can, if of adequate size, contribute to enhancement of the tag antenna gain by eliminating backward radiations. Though this can be the case, there is still a drop in antenna directivity and gain in general when the tag antenna size is reduced, which is likely the cause of the poor read range performance of smaller size tags. Depending on the type of application, if the read range requirement is lower, a smaller tag will still be beneficial in terms of cost and the ease of attaching the tag to smaller metallic objects.
5.5 Conclusion

![Figure 5.18](image)

**Figure 5.18.** Simulated directivity pattern of the tag antenna (with a shortened patch length and a full shorting wall) located on a $1.5\lambda \times 1.5\lambda$ metallic plane. Directivity pattern was plotted in the form of: (a) $yz$-plane plot (Radial scale markings are in dB.), and (b) three dimensional polar plot (The reference direction for the "Theta", $\theta$ coordinate is the $z$-axis and the reference direction for the "Phi", $\phi$ coordinate is the $x$-axis.).

![Figure 5.19](image)

**Figure 5.19.** Fabricated RFID tag with a shortened patch length and a full shorting wall. The tag has dimensions $W_{\text{patch}} = 19$ mm, $L_{\text{patch}} = 38$ mm, $x_{\text{in}} = 6$ mm, $l_{\text{line}} = 4$ mm, $w = 3$ mm, $a = 2$ mm and $b = 3$ mm. Class 1 Generation 1 (C1G1) tag chips were used for both tags.
Tags for Metallic Cans

This chapter presents the design and analysis of an RFID tag that can be used in an RFID application involving the tagging of small metallic cans at item-level. Small metallic cans for containing beverages were chosen as the focus during the designing of the tag antenna. Detailed designs and measurement results are shown in this chapter.
6.1 Introduction

The presence of metallic objects in supply chains poses a great challenge in the tagging of such objects. The challenge is further magnified when tagging of small metallic objects at item-level is involved. In previous chapters in this thesis, different RFID tag designs for metallic objects consisting of wide strip loop antennas (Chapter 4) and patch antennas (Chapter 5) have been analysed and investigated in detail. The positive potential of these RFID tags for use on metallic objects or surfaces has been shown. In this chapter, taking a step further and to meet the challenge of tagging small metallic objects at item-level, the possibility in designing an RFID tag suitable for tagging small metallic cans is explored.

The target metallic object that the tag is designed for is a metallic can used for containing beverages such as soft drinks. This type of metallic can was chosen because it is a very common item in supply chains and in our daily lifestyle. In this chapter, first preliminary tag design considerations and investigations for metallic cans are discussed. This is then followed by a presentation of a novel tag antenna design suitable for metallic cans. Later in the chapter, further analysis and measurement results related to the tag design are presented.

6.2 Design Considerations

6.2.1 Basic Requirements

As with the tags presented in Chapters 4 and 5, other than being able to operate near metallic surfaces, one of the design objectives is to maintain a low tag cost. This is particularly important for the tag in the case considered in this chapter because it involves tagging metallic cans for beverages that are not usually sold at a high price. It is simply not feasible from the business model perspective to have a tag with a higher tag cost compared with the cost of the object tagged. Hence, cheap and common materials should be used for the tag and the tag design should be kept as simple as possible.
As the tag presented in this chapter is targeted for use at item-level tagging, and not at pallet-level tagging or case-level tagging, the read range requirement is lower. The read range will be considered as sufficient as long as the tagged metallic cans can be detected at a short range at a checkout point. For example at a supermarket checkout point, any range say within 0.5 m is believed to be good enough.

One of the emphases on the tag design is that the tag must be small enough to fit neatly on a metallic can. It should also be well protected in order to avoid being damaged easily during the handling, shelving or delivery of the tagged metallic cans. However, the tag should not be protected in a way that the tag is covered by material that may perturb or obstruct the interrogation fields from the RFID reader antenna from reaching the tag.

### 6.2.2 Deciding a Location

To decide a feasible location for attachment of the RFID tag, the external structure of a typical metallic can for beverages was examined. There can be three possible locations. First, the top of the metallic can where a metallic ring is located and that, when the rings is pulled, will create an opening that allows the dispensing of the beverage contained in the metallic can (Figure 6.1(a)). The second possible location is the bottom of the metallic can where the surface at the centre is slightly concaved in and there is an extrusion on the rim along the circumference to allow better support when the metallic cans are stacked on one another (Figure 6.1(b)). Lastly, since the metallic can is cylindrical in shape, the third possible location is at the side of the metallic can along the curvature of the cylindrical shape (Figure 6.1(c)).

For the first location (top of the metallic can), the metallic ring and the opening where the beverage can be dispensed occupy quite a significant area. This leaves little area for attachment of the RFID tag, making it not a good location.

Metallic cans are often arranged and packaged in close contact side by side with each other. A top view illustration of a half-dozen metallic cans arrangement is as shown in Figure 6.2. If the RFID tag is to be attached to the side of a metallic can, it is best to
Figure 6.1. Possible locations for tag attachment. The red arrow in each figure indicates the possible location on a metallic can where a tag can be attached to. The figures show the (a) top, (b) bottom and (c) side of a metallic can respectively.

attach the tag in a way that the tag does not protrude from the side of the can. This means the tag should have a very small thickness in order for the tag to attach to the can seamlessly. The tag will most likely also need to be able to bend slightly along the can curvature to prevent the tag from being easily damaged or ripped from the can. However, tags suitable for attachment to metallic surfaces usually have a significant thickness. This does not only create a protrusion when the tag is attached to the side of the metallic can, if the tag is made of a dielectric substrate material with significant thickness, the tag will have difficulty to bend along the side curvature of the metallic can. Moreover, metallic cans in the arrangement such as that shown in Figure 6.2 will have a tendency to slide against each other during the handling process, which will increase the chances of damaging the tag. Hence, the third location (side of the metallic can) is also not a good option for attachment of the tag.
With the first and third locations on the metallic can eliminated, the last option remaining was the bottom of the metallic can. The available space at the bottom of a metallic can varies depending on the manufacturer. Although this space is still very limited, its potential in accommodating a tag was seen to be higher compared to the other locations discussed previously. In the tag design work presented in this chapter, the metallic can shown in Figure 6.1 was used as a reference. As mentioned previously, the bottom of the metallic can is slightly concave in at the centre with an extruded rim along the circumference, which creates a small hollow space. The dimensions of the hollow space at the bottom of the metallic can was measured. Figure 6.3 shows the cross-sectional illustration of the bottom section of the metallic can with the measured dimension values shown. The tag designed must be able to fit within the hollow space with the dimensions just specified.

6.3 Preliminary Investigations

For tags that are designed to fit within confined spaces surrounded by metallic material, the closest invention to the case presented in this chapter was found in the literature [91], where a metallic cap is made to have an integral RFID tag. In that reference, the tags shown are made of microstrip patch antennas and they are located on top of
6.3 Preliminary Investigations

metallic caps of standard diameter $1\frac{1}{8}$ inches. However, the tags in [91], though small in size, are designed for operation at the frequencies of either 2.8 GHz or 5.8 GHz.

The tag for metallic cans presented in this chapter is for operation at the frequency 923 MHz (within the Australian 4W EIRP bandwidth of 920 - 926 MHz). For a microstrip patch antenna such as those in [91] to have a resonance around 923 MHz, the antenna will be much larger in size and will not fit within the available space specified in Figure 6.3.

Since the bottom of the metallic can is circular in shape, this size constraint problem was investigated further by using a basic circular patch antenna. Based on [52], to calculate the radius $R$ (in m) of the patch element of a circular patch antenna to achieve an antenna resonance at the desired frequency $f_r$ (in Hz), the following expression were used

$$R = \frac{F}{\left\{1 + \frac{2h}{\pi c_r f_r} \left[ \ln \left( \frac{\pi f_r}{2h} \right) + 1.7726 \right] \right\}^{\frac{1}{2}}} \tag{6.1}$$

where $F$ (in m) is given by

$$F = \frac{8.791 \times 10^7}{f_r \sqrt{\varepsilon_r}} \tag{6.2}$$

$\varepsilon_r$ is the relative dielectric permittivity of the substrate used for the patch antenna and $h$ is the substrate thickness in m. (Note that (6.2) has been modified slightly from the formula supplied in [52] to give a calculated patch radius $R$ in the units of m.)
For resonance at the frequency 923 MHz, the radius $R$ corresponding to arbitrary $\varepsilon_r$ values was calculated. The substrate thickness was fixed to $h = 1.6 \text{ mm}$ and $\varepsilon_r$ was varied from 2 to 10 at incremental steps of 2. Shown in Figure 6.4 are the calculated results plotted in terms of $2R$ (i.e. diameter of the patch element) versus the change in the substrate relative dielectric permittivity $\varepsilon_r$.

![Graph showing calculated diameter of the patch element of a basic circular patch antenna.](image)

**Figure 6.4.** Calculated diameter of the patch element of a basic circular patch antenna. The values were calculated at the frequency 923 MHz with respect to different substrate relative dielectric permittivity values. The substrate thickness $h$ was fixed to 1.6 mm.

Referring again to Figure 6.3, the inner diameter of the hollow space at the bottom of the metallic can is $D_{inner} = 45 \text{ mm}$. Hence, this is the maximum size that a tag can have in order to fit and attach to the bottom of the metallic can. From Figure 6.4, it can be seen that even for the case when $\varepsilon_r$ is as high as 10, the diameter of the circular patch is about 60 mm, which is much higher than the 45 mm size limit. Moreover, the calculated results did not include the size of the patch antenna ground plane. Usually, the ground plane will be slightly bigger than the size of the patch element to allow the fringing of fields. It is obvious that a conventional patch antenna is not suitable for the application considered in this chapter.

There have been a number of research efforts towards minimising patch antenna sizes, for instance those discussed and presented in [90]. One of the techniques shown in [90] for minimising the size of a conventional circular patch antenna is by using a
combination of a patch element meandering and shorting-pin loading methods. Based on a design example given in [90] that applied this technique, a circular patch antenna made of a common FR4 substrate with relative dielectric permittivity $\varepsilon_r = 4.4$ and thickness $h = 1.6$ mm was simulated using Ansoft HFSS. The simulation model is as shown in Figure 6.5.

![Simulation model of circular patch antenna with reduced size.](image)

**Figure 6.5. Simulation model of circular patch antenna with reduced size.** Including the substrate and ground plane size, the antenna has a maximum diameter of 45 mm.

The meandering of the patch element was adjusted in order to achieve a resonance around the target frequency of 923 MHz. The circular patch element has a diameter of 25.8 mm. The substrate and the ground plane (located below) both have a diameter of 45 mm in order to be able to fit within the space at the bottom of the metallic can. A plot of the simulated antenna impedance is as shown in Figure 6.6. As can be seen, the antenna had achieved a resonance close to 923 MHz with an antenna size that had been much reduced and met the size requirement for a metallic can.

However, if the circular patch antenna is used as a tag antenna, having an antenna resonance at 923 MHz is promising but may not necessarily sufficient. As RFID tag chips have both real and imaginary impedance (resistance and reactance), tag antennas should have at least sufficient reactance for tuning with the tag chip for an overall tag resonance. It will be even better, of course, if the tag antenna impedance is conjugate
Figure 6.6. Plot of simulated impedance of the circular patch antenna with reduced size. The vertical axis markings are in Ω. The blue and red curves correspond to the real and imaginary parts of the antenna impedance respectively. An antenna resonance close to 923 MHz was achieved.

to the tag chip impedance for a complete impedance matching for maximum power transfer.

The tag chip that will be used in the tag design has an assumed impedance of $Z_c = 20 - j141\, \Omega$ (This is the equivalent chip impedance at the frequency 923 MHz of having a resistor with resistance 1 kΩ and capacitor with capacitance 1.2 pF in parallel.). The results in Figure 6.6 have shown that the circular patch antenna’s inductive reactance has only reached a maximum of approximately 54 Ω (at the frequency slightly away from the antenna resonance point), which is insufficient compared to the tag chip’s capacitive reactance of 141 Ω.

Impedance matching network can be added to transform the antenna impedance such that to at least provide enough inductive reactance. However, due to the antenna size limitation and space constraint, implementing an impedance matching network will be difficult. If a substrate with high relative dielectric permittivity is used to reduce the size of the patch antenna in order to create more space for implementation of the impedance matching network, the cost of the tag will be increased.
6.4 A Novel Tag Design

Hence, a new tag design is required for the metallic cans. The tag should not only have a suitable size to fit within the space at the bottom of the metallic cans, it should also be made of not too expensive a material with a simple tag antenna design to maintain a low tag cost. The tag antenna should be able to provide at least enough inductive reactance to tune with the tag chip capacitive reactance for achieving the desired tag resonance.

6.4 A Novel Tag Design

6.4.1 Concept and Design Descriptions

The basic idea developed for the new tag design for metallic cans is as shown in Figure 6.7. Inspired by the circular patch antennas studied during the preliminary investigation stage in Section 6.3, dielectric substrate had been used as the tag antenna material. By using this material, the tag antenna will be more durable and most importantly will have a low profile in order to fit within the available space at the bottom of a metallic can. A low cost double-sided copper clad FR4 substrate was chosen. This dielectric substrate has a thickness of $h = 1.6$ mm and a relative dielectric permittivity of $\varepsilon_r = 4.4$.

The tag was designed to be located in the shaded area as shown in Figure 6.8 (in a cross-sectional view). Hence, care was taken not to choose dielectric substrates that are too thick so that the rim along the circumference at the bottom of the metallic can will still slightly protrude to allow a stable stacking of metallic cans on one another. In an approximate measurement, it was found that the dielectric substrate thickness $h$ should be less than 2 mm in order to allow a proper metallic cans stacking. The mentioned FR4 substrate chosen for the tag met this requirement. Referring to Figure 6.7, $D_s$ is the diameter of the dielectric substrate and it was fixed to 45 mm, which is the maximum size allowed corresponding to the inner diameter $D_{inner}$ at the bottom of the metallic can.

The dielectric substrate was backed by a ground plane (a copper layer) of the same size with it. The reason a ground plane was included in the tag design instead of making
**Figure 6.7.** Initial concept of an RFID tag antenna for metallic can. $D_s$ is the diameter of the dielectric substrate. It is also the diameter of the ground plane (located below and not shown in this illustration). $D_e$ is the diameter of the meandered element (top copper layer). $a$, $b$ and $c$ are the lengths of the various slits on the top copper layer that formed a meandered path. The RFID tag chip is located as close as practicable to but not quite at the edge.

**Figure 6.8.** Location of the RFID tag at the bottom of the metallic can. This illustration is similar to that in Figure 6.3, except that the intended location for the placement of the tag is shown (area shaded in red). The tag designed must fit within the shaded area.

use of the metallic surface of the metallic can is to improve the consistency of the tag performance. First, the bottom of the metallic can is not flat and is concaved in at the centre, and secondly, not all metallic cans have the same concavity at the bottom. Having a ground plane will ensure a more controlled environment for the tag antenna.

The copper layer on top of the dielectric substrate (Figure 6.7) was also made circular in shape but of smaller diameter. The diameter of this element is denoted as $D_e$. As
6.4 A Novel Tag Design

can be seen in Figure 6.7, the top copper layer was meandered by inserting slits at various positions. Four slits each of length \(a\) were spaced evenly and radially around the circumference of the top copper layer. Three slits each of length \(b\) were located near the centre of the top copper layer. Also, a longer slit of length \(c\) was inserted to create a feed terminal for attachment of the tag chip. This slit meets the three other slits of length \(b\) at the centre of the tag.

Most antennas are usually designed to accommodate a coaxial feed. However, as can be seen, the antenna presented here was specially designed to allow easy attachment of an RFID tag chip. Also, the meandered track (top copper layer) will provide some inductance, and having a ground plane (bottom copper layer) below this track will provide some capacitance. This will create some form of tuning and hence an antenna resonance.

The length of the slits that formed the meandering of the top copper layer can be adjusted in order to fine-tune the antenna impedance by shifting the antenna resonance point. This is because, by changing the lengths of the slits, the length of the current path along the meandered track will also change.

6.4.2 Simulations

The adjustment of the slit lengths was carried out through simulations using Ansoft HFSS. The simulation model of the tag antenna (just the tag antenna, not yet on a metallic can) is as shown in Figure 6.9. The substrate (and ground plane) diameter \(D_s\) were both fixed to 45 mm as mentioned before. Also, the diameter \(D_e\) of the area occupied by the top copper layer was fixed to 35 mm and the length \(c\) of the longer slit was fixed to 17.5 mm (i.e. \(D_e/2\)). The lengths of the shorter slits were adjusted such that at 923 MHz, the antenna would at least provide sufficient inductive reactance in order for the antenna to tune with the RFID tag chip. This means an antenna reactance of approximately 141 \(\Omega\) was required. To achieve this, the slit lengths were found to be \(a = 9.5\) mm and \(b = 6.1\) mm. The widths of all the slits were fixed to 1 mm. (Note that it was rather difficult to achieve an antenna reactance of exactly 141 \(\Omega\). Hence, the
slit lengths were adjusted in a way the antenna reactance was as close as possible to 141 $\Omega$.)

**Figure 6.9.** Simulation model of the tag antenna for a metallic can. This model has the following dimensions (with respect to Figure 6.7): $D_s = 45$ mm, $D_e = 35$ mm, $a = 9.5$ mm, $b = 6.1$ mm and $c = 17.5$ mm.

**Figure 6.10.** Simulated impedance of the tag antenna for a metallic can. The vertical axis markings are in $\Omega$. The blue and red curves correspond to the real and imaginary parts of the antenna impedance respectively. An antenna impedance of $7.0 + j147.6\Omega$ at 923 MHz was achieved.

The plot of the simulated tag antenna impedance is as shown in Figure 6.10. The resonant point of the antenna itself is located at the frequency 1.085 GHz, but what is more
important is at the frequency 923 MHz, the simulated impedance is approximately 7.0 + j147.6Ω. Although this impedance is not exactly the conjugate of the assumed tag chip impedance of 20 – j141Ω, it has at least provided sufficient inductive reactance in order for the tag antenna to tune with the tag chip for a tag resonance at 923 MHz.

Another interesting simulation result is the antenna pattern. The antenna directivity pattern in the xz-plane and in the form of a three dimensional polar plot is shown in Figure 6.11. It can be observed that since the antenna is symmetrical about the xz-plane, the directivity pattern is symmetrical about this plane as well. However, the directivity pattern is not symmetrical about the yz-plane. Referring to Figure 6.11(a), the maximum of the pattern is slightly tilted approximately 30° from the z-axis. This is caused by the unique structure of the antenna as compared with basic antennas such as a loop antenna. This is an indication that the read range performance of a tag using this antenna will be better in a certain direction than the rest. From the simulation, a peak directivity of 1.53 and a peak gain of 0.0051 were obtained.

**Figure 6.11. Simulated directivity pattern of the tag antenna located in free space.** Directivity pattern was plotted in the form of: (a)xz-plane plot (Radial scale markings are in dB.), and (b) three dimensional polar plot (The reference direction for the "Theta", θ coordinate is the z-axis and the reference direction for the "Phi", φ coordinate is the x-axis.).
Since the tag was designed for attachment on metallic cans, the tag antenna was also simulated on a metallic cylinder to mimic a real-life metallic can. As it is rather complex to build a model that is an exact of a real-life metallic can, the metallic cylinder in the simulation model was just a basic cylinder with a height and a diameter close to a real-life metallic can. The simulation results gave an antenna impedance of $7.1 + j149.0 \Omega$ at 923 MHz, with the antenna resonance occurred at the frequency 1.085 GHz. Simulated peak directivity and peak gain values of 1.87 and 0.0069 were obtained respectively. The directivity pattern of the antenna in the $xz$-plane and in the form of a three dimensional polar plot is shown in Figure 6.12. Besides the directivity pattern of the antenna appearing fuller on the upper-half side and slightly less tilted with respect to the $z$-axis, the rest of the simulation results here are very close to the results for the case without the metallic cylinder. Hence, the antenna parameters are consistent with or without a metallic cylinder near the antenna.

![Simulated directivity pattern of the tag antenna located on a metallic cylinder to mimic a real-life metallic can.](image)

**Figure 6.12.** Simulated directivity pattern of the tag antenna located on a metallic cylinder to mimic a real-life metallic can. Directivity pattern was plotted in the form of: (a)$xz$-plane plot (Radial scale markings are in dB.), and (b) three dimensional polar plot (The reference direction for the "Theta", $\theta$ coordinate is the $z$-axis and the reference direction for the "Phi", $\phi$ coordinate is the $x$-axis.).
6.4 A Novel Tag Design

6.4.3 Antenna Fabrication and Read Range Measurement

Once the dimensions of the tag antenna was determined through simulations such that a satisfactory antenna impedance was obtained at the frequency 923 MHz, the tag antenna was fabricated. The fabricated antenna was made of low cost double-sided copper clad FR4 substrate with a thickness of \( h = 1.6 \) mm and relative dielectric permittivity of \( \varepsilon_r = 4.4 \), consistent with the antenna material in the simulation stage. A Class 1 Generation 2 (C1G2) tag chip was used. It was attached across the feed terminals of the tag antenna using a z-axis conductive tape. Figure 6.13 shows the tag prototype.

![Figure 6.13. A fabricated RFID tag suitable for attachment to the bottom of a metallic can. A Class 1 Generation 2 (C1G2) RFID tag chip was used.](image)

The measurement of the tag prototype’s read range performance was carried out. A set of RFID reader (Model ID ISC.LRU2000) and a circularly polarised RFID reader antenna (Model ID ISC.ANT.U250/250) both manufactured by Feig Electronic were used for the read range measurement. The reader was set, with the reader antenna, to give a total equivalent isotropic radiated power (EIRP) of 3.7 W. The reader operated within the Australian 4 W EIRP RFID bandwidth of 920 - 926 MHz.

The tag read range was measured with the reader antenna located above the tag and radiating at normal incidence to the plane of the tag. The measurement was performed
with just the tag itself and with the tag located on an actual metallic can. Figure 6.14 shows the tag fitted neatly within the available space at the bottom of a metallic can. Without the presence of a metallic can, the tag free space read range was measured to be 0.23 m. With the metallic can, the tag read range was measured to be 0.20 m. From these measurement results, it can be seen that the tag had given almost the same performance with or without a metallic can.

![Image: An RFID tag fitted neatly to the bottom of a metallic can.]

The metallic can shown is a typical metallic can for containing beverages.

The read range measurement results shown here correspond to interrogating or reading the tag in a common direction, that is, straight from above the tag. Results for further read range measurements from different directions will be presented and discussed later in this chapter.

### 6.5 Effect of Change in Slit Length

For the tag antenna presented in the previous section, the antenna resonant frequency was adjusted (by varying the slit length) in order to obtain the desired antenna impedance at the frequency 923 MHz. In this section, the effect of the change in the slit length towards the antenna resonant frequency is discussed further.
6.5 Effect of Change in Slit Length

Previously, during the adjustments of the slit lengths $a$ and $b$ through simulations, it was noticed that a small change to either slit lengths $a$ or $b$ could shift the antenna resonant frequency quite significantly. It was also found that changing the slit lengths $a$ or $b$ gave the same effect as long as the change would lead to the same contribution of either increasing or decreasing the current path of the meandered track (top copper layer). For example, to increase the current path, either the slit length $a$ or $b$, or both can be increased. Since there were more than one parameter that could be changed, to maintain a consistency for easy comparison of results with the original tag antenna later, only the slit length $b$ was changed for the investigation presented in this section. Slit length $a$ and all the other antenna dimensions remained the same as those for the original tag antenna presented in the previous section.

The investigation started with the increment of slit length $b$. For the first case, $b$ was increased to 6.4 mm from the initial length of 6.1 mm. The antenna was simulated and shown in Figure 6.15 is the plot of the simulated antenna impedance. As can be seen, the antenna resonant frequency has shifted down to about 1.07 GHz from the initial resonant frequency of 1.085 GHz. This is as expected as increasing the slit length $b$ led to an increased current path along the meandered track of the top copper layer of the antenna, which in turn corresponds to a lower antenna resonant frequency. With the frequency shift, the antenna impedance at 923 MHz has also changed. Referring to Figure 6.15, since the frequency shift is downwards, the antenna impedance at 923 MHz has increased to $8.3 + j158.8 \Omega$. A peak directivity and peak gain of 1.51 and 0.0050 were obtained from the simulation. The simulated directivity pattern of the antenna remained very close to that of the original antenna in the previous section and hence is not shown here.

The slit length $b$ was then increased further to 6.7 mm and later followed by 6.9 mm to confirm the observation on the shift in the antenna resonant frequency. The antennas corresponding to both cases were simulated. For the case where $b = 6.7$ mm, the simulation results gave an antenna resonance at the frequency 1.05 GHz. At 923 MHz, the antenna impedance is $11.3 + j180.5 \Omega$. The simulated peak directivity and peak
gain are 1.65 and 0.0057 respectively. For the case where $b = 6.9$ mm, an antenna resonance at the frequency 1.045 GHz was obtained. At 923 MHz, the antenna impedance is $12.9 + j191.3 \Omega$. The simulated peak directivity and peak gain are 1.59 and 0.0052 respectively. Once again, the simulated directivity pattern of the antenna in both cases remained very close to that of the original antenna presented in the previous section. Hence, it is not shown here.

As can be seen from the results above, increasing the slit length $b$ had consistently shifted the antenna resonant frequency downwards, which led to an increasing antenna impedance at 923 MHz. This is due to the lengthening of the current path along the meandered track of the antenna.

From the observation above, it means that if slit length $b$ is decreased, the current path along the meandered track will be shortened, which will lead to an increase in the antenna resonant frequency. Hence, as an addition to the investigation here, the slit length $b$ was decreased to 5.9 mm. Shown in Figure 6.16 is the plot of the simulated antenna impedance. As can be observed, the antenna resonant frequency has shifted...
upwards to 1.10 GHz which caused the antenna impedance at 923 MHz to decrease to $5.7 + j135.4\Omega$. The simulated peak directivity and peak gain are 1.52 and 0.0053 respectively. These results are as expected and are consistent with prior observations.

Figure 6.16. Simulated impedance of the tag antenna with slit length $b = 5.9$ mm. The vertical axis markings are in $\Omega$. The blue and red curves correspond to the real and imaginary parts of the antenna impedance respectively. The antenna resonant point is located at the frequency 1.10 GHz. The antenna impedance at 923 MHz is $5.7 + j135.4\Omega$.

Being able to shift the antenna resonant frequency predictably means the antenna impedance can be easily adjusted or fine-tuned to the required value at the desired frequency in order for the antenna to be able to tune with an RFID tag chip.

6.6 Further Read Range Measurements

Previously in Section 6.4.3, the read range results for the metallic can tag in both free space and when attached to the bottom of a metallic can were presented. Those results corresponded to reading or interrogating the tag straight from directly above the tag. In this section, results and discussions of further read range measurements involving the reading of the tag from directions different from that considered in Section 6.4.3 are presented.
First, since the directivity pattern in Figure 6.11 and Figure 6.12 (corresponding to the tag in free space and on a metallic cylinder respectively) both show a maximum that is slightly tilted approximately 30°, the tag read range was measured at a tilt in the direction of the expected antenna pattern maximum. For simplicity, the read range measurement was done at a 45° tilt. As an addition to the measurement, the tag read range was also measured from the sides in four different directions. Figure 6.17 shows all the directions considered during the read range measurements. Also shown in this figure is the direction of reading the tag from the top (or above), considered initially in Section 6.4.3.

The experiment setup was similar to that described in Section 6.4.3, with the same set of RFID reader and reader antenna used for the read range measurement. The tag was read both with and without the presence of a metallic can, in all the directions specified in Figure 6.17. The read range results obtained are shown, highlighted in bold, in Table 6.1 for the tag in free space (i.e. without the presence of metallic can) and Table 6.2 for the tag attached to the bottom of a metallic can.

<table>
<thead>
<tr>
<th>Tag slit length ( b ) (mm)</th>
<th>Read range (m)</th>
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</thead>
<tbody>
<tr>
<td>Figure 6.17(a)</td>
<td>Figure 6.17(b)</td>
</tr>
<tr>
<td>5.9</td>
<td>0.22</td>
</tr>
<tr>
<td>6.1 (Original)</td>
<td>0.23</td>
</tr>
<tr>
<td>6.4</td>
<td>0.16</td>
</tr>
<tr>
<td>6.7</td>
<td>0.11</td>
</tr>
<tr>
<td>6.9</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table 6.1. Read range measurement results for a number of metallic can tags in free space. Read range was measured from various directions shown in Figure 6.17. Each tag measured has a different slit length \( b \). Except for \( b \), the remaining dimensions are the same for all tags: \( D_s = 45 \) mm, \( D_e = 35 \) mm, \( a = 9.5 \) mm and \( c = 17.5 \) mm.
Figure 6.17. Tag read range measured from different directions. The red arrows in the illustration indicate the directions. The tag read range was measured from the top (straight from above), 45° with respect to the z-axis in the direction of the expected antenna pattern maximum, and from the sides (4 sides as shown).
Table 6.2. Read range measurement results for a number of metallic can tags attached to the bottom of a metallic can. Read range was measured from various directions shown in Figure 6.17. Each tag measured has different slit length $b$. Except for $b$, the remaining dimensions are the same for all tags: $D_s = 45$ mm, $D_e = 35$ mm, $a = 9.5$ mm and $c = 17.5$ mm.

<table>
<thead>
<tr>
<th>Tag slit length $b$ (mm)</th>
<th>Read range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Figure 6.17(a)</td>
</tr>
<tr>
<td>5.9</td>
<td>0.20</td>
</tr>
<tr>
<td>6.1 (Original)</td>
<td>0.20</td>
</tr>
<tr>
<td>6.4</td>
<td>0.14</td>
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<tr>
<td>6.7</td>
<td>0.12</td>
</tr>
<tr>
<td>6.9</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Observing the read range results, it can be seen that the read range values for both cases, with or without the presence of a metallic can, are higher when the tag was read in the direction shown in Figure 6.17(b). This is as expected since it was shown previously in the simulation stage that the maximum of the antenna pattern of the tag is slightly tilted towards this direction.

However, it can be observed that for the case where the tag was located at the bottom of a metallic can, the difference between the read range values of reading the tag from the directions shown in Figure 6.17(a) and Figure 6.17(b) is smaller compared with the tag in free space case. This is most likely caused by the slight difference in the shape of the antenna pattern, which for the case with the presence of a metallic can, the antenna pattern was shown in the simulations to be fuller in the upper-half and less tilted compared with the free space case. It is believed that this is also the reason for the observation that when the tag was attached to a metallic can and read from the side directions shown in Figure 6.17(d) and Figure 6.17(f), the tag was almost unreadable.
6.6 Further Read Range Measurements

This is because when the antenna pattern is less tilted for the case with a metallic can, the minimum (null) in the antenna pattern may be facing more towards the direction the tag was read compared with the free space case.

As mentioned previously, for the work presented in this chapter, an RFID tag chip impedance of $20 - j141\Omega$ at 923 MHz was assumed. The actual tag chip impedance may slightly deviate from this value in real-life. Hence, since the antennas just discussed in Section 6.5 each had an antenna impedance that slightly deviated from that of the original tag antenna in Section 6.4, those antennas became suitable for use to check on whether an acceptable tag chip impedance was initially assumed. To do this, those antennas were fabricated and each was attached with a C1G2 tag chip. The read range of each of the tags were then measured and compared to see if a better read range than that of the original tag could be obtained. The read range was measured from all directions illustrated in Figure 6.17 for the tag in free space and attached to the bottom of a metallic can.

The read range measurement results are shown in Table 6.1 (free space) and Table 6.2 (with metallic can), together with the read range values of the original tag. Since all the tags, including the original one, have the same dimensions except for the slit length $b$, the different tags are distinguished using their respective slit length $b$ in both tables.

It can be observed from the read range values recorded in both tables that for each tag, disregarding the difference in the slit length $b$, the read range is better when measured in the direction shown in Figure 6.17(b) than in the direction shown in Figure 6.17(a). In addition, the difference between the read range values corresponding to these two directions are smaller when the tags were attached to a metallic can. When the tags were read from the side directions shown in Figure 6.17(d) and Figure 6.17(f), they were all almost unreadable when attached to a metallic can. All these observations here are consistent with that of the original tag discussed above.

In general, for each of the directions the tags were measured, it can be observed that the read range has dropped as the slit length $b$ was varied from the original slit length of $b = 6.1$ mm. The read range values corresponding to the original tag are the best overall
compared with the rest. Hence, the results have indicated that a good approximation of the RFID tag chip impedance was made.

### 6.7 Variation in Tag Antenna Material

Up to this point, the tag antennas presented were made of low cost double-sided copper clad FR4 substrates with thickness $h = 1.6$ mm and relative dielectric permittivity $\varepsilon_r = 4.4$. For research interest, the use of different material for the tag antenna was investigated and the results of this investigation are presented in this section.

Two different materials with much higher dielectric permittivity than the FR4 substrate used previously were considered. First was Rogers RT/duroid 6010 with thickness $h = 1.27$ mm and relative dielectric permittivity $\varepsilon_r = 10.2$. The second material considered was also Rogers RT/duroid 6010 but with thickness $h = 0.64$ mm and relative dielectric permittivity $\varepsilon_r = 10.8$. Both materials have higher costs than FR4 substrates, but they are still used here for research purposes. Notice that the first material has a substrate thickness fairly close to that of the FR4 substrate used previously and the second material has quite a thin substrate. Due to the limited availability of material during the time when the investigation work took place, we were unable to obtain both materials with the same relative dielectric permittivity but with different thickness. Though this is the case, the relative dielectric permittivities of both the Rogers RT/duroid 6010 substrates considered are still very close.

The same tag antenna design concept as that discussed in Section 6.4 was applied. The antenna dimensions were also determined through simulations. They were adjusted such that the antenna could provide at least sufficient inductive reactance (approximately $141\Omega$) at the frequency 923 MHz in order for the antenna to tune with the tag chip. Due to the difference of both materials used compared with a FR4 material, the antenna dimensions were rather different from that of the tag antennas presented previously. When substrates of high relative dielectric permittivity were used, the top copper layer of the antenna design required a smaller area. When a thin substrate was used, the area of the top copper layer reduced further. Details of the antenna dimensions will follow later in this section.
6.7 Variation in Tag Antenna Material

6.7.1 Material: Rogers RT/duroid 6010 ($h = 1.27$ mm; $\varepsilon_r = 10.2$)

With this material, the tag antenna dimensions were determined through simulations to be $D_s = 45$ mm, $D_e = 29$ mm, $a = 5.5$ mm, $b = 3.7$ mm and $c = 14.5$ mm. Although the antenna dimensions were adjusted to achieve as closely as possible the inductive reactance required, it was found that with this material, the antenna impedance could be more easily affected by just a slight change to the antenna dimensions during the adjustment process than with the FR4 material. Hence, the antenna dimensions were adjusted to give the best achievable antenna impedance possible.

From simulation, an impedance plot for this antenna was obtained and is shown in Figure 6.18. As can be seen, the antenna resonance occurred at around the frequency 995 MHz. At 923 MHz, the antenna impedance is $3.8 + j158.1\Omega$. The simulations also gave an antenna peak directivity and peak gain of 1.63 and 0.019 respectively. Shown in Figure 6.19 is the directivity pattern of the antenna in the $xz$-plane and in the form of a three dimensional polar plot.

![Figure 6.18](image_url)

**Figure 6.18.** Simulated impedance of the tag antenna made of Rogers RT/duroid 6010 ($h = 1.27$ mm; $\varepsilon_r = 10.2$). The vertical axis markings are in $\Omega$. The blue and red curves correspond to the real and imaginary parts of the antenna impedance respectively. The antenna resonant point is located at the frequency 995 MHz. The antenna impedance at 923 MHz is $3.8 + j158.1\Omega$. 

Page 158
Figure 6.19. Simulated directivity pattern of the tag antenna made of Rogers RT/duroid 6010 \((h = 1.27 \text{ mm}; \varepsilon_r = 10.2)\) located in free space. Directivity pattern was plotted in the form of: (a)\(xz\)-plane plot (Radial scale markings are in dB.), and (b) three dimensional polar plot (The reference direction for the "Theta", \(\theta\) coordinate is the \(z\)-axis and the reference direction for the "Phi", \(\phi\) coordinate is the \(x\)-axis.).

The antenna was also simulated on a metallic cylinder (a representation of a real-life metallic can). The simulation results gave an antenna resonance at around the frequency 1.005 GHz and an antenna impedance of \(3.4 + j154.6\Omega\) was obtained at 923 MHz. The simulated peak directivity and peak gain are 1.91 and 0.031 respectively. The antenna directivity pattern is shown in Figure 6.20.

The antenna was fabricated and a C1G2 RFID tag chip was attached to the antenna. The tag is shown in Figure 6.21. The tag read range was first measured from directly above the tag (Figure 6.17(a) and later at a 45° tilt in the direction of the antenna pattern maximum (Figure 6.17(b)). The read range was measured with and without having the tag attached to a metallic can. For the tag in free space, the read range for the first and second directions stated above were measured to be 0.21 m and 0.22 m respectively. For the tag on a metallic can, the read range for the first and second directions were measured to be 0.26 m and 0.25 m respectively.
6.7 Variation in Tag Antenna Material

Figure 6.20. Simulated directivity pattern of the tag antenna made of Rogers RT/duroid 6010 \((h = 1.27\; \text{mm}; \varepsilon_r = 10.2)\) located on a metallic cylinder. Directivity pattern was plotted in the form of: (a)\(xz\)-plane plot (Radial scale markings are in dB.), and (b) three dimensional polar plot (The reference direction for the "Theta", \(\theta\) coordinate is the \(z\)-axis and the reference direction for the "Phi", \(\phi\) coordinate is the \(x\)-axis.).

Figure 6.21. A fabricated metallic can RFID tag made of Rogers RT/duroid 6010 \((h = 1.27\; \text{mm}; \varepsilon_r = 10.2)\). A Class 1 Generation 2 (C1G2) RFID tag chip was used.
Chapter 6  
Tags for Metallic Cans

Compared with the original tag using FR4 material presented in Section 6.4, fairly good read range results were obtained. Although a Rogers RT/duroid 6010 substrate has a lower loss tangent \(\tan\delta = 0.0023\) compared with a FR4 substrate \(\tan\delta = 0.02\) and hence the tag antenna here has a better gain, the tag read range values obtained are not much better than that of the original tag in Section 6.4. This may be because the impedance of the antenna using Rogers RT/duroid 6010 substrate here is sensitive and easily affected by slight variation of the physical antenna dimensions.

6.7.2 Material: Rogers RT/duroid 6010 \((h = 0.64\, \text{mm}; \varepsilon_r = 10.8)\)

With this material, the tag antenna dimensions were determined through simulations to be \(D_s = 45\, \text{mm}, D_e = 21\, \text{mm}, a = 4.3\, \text{mm}, b = 5.5\, \text{mm}\) and \(c = 10.5\, \text{mm}\). Notice that because the antenna material has a high relative dielectric permittivity and a thin substrate, the size or area occupied by the meandered track element (top copper layer) was reduced. Similarly to the case in Section 6.7.1 above, the impedance of the antenna here could also be easily affected by slight variations of the antenna dimensions.

The simulated antenna impedance is shown in Figure 6.22. Referring to this plot, the antenna resonant frequency is at approximately 1.005 GHz. At 923 MHz, the antenna impedance is \(5.1 + j150.5\, \Omega\). A peak directivity of 1.53 and peak gain of 0.0019 were obtained from the simulations. The directivity pattern of the antenna in free space is shown in Figure 6.23.

The antenna was then simulated on a metallic cylinder. The antenna resonance occurred at the frequency 1.005 GHz and an antenna impedance of \(5.4 + j156.0\, \Omega\) was obtained at 923 MHz. The simulations gave a peak directivity and peak gain of 1.89 and 0.0031 respectively. The antenna directivity pattern is shown in Figure 6.24.

The antenna was then fabricated and is shown in Figure 6.25. As with all the previous tags presented in this chapter, C1G2 RFID tag chip was used. The read range of the tag was measured in the directions shown in Figure 6.17(a) and Figure 6.17(b). For the tag in free space, measurement in the first and second directions gave a read range of
6.7 Variation in Tag Antenna Material

![Graph showing impedance variation](image)

**Figure 6.22.** Simulated impedance of the tag antenna made of Rogers RT/duroid 6010 ($h = 0.64 \text{ mm}; \epsilon_r = 10.8$). The vertical axis markings are in $\Omega$. The blue and red curves correspond to the real and imaginary parts of the antenna impedance respectively. The antenna resonant point is located at the frequency 1.005 GHz. The antenna impedance at 923 MHz is $5.1 + j150.5\Omega$.

0.06 m and 0.07 m respectively. When the tag was attached to a metallic can, the read range measured in both directions was 0.10 m.

As can be seen, very poor read range values were obtained for both the tag in free space and when located on a metallic can. These observations are consistent with the general principles that as antennas are made smaller, they suffer a penalty of bandwidth or efficiency, or both. A reduced size or area occupied by the meandered track element (top copper layer) has most likely caused a reduction in the antenna gain, which then led to a poor read range performance. It can be seen from the simulation results that the tag antenna here has by far the worst peak gain among all the other tag antennas presented previously in this chapter. Another reason to the poor read range performance may be the sensitivity of the antenna impedance with respect to tolerances in the antenna dimensions. From the results observed, it shows that using thin substrates with high relative dielectric permittivity is not a good option for the implementation of the tag antenna design presented here.
Chapter 6  

Tags for Metallic Cans

6.8 Conclusion

This chapter has presented a novel design of an RFID tag suitable for tagging metallic cans. The main design issue and constraint is the space limitation of a metallic can. The tag presented is designed for attachment to the bottom of a metallic can, where the tag must have a low-profile and also be small in area to fit within the available space. In addition to the presentation of a successful tag design, analyses and discussions on the variation of an important tag antenna dimension and also the variation of antenna materials have been included. This successful research shows that with proper tag antenna design, despite the constraint, the aim of creating a metallic can tag can be achieved. In addition, results from the research show that a low-cost material can be used and expensive high relative dielectric permittivity materials are not necessary. Future work can include further investigations of the change in antenna parameters, and hence of tag performance, with the antenna dimensions. A larger range
6.8 Conclusion

Figure 6.24. Simulated directivity pattern of the tag antenna made of Rogers RT/duroid 6010 \((h = 0.64 \text{ mm}; \varepsilon_r = 10.8)\) located on a metallic cylinder. Directivity pattern was plotted in the form of: (a)\(xz\)-plane plot (Radial scale markings are in dB.), and (b) three dimensional polar plot (The reference direction for the "Theta", \(\theta\) coordinate is the \(z\)-axis and the reference direction for the "Phi", \(\phi\) coordinate is the \(x\)-axis.).

Figure 6.25. A fabricated metallic can RFID tag made of Rogers RT/duroid 6010 \((h = 0.64 \text{ mm}; \varepsilon_r = 10.8)\). A Class 1 Generation 2 (C1G2) RFID tag chip was used.
of materials with different characteristics can also be considered for the tag antenna implementation in the future.
Chapter 7

Tag in Metallic Depressions

The performance of conventional passive UHF (860-960 MHz) RFID systems will be affected when they involve the tagging of metallic objects. Reduced performance can be either due to the detuning of the resonant frequency of the RFID tag or insufficient interrogation field from the RFID reader antenna reaching and powering the tag near metallic surfaces. In this chapter, an analysis of the performance of a magnetic field sensitive RFID tag located in metallic depressions of different shapes, sizes and depths is presented. The analysis includes the use of simulation results and theoretical calculations to predict the tag’s read range performance. Practical read range measurements, consistent with theory, are given.
7.1 Introduction

RFID involves tagging of different types of objects and a tag may be required to be located in a depression of a metallic object or structure, for example a metallic beer keg. In addition, for space saving purposes, new metallic objects created to cater for RFID implementations may require that the tag be located in a specifically designed depression so that the tag does not protrude from the tagged object. This chapter presents an analysis of the performance of a passive UHF RFID tag when the tag is located in metallic depressions of various shapes, sizes and depths. In addition, the aim of the work presented here is to form a model and procedure that is able to estimate or predict the read range of the tag located in a metallic depression. The RFID tag used is a magnetic field sensitive tag and consists of a simple rectangular loop antenna (Figure 7.1). This tag is designed to operate well close to metallic surfaces. The tag design details have been discussed in Chapter 4.

![Diagram of RFID tag](image)

Figure 7.1. **Structure of the RFID tag considered in the analysis.** The RFID tag consists of a rectangular loop antenna and has dimension with length $L_{rec} = 25$ mm, width $W_{rec} = 15$ mm and height $H_{rec} = 10$ mm. The feed point terminals has gap $g = 3$ mm. This tag uses a Class 1 Generation 2 (C1G2) tag chip. (From Figure 4.1).

In this chapter, first the variation of the magnetic field concentration in metallic depressions of different shapes, sizes and depths was determined by simulation. Next, the simulation results obtained were extended using theory to predict the read range performance of the RFID tag. Lastly, experiments were set-up and performed to verify and compare between the predicted and measured read range performances.
Chapter 7
Tag in Metallic Depressions

7.2 Depression Types

The analysis covered three common depression shapes: circular, square and rectangular. For the square and rectangular depressions, each involved the placing of the RFID tag in two different orientations. Hence, including the circular depression, there were a total of five different tag and depression combinations or cases considered. This is as shown in Figure 7.2.

In the analysis, the sizes of the depressions were expressed in terms of wavelength $\lambda$. The diameter of the circular depression started from a minimum size of $0.25\lambda$ and was increased at a step of $0.25\lambda$ up to $1.25\lambda$. The size of the square depression followed this same trend, with the sides of the square depression started from a length of $0.25\lambda$. For the rectangular depression, since there can be many different ratios of the length of the longer side to the width of the shorter side, the ratio was fixed to 2:1 in this analysis. The size variation for the rectangular depression was referenced to the length of the longer side, with the minimum length started from $0.25\lambda$ and up to $1.25\lambda$ at a similar $0.25\lambda$ step size.

The frequency of interest in the analysis is at 923 MHz, which is situated in the middle of the Australia 4 W UHF RFID frequency band of 920-926 MHz. Hence, it should be noted that for this frequency, the wavelength $\lambda$ is approximately 325 mm.

For each depression shape and size, four different depression depths $h$ were considered. They were $h = 0, 20, 40$ and $80$ mm. Note that for the depth $h = 0$ mm, the structure would be like a flat ground plane.

7.3 Concept For Read Range Prediction

The approach used for read range prediction is from the driving field point of view, in which the available source power at the tag antenna is seen to depend on the antenna induced voltage, and the resistance of the antenna for its particular environment. To begin, the first step is to obtain a numerical value for the minimum magnetic field required to power-up the tag. Since the RFID tag considered in the analysis is a magnetic
7.3 Concept For Read Range Prediction

![Circular Depression](image1)

![Square Depression (Orientation 1)](image2)

![Square Depression (Orientation 2)](image3)

![Rectangular Depression (Orientation 1)](image4)

![Rectangular Depression (Orientation 2)](image5)

Figure 7.2. Different tag and depression combinations considered. Three depression shapes were covered. Two orientations were considered for the square and rectangular depressions. Tag positions in the depressions are shown in the top view of the depressions.

field sensitive tag, it is assumed that the main driving field for the tag is the magnetic field. In the analysis, there will not be a concern as to whether the magnetic field
is contributed by either the main incident wave or waves caused by electromagnetic phenomena such as reflections, as long as there is sufficient magnetic field to power-up the tag.

The free space magnetic field that just excites the tag is defined to be $|\mathbf{H}|_{\text{min,fs}}$. However, both the field at the position of the RFID tag and the tag antenna impedance will change as a result of the presence of the metallic depression and in a way that depends on the shape, size and depth of the depression that the RFID tag is attached to. Hence, the term $|\mathbf{H}|_{\text{min,m}}$ is introduced to represent the minimum amount of magnetic field required at the position of the tag to power-up the tag chip when the RFID tag is located in the metallic depression.

There is, for the tag considered, a mismatch between the tag antenna and chip impedances. A ratio $p_{\text{loss}}$ representing the amount of power lost caused by the impedance mismatch compared to the maximum power available to the tag chip in a matched condition is introduced. It can be calculated for both the tag in free space ($p_{\text{loss,fs}}$) and the tag located in a metallic depression ($p_{\text{loss,m}}$) by knowing the tag antenna and chip impedances. A general expression for $p_{\text{loss}}$ is [52]

$$p_{\text{loss}} = \left| \frac{Z_c - Z_a^*}{Z_c + Z_a} \right|^2$$  \hspace{1cm} (7.1)

where $Z_a$ is the tag antenna impedance and is obtained through simulations, and $Z_c$ is the tag chip impedance. Assuming that there is no ohmic losses for the antenna, $Z_a$ is expressed as $R_r + jX_a$ here, noting that $R_r$ and $X_a$ is the antenna radiation resistance and reactance respectively. The tag chip impedance $Z_c$ is expressed as $R_c + jX_c$, which consists of the equivalent resistance $R_c$ and reactance $X_c$ of the tag chip.

The fraction of the available source power delivered to the load resistor (in this case, $R_c$) is hence, in general, $(1 - p_{\text{loss}})$. In [82], the fraction of the available source power delivered to the load resistor is expressed as

$$q = \frac{P_D}{P_{D\text{max}}}$$  \hspace{1cm} (7.2)

where $P_D$ is the power delivered to the load resistor and $P_{D\text{max}}$ is the maximum power available to the load resistor from the antenna in a matched condition. Referring to
7.3 Concept For Read Range Prediction

Figure 7.3. Simplified equivalent circuit of the RFID tag. The tag antenna impedance is expressed in terms of the antenna radiation resistance $R_r$ and reactance $X_a$, assuming the antenna has no ohmic losses. The tag chip impedance shown is the total equivalent impedance of the chip and is expressed in terms of resistance $R_c$ and reactance $X_c$.

Figure 7.3, if the induced voltage of the tag is $V_{in}$ and assuming no ohmic losses,

$$P_D = \frac{1}{2} \frac{|V_{in}|^2}{(R_r + R_c)^2 + (X_a + X_c)^2} R_c$$

and

$$P_{D_{max}} = \frac{|V_{in}|^2}{8R_r}.$$  \hspace{1cm} (7.3)

Also, clearly

$$q = 1 - p_{\text{loss}}.$$  \hspace{1cm} (7.4)

Since it is assumed that the magnetic field is the main driving field of the tag, the induced voltage $V_{in}$ of the tag will be proportional to the magnetic field $H$ at which the tag is located (Note that $H$ is a peak value phasor. As mentioned in the Conventions, peak value phasors are used in this thesis). Hence, it can be written $V_{in} = k|H|$, where $k$ is a constant of unit $\Omega$m. If $P_{th}$ is the threshold power required for the RFID tag chip to operate and $|H|_{\text{min}}$ is the minimum magnetic field required to provide at least $P_{th}$ for the tag chip (hence the powering-up of the tag), then it can be written based on (7.2), (7.4) and (7.5) that

$$P_{th} = (1 - p_{\text{loss}}) \frac{k^2|H|_{\text{min}}^2}{8R_r}.$$  \hspace{1cm} (7.5)

Notice that this expression can allow for the case when there is a mismatch between either or both of the antenna and chip resistances or antenna and chip reactances.

While the presence of the metallic depression will affect the electromagnetic fields and the tag antenna impedance, the threshold power $P_{th}$ for the same chip will not be affected and will always remain the same whether the tag is in free space or located in
the metallic depression. Hence, following (7.6), it can be expressed for the case when the tag is in free space

\[ P_{th} = (1 - p_{loss,fs}) \frac{k^2|H|_{min,fs}^2}{8R_{r,fs}} \]  

(7.7)

and for the case where the tag is located in a metallic depression

\[ P_{th} = (1 - p_{loss,m}) \frac{k^2|H|_{min,m}^2}{8R_{r,m}} \]  

(7.8)

where \( R_{r,fs} \) and \( R_{r,m} \) is the antenna resistance when the tag is in free space and located in a metallic depression respectively. Dividing (7.8) with (7.7) and rearranging will give

\[ \frac{|H|_{min,m}}{|H|_{min,fs}} = \sqrt{\frac{1 - p_{loss,fs}}{1 - p_{loss,m}}} \left( \frac{R_{r,m}}{R_{r,fs}} \right). \]  

(7.9)

This is the ratio for the minimum magnetic field required for powering-up the tag, and is expressed in the form of \( |H|_{min,m} \) normalised to \( |H|_{min,fs} \).

![Simplified equivalent circuits of tag in two particular cases](image)

**Figure 7.4. Simplified equivalent circuits of tag in two particular cases.** (a) Tag in free space, and (b) Tag against a large flat metallic surface. In both cases, the tag experiences the same magnetic field.

Simulation results in Chapter 4 have shown that, when the tag is moved from free space to above a ground plane, the antenna reactance \( X_a \) will be minimally affected and the antenna resistance \( R_{r,m} \) for the tag above a metallic ground plane could possibly reach \( 2R_{r,fs} \), that is twice the antenna free space resistance. These effects are shown in Figure 7.4. It can be first noted that if the same amount of magnetic field is present the same induced voltage occurs, but the radiation resistance of the tag antenna is doubled in case (b) relative to the value for case (a). Even if there is no mismatch between the tag
antenna and chip impedances, the value of $|H|_{\text{min}}$ required to power-up the tag will be different between the two cases because of the change of antenna impedance, whereas the power required to power-up the tag chip is assumed not to change. Secondly, if there is a mismatch between the antenna and chip impedances, there is an additional change in $|H|_{\text{min}}$ because the power transfer to the tag chip contains an additional factor $(1 - p_{\text{loss}})$ where calculation of $p_{\text{loss}}$ requires knowledge of the tag antenna and chip impedances and involves (7.1). Therefore, as can be observed, (7.9) involves an available source power ratio $R_{r,m}/R_{r,fs}$ which depends on how the antenna resistance $R_r$ varies between the free space value $R_{r,fs}$ and the value $R_{r,m}$ for a tag against a metallic depression, and also a power transfer change ratio $(1 - p_{\text{loss,m}})/(1 - p_{\text{loss,fs}})$ that depends on all aspects of antenna impedance versus chip impedance. The latter ratio involves two mismatches, one in free space and one against the metallic depression. Note that, it is assumed that the induced voltage $V_{\text{in}}$ of the equivalent circuit of the tag, acting as receiver, bears a constant relationship with the magnetic field at the position (free space or on the metallic depression) at which the tag is located, even if the tag impedance changes with its environment.

![Simulation model to obtain the simulated magnetic field intensity $|H|_{\text{sim,m}}$.](a) A cross sectional view illustration of a half-wavelength electric dipole antenna located a distance $r_{\text{sim}}$ above a metallic depression, and (b) An example of an HFSS simulation model consisting of a half-wavelength electric dipole antenna and a circular metallic depression.

**Figure 7.5. Simulation model to obtain the simulated magnetic field intensity $|H|_{\text{sim,m}}$.**
In the next step, using Ansoft HFSS simulation, the effect of a half-wavelength electric dipole antenna (with gain $g_t$ and accepting a known time-average input power $P_i$) is modelled at a known distance $r_{sim}$ above a structure representing a metallic depression. This is shown in Figure 7.5. The magnitude of the magnetic field intensity $|H|_{sim,m}$ at the point very close to the base and at the centre of the metallic depression (the intended position to place the tag) is simulated. With the input power of the dipole antenna fixed, it is observed that if the distance between the dipole antenna and the depression (i.e. $r_{sim}$) is varied, $|H|_{sim,m}$ will also vary in a way that the product of $|H|_{sim,m}r_{sim}$ will be approximately constant. If the value of the magnetic field $|H|_{min,m}$ at which the tag is just turned on is known, and by varying $r_{sim}$ such as to obtain $|H|_{sim,m}$ equal to $|H|_{min,m}$, then, the corresponding $r_{sim}$ will be the predicted maximum read range $r_{max,m}$ at which the tag just becomes energised when the tag is located in a metallic depression, for the originally assumed dipole antenna $g_t$ and $P_i$. Thus

$$|H|_{min,m}r_{max,m} = |H|_{sim,m}r_{sim}. \quad (7.10)$$

The same situation occurs for the free space case (i.e. without the presence of the metallic depression). If $|H|_{sim,fs}$ is the simulated magnitude of the magnetic field in free space corresponding to the half-wavelength electric dipole antenna with fixed $g_t$ and $P_i$ located $r_{sim}$ away from the point of measurement, then it can be written for the free space case

$$|H|_{min,fs}r_{max,fs} = |H|_{sim,fs}r_{sim}. \quad (7.11)$$

Following this, the maximum predicted read range $r_{max,m}$ when the tag is located in a metallic depression normalised with the maximum predicted read range $r_{max,fs}$ when the tag is in free space can be found, that is

$$\frac{r_{max,m}}{r_{max,fs}} = \left(\frac{|H|_{sim,m}}{|H|_{sim,fs}}\right) \left(\frac{|H|_{min,fs}}{|H|_{min,m}}\right). \quad (7.12)$$

The entire concept and steps towards read range prediction discussed above are summarised in Figure 7.6. As shown in the flowchart, the read range prediction consists of two parts. The first part involves simulation work, where the tag antenna impedance ($R_{r,fs}$ and $X_{a,fs}$ for tag in free space, and $R_{r,m}$ and $X_{a,m}$ for tag in metallic depression)
7.4 Alternative Calculations

It can be noted that instead of using (7.6) to reach (7.9) where the ratio $|H|_{min,m} / |H|_{min,fs}$ is expressed in terms of the power transfer change ratio and available source power ratio as discussed in Section 7.3, (7.3) can be used directly.

Figure 7.6. Concept flowchart for read range prediction. The read range prediction consists of simulation and calculation parts. The predicted read range is compared to the real-life measured read range in the later part of the process.

and the magnitude of the magnetic field ($|H|_{sim,fs}$ for free space and $|H|_{sim,m}$ when a metallic depression is present) from a half-wavelength electric dipole antenna located $r_{sim}$ away are simulated. In the second part, calculations are performed which involve using the simulation results from the first part and the equations presented in the discussions. The end result of the calculations is the predicted read range in the form of $r_{max,m} / r_{max,fs}$ ratio. Also shown in Figure 7.6 is a part where experiments are performed to measure the real-life practical read range. The predicted and the measured read range results are compared in the later part of the process.
With (7.3), it can be written for the cases of the tag in free space and located in a metallic depression respectively

\[ P_{th} = \frac{1}{2} \left( \frac{k^2 |H|_{\text{min},fs}^2}{(R_{r,fs} + R_c)^2 + (X_{a,fs} + X_c)^2 R_c} \right) \] \hspace{1cm} (7.13)

and

\[ P_{th} = \frac{1}{2} \left( \frac{k^2 |H|_{\text{min},m}^2}{(R_{r,m} + R_c)^2 + (X_{a,m} + X_c)^2 R_c} \right) \] \hspace{1cm} (7.14)

Bearing in mind that \( P_{th} \) remains the same for both cases, this will then yield

\[ \frac{|H|_{\text{min},m}}{|H|_{\text{min},fs}} = \sqrt{\frac{(R_{r,m} + R_c)^2 + (X_{a,m} + X_c)^2}{(R_{r,fs} + R_c)^2 + (X_{a,fs} + X_c)^2}} \] \hspace{1cm} (7.15)

Whether (7.9) or (7.15) is used, the same calculated \( |H|_{\text{min},m}/|H|_{\text{min},fs} \) values will be obtained and the same remaining steps for read range prediction will then follow. However, in the analysis presented in this chapter, (7.9) will be used since it can allow a clear display of the variations in power transfer and available source power.

7.5 Prediction of Read Range

The steps outlined in Figure 7.6 were used for the read range prediction. The aim is to obtain the ratios \( |H|_{\text{min},m}/|H|_{\text{min},fs} \) and \( |H|_{\text{sim},m}/|H|_{\text{sim},fs} \) in order to calculate the predicted read range ratio \( r_{max,m}/r_{max,fs} \).

7.5.1 Ratio \( |H|_{\text{min},m}/|H|_{\text{min},fs} \)

The RFID tag antenna impedance is affected by the metallic depression structures especially when the size of the depressions are small. Hence, for the first part of the simulation work, the RFID tag was modelled with each depression of different shape, size and depth in HFSS and the impedance of the tag antenna for each case was obtained from the simulations before calculations were carried out. In the simulation, a copper material was assigned for the tag antenna and an aluminium material for the depression structure. The simulation results provided the parameters \( R_{r,m} \) and \( X_{a,m} \).
7.5 Prediction of Read Range

The parameters $R_{r,fs}$ and $X_{a,fs}$ were obtained by simulating just the tag antenna itself in a free space environment in HFSS. While the impedance of the tag antenna located in a depression varied from case to case depending on the depression shape, size and depth, there was only one impedance value for the tag in free space. The simulation results gave $R_{r,fs} = 0.351 \, \Omega$ and $X_{a,fs} = 99.3 \, \Omega$.

With the simulated tag antenna impedance, $p_{loss,m}$ and $p_{loss,fs}$ were calculated using (7.1). The tag chip impedance used in the calculations was $Z_c = 12 - j132 \, \Omega$ (This is the equivalent chip impedance at the frequency 923 MHz of having a resistor with resistance 1.5 k$\Omega$ and capacitor with capacitance 1.3 pF in parallel.). The power transfer change ratio $(1 - p_{loss,m})/(1 - p_{loss,fs})$ and also the available source power ratio $R_{r,m}/R_{r,fs}$ were then calculated. Hence, using (7.9), the $|H|_{min,m}/|H|_{min,fs}$ ratio was determined.

![Figure 7.7. Ratio $(1 - p_{loss,m})/(1 - p_{loss,fs})$ corresponding to a tag in a circular depression.](image)

The ratio was calculated using simulated tag antenna impedance values and a chip impedance value of $Z_c = 12 - j132 \, \Omega$. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

Shown in Figures 7.7, 7.8 and 7.9 are the plots of the ratios $(1 - p_{loss,m})/(1 - p_{loss,fs})$, $R_{r,m}/R_{r,fs}$ and $|H|_{min,m}/|H|_{min,fs}$ respectively corresponding to the circular depression case. As can be observed, the variation of the ratio $|H|_{min,m}/|H|_{min,fs}$ with respect to the change in depression size and depth is very minimal. This can be explained by
Figure 7.8. Ratio $R_{r,m}/R_{r,fs}$ corresponding to a tag in a circular depression. The ratio was calculated using simulated tag antenna impedance values. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

Figure 7.9. Ratio $|H|_{min,m}/|H|_{min,fs}$ corresponding to a tag in a circular depression. The plot shows that the variation of this ratio with respect to the change in size and depth of the depression is minimal. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

looking at the $(1 - p_{loss,m})/(1 - p_{loss,fs})$ and $R_{r,m}/R_{r,fs}$ ratios. As the tag antenna considered in this analysis has a much lower radiation resistance compared to the resistance of the tag chip, when there is an increase in $R_{r,m}$, the available source power will reduce but at the same time the amount of power transfer from the antenna to the chip (load) will increase, and vice versa. Hence, noting that in (7.9) the factors involving $p_{loss}$ and $R_r$ are inverted between the free space and on metal situations, the decrease
7.5 Prediction of Read Range

of one factor and the increase of the other in (7.9) have managed to compensate each
other, which leads to a minimal variation of the ratio $|H_{\text{min},m}| / |H_{\text{min},fs}|$.

Although the variation is minimal, the $|H_{\text{min},m}| / |H_{\text{min},fs}|$ curves in Figure 7.9 have
all appeared slightly above the unity line. This means that the minimum amount of
magnetic field $|H_{\text{min},m}|$ required to power-up the tag located in the metallic depression
is, in general, slightly more than the minimum amount of the magnetic field $|H_{\text{min},fs}|$
required by the tag in free space.

As almost the same minimal variation in the ratio $|H_{\text{min},m}| / |H_{\text{min},fs}|$ is observed for all
other depression cases, plots of this ratio for all other depression cases are included in
Appendix C. Plots of the $(1 - p_{\text{loss},m}) / (1 - p_{\text{loss,fs}})$ and $R_{r,m} / R_{r,fs}$ ratios for all other
depression cases can also be found in Appendix C.

7.5.2 Ratio $|H_{\text{sim},m}| / |H_{\text{sim},fs}|$

In the second part of the simulation work, the aim is to model a half-wavelength elec-
tric dipole antenna located at a distance $r_{\text{sim}}$ above a metallic depression in HFSS and
obtain, from simulations, the amount of magnetic field from the dipole antenna present
at the point where the tag will be placed in the depression. The dipole antenna was ori-
ented such that the length of the dipole antenna was along the axis that was favourable
with respect to the tag antenna orientation (i.e. the dipole antenna was in line with the
plane of the tag loop antenna). In the simulation model, an aluminium material was
assigned for the depression structure and a perfect electric conductor material (pec) for
the dipole antenna. A dipole antenna with a length to wire diameter ratio of 50 was
used. A lumped port excitation was assigned to the dipole antenna, with a 1 W power
incident upon the port boundary of the dipole antenna structure. An example of an
HFSS simulation model for this part of the work is shown in Figure 7.5(b), where a
dipole antenna is located $r_{\text{sim}}$ above a circular metallic depression of diameter $1\lambda$ and
depth $h = 80$ mm.

For the simulation, $r_{\text{sim}} = 1.5\lambda$ was chosen. For each simulation model, a depression
of different shape, size and depth discussed in Section 7.2 was considered, with the
dipole antenna remained at the same fixed distance above the depression. The tag considered in the analysis has a height of 10 mm and is to be located in the depression at a separation gap of 3 mm from the depression base. In addition, the best performance is believed to occur when the tag is located at the centre of the depression. Hence, each case was simulated with the magnitude of the magnetic field $|H|_{\text{sim},m}$ obtained at the point 8 mm above the base and centre of the metallic depression. Note that the 8 mm distance of the point from the depression base will be the centre point of the tag antenna when the tag is located in the depression.

Figure 7.10. Measurement of $|H|_{\text{sim},m}$ in HFSS. (a) A cross sectional view of the HFSS simulation model showing the overall magnitude of the magnetic field in the $yz$-plane. This simulation model consists of a half-wavelength electric dipole antenna located $r_{\text{sim}} = 1.5\lambda$ above a circular aluminium depression structure of diameter $1\lambda$. (b) The position of a point used to obtain $|H|_{\text{sim},m}$ at the intended position of the tag.

Figure 7.10 shows the magnetic field plot in HFSS where $|H|_{\text{sim},m}$ was obtained. As can be observed in the magnetic field plot shown in Figure 7.10(a), the concentration of the magnetic field is higher in and around the centre of the depression base compared to the rest of the areas nearer to the side of the depression base. This observation confirmed the earlier belief that the tag would exhibit a better performance when located at the centre of the depression. Another interesting observation from Figure 7.10(a) is
7.5 Prediction of Read Range

that beside the higher magnetic field concentration at the centre of the depression base, obvious high magnetic field concentrations are also observed at two different locations above the depression base, one at approximately 0.5λ and another 1λ above the depression base. This is most likely caused by the standing electromagnetic wave effect. Figure 7.10(a) shows the overall magnetic field plot in the yz-plane and Figure 7.10(b) shows the position of a point used to obtain $|H|_{sim,m}$ at the intended position of the tag.

To obtain the ratio $|H|_{sim,m}/|H|_{sim,fs}$, the amount of magnetic field $|H|_{sim,fs}$ from the electric dipole antenna in free space was required. It was measured through simulations at the same distance from the dipole antenna as compared to the cases above when a metallic depression was present (i.e. 1.5λ – 8 mm). The value obtained was $|H|_{sim,fs} = 0.0502$ A/m. Note that since this is the free space case, there is only one value for $|H|_{sim,fs}$. Note also that a 1 W power incident upon the port boundary of the dipole antenna structure has been specified.

The plots of the simulation results are shown in Figures 7.11 to 7.15. Figure 7.11 corresponds to the circular metallic depression case, Figures 7.12 and 7.13 correspond to different square depression cases respectively, and Figures 7.14 and 7.15 correspond to different rectangular depression cases respectively. Note that the two different tag and depression orientations (Orientations 1 and 2) for the square and rectangular depressions cases have been defined in Figure 7.2.

Observing the $|H|_{sim,m}/|H|_{sim,fs}$ plots for all depression cases, most of the points in the plots lie above the unity line. This means the magnetic field concentration $|H|_{sim,m}$ with the presence of a metallic depression is higher for most depression sizes and depths as compared to the magnetic field concentration $|H|_{sim,fs}$ for a free space environment. The few points in the plots that fall below the unity line correspond to depressions with greater depths. This is because the higher depression walls have caused greater perturbation to the fields.
Figure 7.11. Ratio $|H|_{\text{sim},m}/|H|_{\text{sim},fs}$ corresponding to the circular depression case. The ratio represents the simulated amount of magnetic field (from an electric dipole antenna) present at the tag position in the circular metallic depression, normalised with the amount of magnetic field in free space (i.e., without the depression) at the same position. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

Figure 7.12. Ratio $|H|_{\text{sim},m}/|H|_{\text{sim},fs}$ corresponding to the square depression (Orientation 1) case. The ratio represents the simulated amount of magnetic field (from an electric dipole antenna) present at the tag position in the square metallic depression, normalised with the amount of magnetic field in free space (i.e., without the depression) at the same position. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.
7.5 Prediction of Read Range

Figure 7.13. Ratio $|H_{\text{sim,m}}|/|H_{\text{sim,fs}}$ corresponding to the square depression (Orientation 2) case. The ratio represents the simulated amount of magnetic field (from an electric dipole antenna) present at the tag position in the square metallic depression, normalised with the amount of magnetic field in free space (i.e. without the depression) at the same position. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

Figure 7.14. Ratio $|H_{\text{sim,m}}|/|H_{\text{sim,fs}}$ corresponding to the rectangular depression (Orientation 1) case. The ratio represents the simulated amount of magnetic field (from an electric dipole antenna) present at the tag position in the rectangular metallic depression, normalised with the amount of magnetic field in free space (i.e. without the depression) at the same position. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.
Figure 7.15. Ratio $|H|_{sim,m}/|H|_{sim,fs}$ corresponding to the rectangular depression (Orientation 2) case. The ratio represents the simulated amount of magnetic field (from an electric dipole antenna) present at the tag position in the rectangular metallic depression, normalised with the amount of magnetic field in free space (i.e without the depression) at the same position. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

### 7.5.3 Ratio $r_{max,m}/r_{max,fs}$

The ratio $H_{min,m}/H_{min,fs}$ obtained in Section 7.5.1 shows how this ratio needs to vary to keep the tag just energized, while the ratio $|H|_{sim,m}/|H|_{sim,fs}$ obtained in Section 7.5.2 shows how the driving field of the tag is influenced by its environment. With these two ratios, $r_{max,m}/r_{max,fs}$ for each case was found using (7.12). This is the predicted read range of the tag located in a metallic depression normalised with the tag free space read range. The plots of the $r_{max,m}/r_{max,fs}$ ratio corresponding to circular, square (two orientations) and rectangular (two orientations) depressions are shown in Figures 7.16 to 7.20.

Since the values for the $r_{max,m}/r_{max,fs}$ ratio were calculated using the $|H|_{min,m}/|H|_{min,fs}$ and $|H|_{sim,m}/|H|_{sim,fs}$ ratios, the predicted read range was expected to be greatly influenced and contributed by the $|H|_{sim,m}/|H|_{sim,fs}$ ratio. This is because, as discussed in Section 7.5.1 above, the variation of the values for ratio $|H|_{min,m}/|H|_{min,fs}$ over the change in depression size and depth were minimal for all depression types considered. Moreover, the $|H|_{min,m}/|H|_{min,fs}$ values were found to be all just slightly above unity.
7.5 Prediction of Read Range

Figure 7.16. Ratio $r_{\text{max},m}/r_{\text{max,fs}}$ for a tag in a circular metallic depression. This ratio is the predicted read range of the tag located in a circular metallic depression with respect to the predicted tag free space read range. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

Figure 7.17. Ratio $r_{\text{max},m}/r_{\text{max,fs}}$ for a tag in a square metallic depression (Orientation 1). This ratio is the predicted read range of the tag located in a square metallic depression with respect to the predicted tag free space read range. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

Hence, it can be observed from Figures 7.16 to 7.20 that the $r_{\text{max},m}/r_{\text{max,fs}}$ plots have close similarity in terms of the overall shape, but with slight difference in magnitude, compared to their corresponding $|H|_{\text{sim},m}/|H|_{\text{sim,fs}}$ plots.
Figure 7.18. Ratio $r_{\text{max},m} / r_{\text{max,fs}}$ for a tag in a square metallic depression (Orientation 2). This ratio is the predicted read range of the tag located in a square metallic depression with respect to the predicted tag free space read range. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

Figure 7.19. Ratio $r_{\text{max},m} / r_{\text{max,fs}}$ for a tag in a rectangular metallic depression (Orientation 1). This ratio is the predicted read range of the tag located in a rectangular metallic depression with respect to the predicted tag free space read range. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

In Figures 7.16 to 7.20, it can be seen that for all depression shapes considered, the predicted read range values are worst when the depression has the smallest size ($0.25\lambda$) and greatest depth ($h = 80$ mm) compared to the predicted read range values corresponding to all other depression sizes and depths. In addition, it is consistent for all
7.5 Prediction of Read Range

Figure 7.20. Ratio $r_{\text{max},m} / r_{\text{max},fs}$ for a tag in a rectangular metallic depression (Orientation 2). This ratio is the predicted read range of the tag located in a rectangular metallic depression with respect to the predicted tag free space read range. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

depression shapes that for the smallest size depression, the read range improves as the depression depth reduces (from 80 mm to 0 mm). It can also be observed from the plots that the variation of the predicted read range values for depressions with depth $h = 0$ mm is less drastic over the change in depression size as compared to that corresponding to depressions with greater depths. Moreover, for all depression shapes considered, most of the points in the plots lie above the unity line, which means that the read range of the tag located in a metallic depression is better compared to the tag free space read range for most of the depression sizes and depths.

From a general observation of the predicted read range plots for all depression shapes, the read range is lesser when the depression size (length or diameter) is smallest and reduces further as the depth of the depression increases. This is because the smaller opening of the depression enable less field to enter into the depression and therefore to the location of the tag. Though this may be the case, it does not always guarantee a better read range when larger size depressions are involved. Lesser read range values are also observed for some of the larger depression sizes (length or diameter), such as some obvious ones in Figures 7.17 and 7.18 corresponding to the square depression
for two different orientations. This is most likely due to electromagnetic phenomena such as the reflections of the fields from the side walls of the depression and also the diffractions caused by the edges of the depression.

### 7.6 Read Range Measurement

![Figure 7.21. Experiment setup for read range measurement. Metallic tray-like structures were constructed to mimic actual metallic depressions.](image)

To observe the real-life performance of the RFID tag located in metallic depressions of various shapes, sizes and depths, a practical read range measurement was carried out. The experiment setup is as shown in Figure 7.21. Care was taken to keep extraneous objects within the room at significant distance. Room reflection did not then appear to have a significant effect on the results as moving such objects within the room produced little effect. Both the ceiling and the floor were at significant distance.

An RFID reader (Model ID ISC.LRU2000) and an RFID reader antenna (Model ID ISC.ANT.U250/250) both manufactured by Feig Electronic and suitable for operation in Australia (920 - 926 MHz) were used in the measurement. The reader antenna used is circularly polarised and has a gain of 8.7 dBi (equivalent to approximately 5.7 dBi or 3.7). With the reader antenna accepting 1 W input power from the RFID reader, the total equivalent isotropic radiated power (EIRP) was 3.7 W. The RFID reader antenna was mounted on a wooden antenna tripod.
7.6 Read Range Measurement

To mimic a real metallic depression, tray-like structures were constructed using thick cardboard material and the surfaces of the cardboard structures were then lined and covered carefully with layers of aluminium foil sheets. The tray-like structures varied in shapes, sizes and depths according to that described in Section 7.2. Figure 7.22 shows some of the constructed depression structures in various shapes.

The RFID tag was placed at the centre of the base of the depression structure such as that illustrated in Figure 7.2 shown earlier in this chapter. The depression structure was then mounted on a plastic trolley. A plastic trolley was used to ensure that the depression structure (with a tag located in it) could be easily moved along a straight line either towards or away from the RFID reader antenna when the read range measurement was performed. The radiation of the RFID reader antenna was inward along the axis normal to the base of the depression structure.

The practical read range values $R_{\text{max, m}}$ for the tag in each different depressions were obtained. They were then normalised to the practical tag free space read range value $R_{\text{max, fs}}$ to obtain the ratio $R_{\text{max, m}} / R_{\text{max, fs}}$. The tag free space read range was found to be $R_{\text{max, fs}} = 1.23$ m. For the measurement of the tag free space read range, the same measurement setup was used except that the read range of the tag was measured without the presence of the metallic depressions. The plots of the $R_{\text{max, m}} / R_{\text{max, fs}}$ ratios corresponding to circular, square (two orientations) and rectangular (two orientations) depressions respectively are shown in Figures 7.23 to 7.27.

![Figure 7.22. Constructed depression structures. Shown are some tray-like structures constructed to mimic circular, square and rectangular typed depressions.](image-url)
Figure 7.23. Ratio $R_{\text{max,m}}/R_{\text{max,fs}}$ for a tag in a circular metallic depression. This ratio is the measured read range of the tag located in a circular metallic depression with respect to the measured tag free space read range. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

Figure 7.24. Ratio $R_{\text{max,m}}/R_{\text{max,fs}}$ for a tag in a square metallic depression (Orientation 1). This ratio is the measured read range of the tag located in a square metallic depression with respect to the measured tag free space read range. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

For each of the depression shapes considered, comparing each plot for the measured read range (Figures 7.23 to 7.27) with its corresponding plot for the predicted read range in Section 7.5.3, close similarity can be seen between the plots in terms of the overall shape or pattern. In addition, same as the predicted read range results, the measured read range results show that lower read range values are obtained when the
7.6 Read Range Measurement

![Graph 1](image1)

**Figure 7.25.** Ratio $R_{\text{max,m}} / R_{\text{max,fs}}$ for a tag in a square metallic depression (Orientation 2).

This ratio is the measured read range of the tag located in a square metallic depression with respect to the measured tag free space read range. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

![Graph 2](image2)

**Figure 7.26.** Ratio $R_{\text{max,m}} / R_{\text{max,fs}}$ for a tag in a rectangular metallic depression (Orientation 1).

This ratio is the measured read range of the tag located in a rectangular metallic depression with respect to the measured tag free space read range. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

depression size (length or diameter) goes down to $0.25\lambda$, with the read range values reducing further for increasing depression depth. It is also observed that the variation of the measured read range values is most drastic for depressions with depth $h = \ldots$
Figure 7.27. Ratio $R_{max,m}/R_{max,fs}$ for a tag in a rectangular metallic depression (Orientation 2). This ratio is the measured read range of the tag located in a rectangular metallic depression with respect to the measured tag free space read range. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

80 mm and least drastic for depressions with depth $h = 0$ mm over the change in depression size for all depression shapes.

All the predicted and measured read range results have overall shown better read range values when the tag is located in depressions of size between $0.5\lambda$ and $1\lambda$, except for the rectangular depression case in the second orientation. Both the predicted and measured read range results for the rectangular depression case in the second orientation have shown that the effect of the depression depth is quite significant on the tag read range. As the size (length) of the rectangular depression in the second orientation increases, it is observed that the increase in the read range value before reaching the first optimum read range value has been slow, with the slowest when the depression depth is 80 mm. The magnetic fields are less inhibited by the side walls (walls perpendicular to the direction of the magnetic field) of the depression if they are at a significant distance away. The length and width of the rectangular depressions are in a fixed proportion. In the second orientation, a small length produces even smaller width which is capable of inhibiting the magnetic field in the width direction.
7.7 Conclusions

The magnitudes of the $R_{\text{max,m}}/R_{\text{max,fs}}$ plots are seen in general to be smaller than the ratios in the $r_{\text{max,m}}/r_{\text{max,fs}}$ plots for all depression cases. This is because, in the practical read range measurement, the depression structures used were made up of a cardboard core with the depression surface lined with layers of aluminium foil sheets. Hence, the depression structures used in the measurement were not purely metallic as compared to that in the simulation model where the depression structures were entirely aluminium. The skin depth of an aluminium material with conductivity $\sigma = 3.8 \times 10^7$ S/m at the frequency 923 MHz was calculated to be 2.69 $\mu$m. As the aluminium foil sheets have a thickness of 10 $\mu$m, they should be thick enough in terms of the skin depth. However, when the aluminium foil sheets were lined in layers during the construction of the depressions, the layers may not be entirely flatly lined and contacting with each other, hence contributing to the inaccuracy in the measured results. Other than the difference in magnitude, the measured read range results are still nevertheless in good agreement with the predicted read range results.

7.7 Conclusions

This chapter has presented a detailed analysis on the performance of a magnetic field sensitive RFID tag located in metallic depressions of various shapes, sizes and depths. Good agreement between theoretical calculations and read range measurements has been shown. The results have also shown that the tag can be embedded in a metallic object (by placing it in a depression of the object) and still offer good read range performance, though note has to be taken that the read range will decrease if the depth of the depression increases when the depression size is small. So it is up to the read range requirement of specific applications to determine the size of the depression where the RFID tag will be located.

While the analysis in this chapter is based on one type of tag design, it is strongly believed that the methods used for read range prediction presented here can be easily extended for many other tag designs. Hence, the work presented can be used to draw guidelines or references for RFID implementations involving the placing of RFID tags.
in metallic depressions. It can even play the role as part of a deciding factor in designing new metallic objects where tags are to be placed in the depression of the objects.

Though this may increase the cost of the experiment setup significantly, future work can include using pure aluminium depression structures for the read range measurements. Moreover, a complete analysis of the testing of embedding the RFID tag in depressions of actual metallic objects for different applications can be carried out. Applying different types of tag design in the analysis will also be of great interest.
Chapter 8

Conclusions and Future Work

This chapter concludes the thesis. It provides a summary of the research work described therein. Recommendations for related future research are discussed, and a summary of the original contributions to knowledge made by the research work presented in this thesis is given.

Page 197
8.1 Thesis Conclusions

Radio Frequency Identification (RFID) technology, the origin of which can be traced back to as early as the World War II era, has advanced considerably since that time. The evolution of this technology and the growth of its applications throughout the years define RFID as it is seen today. The introduction of the Electronic Product Code (EPC) concept has put a new perspective on the potential of RFID, wherein RFID can be used to track and trace every single item in a supply chain, at a possible low cost, to achieve efficient and highly visible supply chain operations.

However, before RFID can be extended to its full potential with full deployment in RFID supply chains, there are a number of issues that need to be solved. These include the challenge of metallic object identification, which is the main concern of the research in this thesis. In Chapter 1 of this thesis, applications and challenges surrounding RFID have been listed. Chapter 2 has provided an introduction to RFID, focusing particularly on a passive Ultra High Frequency (UHF) RFID system. The electromagnetic field behaviour near a metallic surface and metallic object identification using RFID are then discussed and reviewed in that chapter, providing a clear understanding of the main issue tackled in the research of this thesis. In addition, the performance of conventional RFID tags near a metallic surface has been studied.

The general steps involved in tag design and prototyping have been listed and discussed in Chapter 3. The methods used and options made in simulating a tag design using the Ansoft High Frequency Structure Simulator (HFSS) have been outlined. These methodologies have formed a basis for systematic tag design work carried out throughout this research. As part of the foundational work in this research, a series of short experiments have been designed to determine the resistance introduced by the small amount of z-axis conductive tape used for attaching tag chips to tag antennas. The experiments, where the tape resistance was measured at both DC and at higher frequency conditions, have shown that the additional resistance introduced by the tape is small and hence will not put a significant effect on the tag performance.

Also shown in Chapter 3 is a small and low cost passive UHF RFID tag designed during this research. This work serves as part of the tag design familiarisation process in
this research. Most importantly, it displays the possibility of achieving a tag design that is balanced in terms of cost, size and performance, which aspect is emphasised in this research. The deployment of the designed tag for animal identification in a real-life piggery was carried out. The procedures and setups involved in the deployment are described. The field trial, with a population of 10 pigs tagged on their ears, was a success. Results from the deployment have shown that a passive UHF RFID tag can be a better candidate for animal identification than LF and HF RFID tags.

The main focus of this research is to draw solutions balanced in terms of performance, size and cost that allow metallic object identifications using RFID, embracing the vision of item level tagging. In this research, various RFID tags suitable for attaching to metallic objects have been designed. In the tag design work, tag antennas that are based on different concepts of operation have been explored, in addition to the more commonly used patch antennas. In Chapter 4, an RFID tag consisting a wide strip loop antenna that operates by utilising the rich magnetic field concentration near a metallic surface is presented. The concept of operation of this tag is unique compared to other existing published work on tags for metallic objects. Theoretical calculation and fine-tuning methods for the design of this tag are outlined, and measurement results have shown that despite a small tag size, this tag is able to provide a good read range when placed near a metallic surface.

Since a patch antenna is a common antenna choice for RFID tags suitable for metallic objects, design and analysis of a tag consisting a patch antenna have also been performed. This work is presented in Chapter 5. One of the aims of this work is to show that a reasonable tag read range performance can actually be obtained without using a complex and difficult to manufacture patch antenna design for the tag, as compared with many other existing patch antenna tags. This aim has been achieved with the design of a tag consisting a basic rectangular patch antenna with a simple impedance matching implementation. In addition, low cost FR4 substrate has been used for the tag. Another aim of the work is to analyse the changes in tag read range performance when the size of the designed tag is reduced without the use of expensive high relative dielectric permittivity substrates or making the tag design complex. Results have shown that there was a gradual decrease in read range when the tag size was reduced.
8.1 Thesis Conclusions

Though this is the case, the read range performances of the smaller size tags in the analysis are still acceptable. Hence, the smaller size tags can be good candidates for applications where tagging of small metallic objects is involved and that maximum read range is not required.

Chapter 6 has presented a solution, derived in the research of this thesis, to meet the challenging application of tagging metallic beverage cans. As metallic beverage cans are usually small and have a restricted area for attaching an RFID tag, the tag designed has to be not only able to operate when placed on metallic surfaces, it must also be small in size and compact. In this research, a compact RFID tag that can be placed at the bottom of a common type small metallic beverage can was designed. This tag design for metallic beverage cans is believed to be the first of its kind. It consists of a meandered metallic track on a dielectric substrate backed with a small metallic ground plane, and the design allows easy attachment of a tag chip. The work has provided an insight to the possibility of tagging small metallic objects at item-level. Although the current read range of this tag is not high, it is sufficient if the tag is used for item level tagging. Moreover, the tag design is based on an unusual concept, and in so doing displays the use of a tag antenna that is other than a patch antenna, for tagging metallic objects.

Another approach to tackling the challenge of using RFID for metallic object identification is to know the possible effects of metallic structures have on a tag read range performance. This way, an approximate idea can be obtained of how far an RFID deployment involving metallic structures can proceed to meet the read range requirement of an application and hence minimise flaws during deployments. In this research, the effects of metallic depressions on the read range performance of a tag have been analysed. Circular, square and rectangular metallic depressions of various sizes and depths were considered. The tag used in the analysis is a tag with a wide strip loop antenna designed in this research. The analysis is presented in Chapter 7. A method combining theoretical calculations and simulations has been developed to predict the effects of the various metallic depressions on the tag read range performance. Practical measurement results have shown to agree closely to the predicted tag read range performance.
Chapter 8 Conclusions and Future Work

The work performed in this research can still be improved in several ways. For instance, for the small passive UHF RFID tag with a two-element impedance matching network in Chapter 3, a more detailed study can be performed to gain a better understanding of whether the dielectric substrate losses will make the tag performance more constant over a wider frequency band than that would occur with a lossless matching network. An investigation of how the tag performance, from the aspects of read range and bandwidth of good operation, will be influenced by the use of lower loss dielectric substrate can be carried out. For the tag with a wide strip loop antenna in Chapter 4, analysis can be done on the tag performance when the distance between the tag and a metallic surface is varied. In addition, the feasibility of implementing an impedance matching network that is suitable for the structure of this tag can be studied. The possibility of whether there is a certain optimum length-height ratio for the wide strip loop antenna can also be explored. For the tag with a patch antenna in Chapter 5, the extension of the non-radiating edge of the patch element to the substrate edge can be investigated. This way, there may be a possibility of improving the tag performance while still retaining the overall size of the tag (since the substrate size still remains the same), which may be beneficial for smaller tags. Further tag dimensions analysis can also be performed on the metallic beverage can tag in Chapter 6. As for the analysis involving metallic depressions in Chapter 7, more different tags can be considered in the analysis and solid pure metallic depressions can be used for the practical measurements. More application based read range measurements involving the RFID tags designed in this research and various real-life metallic objects can also be performed.

However, due to either the time constraint imposed by the set duration of this research or the current limitation of resources, or both, the ideas for improvements above were unable to be carried out. Nevertheless, most importantly, all the work that has already been done and presented in this thesis has led to achieving the main aim of this research, that of developing small low cost tags that are suitable for attaching to metallic objects. The results have also provided encouragement towards tagging smaller metallic objects at item level. Moreover, this thesis is about the proving of concepts, and some of the tag designs presented have shown the use of various tag antennas.
8.2 Recommendations for Future Work

differing in operating principles from the more commonly employed patch antennas for metallic objects.

8.2 Recommendations for Future Work

This research has opened many possibilities of related future work. Besides improving the work that has already been done in this research (as discussed previously in Section 8.1), the following are the recommendations of possible future work resulting from this research:

1. *Larger scale animal identification trial*

   In the research presented in this thesis, a small low cost passive UHF RFID tag prototype has been designed and applied for animal identification in a field trial involving a population of 10 pigs. The field trial results obtained showed promise in using passive UHF RFID tags for animal identification, hence it will be of great interest to proceed to a larger scale field trial involving an even bigger population of pigs. If a larger field trial is to be carried out, a larger trial area and more resources, such as the number of pigs, RFID reader sets and RFID tags, will be involved. This means the tags required must be commercially made in large quantities. Although a larger scale trial will need a significant amount of time and resources, if it can be performed, it will further simulate a real-life full deployment of passive UHF RFID system for animal identification, and therefore creating a better understanding and developing user confidence in using the technology for applications of this sort.

2. *Mathematical modelling and scattering analysis*

   Through the research work presented in this thesis, it has been shown that commercial simulation software can be quite efficient and reliable when used to simulate an environment with metallic structures. However, for academic research purposes, it is also good to have a more theoretical analysis of electromagnetic fields behaviour in relation to the presence of metallic structures. Phenomena like diffraction and reflection can be analysed from a mathematical point of view.
using numerical methods, and the field scattering caused by metallic structures can be investigated. Metallic structures such as the metallic depressions considered in the research of this thesis can be further studied in the analysis. Other metallic structures such as metallic grids or protruding metallic parts of an object can also be considered.

3. Cost analysis
   While the tags presented in this thesis are designed to be as simple as possible with low cost material used to minimise the overall cost of the tags, it is of great interest to be able to calculate and estimate the actual cost of these tags if they are manufactured commercially in larger quantities. A common manufacturing knowledge is that the larger the quantity of the tags manufactured, the lower the tag cost will be. Therefore the first part of the cost analysis is to obtain relevant tag material and manufacturing cost information to predict how tag manufacturing cost varies with respect to the quantity of tags manufactured. The second part of the cost analysis will be to estimate the percentage of a product (or object) cost that can be allocated to RFID tagging to meet a feasible business profit margin. That calculation should take into account both costs and business benefits of having tagged items. Information on the desirable scale of tagging for a certain product will be obtained by combining the analysis from both parts. The calculation will provide the number of products to be tagged and the quantity of tags required to be manufactured, to meet a defined cost or benefit requirement.

4. Stacking policy
   The future research on stacking policy will involve the study on how objects, particularly those made of complex materials such as metal, should be stacked and arranged on shelves and packagings to allow all RFID tags (and hence objects) to be identified easily. Passive RFID tags will require the fields from an RFID reader antenna to power-up, hence RFID tagged objects must be arranged in a way that allows the fields from the reader antenna to reach the tags. When metallic objects are involved and they are required to be arranged in tiers and layers, one possible
8.2 Recommendations for Future Work

solution is to create gaps between the populations of tagged metallic objects to allow the fields from a reader antenna to propagate through the gaps and reach tags that are located at deeper layers. Hence, the amount of gap allocation required to allow sufficient field to reach to deeper layers at the back of a population of tagged objects can be analysed. Since the allocated gaps between metallic objects are like narrow passages surrounded by metallic walls, besides performing simulations using software, theoretical analysis incorporating waveguide theory can be done.

5. RFID reader antennas in metallic environment

To allow an RFID system to be effectively deployed in an environment containing metallic structures, another research area that can also be explored is the placement of RFID reader antennas near metallic structures. A reader antenna may be required to be placed in tight corners mostly surrounded by metallic surfaces, which may perturb the fields around the antenna. Analysis can be done to find the optimum placements of RFID reader antennas on places such as forklifts, along assembly and production lines in a factory and dock doors where metallic structures are commonly present. The approach to the analysis can be either theoretical (by means of calculations or simulations) or empirical (by means of experiments), or both.

6. Active tags for metallic object identification

In the research presented in this thesis, the focus is on using passive UHF RFID tags for metallic object identification because passive tags are generally smaller in size, require no maintenance and are potentially cheaper than active tags, hence making passive tags more feasible for item level tagging. Though this is the case, active tags can have additional functionalities (such as sensors), which may be required for some applications. Hence, a study on the performance of active tags when used on metallic surfaces or objects, can be beneficial in future work.
8.3 Summary of Original Contributions

The contributions to knowledge of the research work presented in this thesis have been discussed earlier in Chapter 1 (Section 1.3). They are summarised here as follow:

1. Performance of conventional commercial RFID tags on a metallic surface
   Experiments were performed to measure the read range performances of a number of conventional commercial passive UHF flexible adhesive label RFID tags placed on or near a metallic surface. The measurement results obtained confirm and strengthen knowledge of the severity of metallic surfaces in degrading the performance of conventional label-like passive UHF RFID tags. The results add to findings by other researchers in similar studies.

2. Resistance of z-axis conductive tape
   A z-axis conductive tape is commonly used for attaching a tag chip to a tag antenna when producing a tag prototype. A series of short experiments were designed and performed to measure the additional resistance introduced by a z-axis conductive tape (with respect to a tape amount enough for a tag chip attachment). Results from the experiments have shown that the additional tape resistance is small and hence will not put a significant effect on a tag performance.

3. A low cost small passive UHF RFID tag
   A novel passive UHF RFID tag was designed. This tag uses low cost material, is easy to manufacture and has a design that allows easy tag chip attachment and fine-tuning. The size of the tag is much smaller than many of the existing commercial passive UHF RFID tags. Even with a small tag antenna size (which means lower radiation resistance) and significant losses that are analysed to be mainly caused by the low cost dielectric substrate material used for the tag, the tag is still able to offer a good read range. The use of lower loss dielectric material would provide further improvement.

4. Passive UHF RFID for animal identification
   A study of the feasibility of using passive UHF RFID tags for animal identification was performed. The study was done in parallel with a study of using HF
8.3 Summary of Original Contributions

RFID tags for the same purpose, as both UHF and HF RFID systems can offer anti-collision capability compared with a LF RFID system currently employed for animal identification. Passive UHF RFID tags designed in the research of this thesis was used in the study. Results from a field trial involving a population of 10 pigs have shown that the UHF RFID tags have outperformed the HF RFID tags. The field trial is a first in Australia.

5. Tag with wide strip loop antenna

A small passive UHF RFID tag consisting a wide strip loop antenna suitable for attaching to metallic objects was designed. This tag operates by utilising the rich tangential components of magnetic fields present near a metallic surface. This is the first RFID tag for metallic objects that is based on such principle of operation. Theoretical calculations and fine-tuning methods for the designing of this tag are shown. This tag has achieved a promising read range performance when placed near a metallic surface. The research work on this tag explored the use of a tag antenna based on different principles of operation than are used in the more commonly employed patch antennas for metallic object identification.

6. Tag with patch antenna

Patch antennas are commonly used for RFID tags designed for metallic objects. An RFID tag consisting a rectangular patch antenna and a simple impedance matching implementation was designed. It was made using a low cost material. With a reasonable tag read range performance obtained, this work has demonstrated that a tag with a complex patch antenna design is not necessarily required. For smaller and more cost effective tags, the possible reduction of tag size without involving the use of expensive tag material and increasing the complexity of tag design was analysed. Results show that the read range performance of most of the reduced sized tags, though made worse by the size reduction, can still be acceptable to meet applications with lower read range requirements, involving small metallic objects, in a cost effective way.

7. Tag for metallic beverage can

A novel compact passive UHF RFID tag for metallic beverage cans was designed.
The tag was specifically made to be attached to the bottom of a common type metallic beverage can. With this tag design, alterations to the existing shape and design of the metallic beverage can was not required in order to accommodate the tag. This tag design is believed to be the first of its kind. The work on this tag has demonstrated the possibility of tagging small metallic objects, which is important to encourage full deployment of passive UHF RFID systems for item level tagging.

8. Effects of metallic depressions on tag performance

The effects of metallic depressions of various shapes, sizes and depths on the read range performance of a tag were analysed. A novel method combining theoretical calculations and simulations was developed to predict the read range performance of a tag designed earlier in the research of this thesis. The predicted read range performance has been shown to agree well with practical measured read range performance. There is still very limited research work that analyses the effects of metallic structures on tag read range performances. It is hoped that this work will be a foundation of more research to come in the RFID area concerning the study of the effects of various metallic structures.

8.4 Conclusions

This chapter summarises the research carried out in the duration of the Ph.D study. The original contributions of the work done in this research, as summarised, show that significant solutions have been drawn to meet the challenge of metallic object identification, particularly focusing on maintaining a balance between size, cost and performance. The work done in this research and the related future work recommended in this chapter will open more research possibilities in the RFID area on efficient metallic object identification, as well as on small size and cost effective RFID tags for general item level tagging.
From the HFSS simulation of the tag design discussed in Section 3.5, it was found that the simulated tag antenna gain was quite low compared with the simulated directivity. In the tag design calculations prior to the HFSS simulations, the tag was assumed lossless. However, this will not be the case in practice. Hence, the small gain to directivity ratio, which indicated an inefficient tag antenna, is most likely caused by the losses introduced by the dielectric substrate used and also the surface resistivity of the copper layer that the antenna was made of. This appendix provides an analysis to estimate the losses of the tag. The aim of this analysis is to obtain an idea of which is the major source (either one or both of the sources mentioned above) contributed to the losses. This analysis also provides a brief confirmation that the results obtained from HFSS simulation are of the correct order. It has to be noted that the results of this analysis are only an estimation in order to provide a general idea of the possible losses, and is not aiming at finding the accurate losses.

A.1 Dielectric Substrate Loss

The tag presented in Section 3.5 was implemented on a double-sided copper clad FR4 substrate with the loop antenna located on one side of the substrate and the impedance matching network on the other (See Figure 3.18). In this analysis, the losses contributed by the FR4 substrate are visualised as a circuit having a loss resistor in parallel to each of the capacitors ($C_1$ and $C_2$) of the impedance matching network. Using the general expression

$$r = \frac{1}{\omega C \tan\delta},$$

(A.1)
A.2 Surface Resistivity Loss

A loss resistance $r$ caused by the dielectric substrate with loss tangent $\tan\delta$ and corresponding to a capacitor $C$ can be estimated ($\omega = 2\pi f$ where $f$ is the operating frequency). Using (A.1), for a FR4 substrate with $\tan\delta = 0.02$, and $C_1 = 0.63 \ pF$ and $f = 915 \ MHz$, the corresponding loss resistance was calculated to be $r_1 = 13.8 \ k\Omega$. Similarly, for $C_2 = 6.5 \ pF$, the corresponding loss resistance was calculated to be $r_2 = 1.3 \ k\Omega$.

A.2 Surface Resistivity Loss

The surface resistivity $R_s$ of a copper with conductivity $5.8 \times 10^7 \ S/m$ was calculated to be about $7.89 \ m\Omega$ per square.

The average diameter of the loop antenna of the tag is approximately $22 \ mm$. This gives a loop antenna perimeter of $69 \ mm$. The width of the copper track of the loop antenna is $2 \ mm$. Hence, the loop perimeter to track width ratio $R$ was calculated to be $34.5$.

The product of $R_s$ and $R$ will give the loss resistance caused by the copper layer. Hence with the values calculated above, the loss resistance caused by the copper layer was calculated to be $0.27 \ \Omega$. Since there are two sides to the copper track, a parallel combination of two loss resistances (each contributed by one side of the track) gave a total loss of $r_c = 0.135 \ \Omega$. This loss is visualised as a circuit having a loss resistor in series with the inductor and radiation resistor of the loop antenna.

A.3 PSPICE Simulations

With the losses caused by the dielectric substrate and the surface resistivity estimated, the next step was to determine the amount power, out of the maximum available source power, that is delivered to the tag chip (load) for the cases with and without the estimated losses above taken into account. The ratio of the power (real) delivered to the tag chip to the maximum available source power gives the efficiency. For an ideal lossless tag circuit, the efficiency is expected to be $100\%$. For a tag circuit with
losses, the efficiency is expected to be less than 100%, and the drop in the efficiency depends on the amount of loses.

The circuit representing the tag was simulated using the software PSPICE. A known voltage source was included in the circuit and the voltage across the tag chip resistor $R_c$ was measured from PSPICE simulation in order to allow the calculation of the power (real) delivered to the tag chip.

The PSPICE simulation schematic for the case of an ideal lossless circuit is shown in Figure A.1. For the case of an ideal lossless circuit, the amount of power (real) delivered to the tag chip over the maximum available source power (in short, efficiency) was found to be 96.8%. The fact that it falls short of 100% can be attributed to rounding of component or frequency values, and the fact that the impedance match is inherently narrow band. Nevertheless, the efficiency is still very close to 100% and is as expected.

![Figure A.1. PSPICE simulation schematic - Case 1. Case 1: Ideal lossless circuit.](image)

The PSPICE simulation schematic for the case with just the losses of the dielectric substrate corresponding to capacitor $C_1$ and $C_2$ of the impedance matching network added, but not the loss by the copper, is shown in Figure A.2. For this case, the efficiency was found to be 1.6 %.
A.3 PSPICE Simulations

Figure A.2. PSPICE simulation schematic - Case 2. Case 2: Circuit with losses of dielectric substrate added.

The PSPICE simulation schematic for the case with all the losses calculated above included in the circuit is shown in Figure A.3. For this case, the efficiency was found to be 1.5%.

Figure A.3. PSPICE simulation schematic - Case 3. Case 3: Circuit with losses of dielectric substrate and copper added.
Hence, from these results, it can be seen that the dielectric substrate is the main contributor of the losses in the tag. The simulated gain and directivity from HFSS was found to be 0.13 and 1.53 respectively. Based on these values, the efficiency is about 8.5%. The efficiency resulted from this analysis is slightly different from that from HFSS simulation. This is because the analysis here is giving just an estimation of the possible losses in a tag, whereas HFSS can be more accurate and takes into account of more factors such as the actual physical shape of the tag implementation. Nevertheless, the order of the estimated efficiency through this analysis is of the same as that obtained through HFSS simulations, which confirms the observation in HFSS.
Appendix B

Simulation Results for Patch Antennas of Various Widths

B.1 Tag Antenna in Free Space

Below are the simulation results corresponding to the tags each with a half wavelength patch antenna of different width \((W_{\text{patch}})\) discussed in Chapter 5:

**Table B.1.** Summary of simulation results for tags each with a half wavelength patch antenna of different width \((W_{\text{patch}})\). Tags were simulated in free space.

<table>
<thead>
<tr>
<th>Patch width, (W_{\text{patch}}) (mm)</th>
<th>Antenna impedance, (Z_a) (Ω)</th>
<th>Peak directivity</th>
<th>Peak gain</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>(14 + j141)</td>
<td>2.41</td>
<td>0.30</td>
<td>12.4</td>
</tr>
<tr>
<td>29</td>
<td>(18 + j146)</td>
<td>2.67</td>
<td>0.37</td>
<td>13.9</td>
</tr>
<tr>
<td>39</td>
<td>(18 + j143)</td>
<td>2.81</td>
<td>0.42</td>
<td>14.9</td>
</tr>
<tr>
<td>49</td>
<td>(17 + j138)</td>
<td>2.93</td>
<td>0.46</td>
<td>15.7</td>
</tr>
<tr>
<td>59</td>
<td>(18 + j147)</td>
<td>3.13</td>
<td>0.49</td>
<td>15.7</td>
</tr>
<tr>
<td>69</td>
<td>(18 + j148)</td>
<td>3.13</td>
<td>0.48</td>
<td>15.3</td>
</tr>
<tr>
<td>79</td>
<td>(17 + j148)</td>
<td>3.28</td>
<td>0.51</td>
<td>15.5</td>
</tr>
<tr>
<td>89</td>
<td>(16 + j153)</td>
<td>3.41</td>
<td>0.38</td>
<td>11.1</td>
</tr>
<tr>
<td>99</td>
<td>(16 + j144)</td>
<td>3.55</td>
<td>0.48</td>
<td>13.5</td>
</tr>
</tbody>
</table>
B.2 Tag Antenna on Metallic Plane

Below are the simulation results corresponding to the tags each with a half wavelength patch antenna of different width ($W_{\text{patch}}$) discussed in Chapter 5:

Table B.2. Summary of simulation results for tags each with a half wavelength patch antenna of different width ($W_{\text{patch}}$). Tags were simulated on a $1.5\lambda \times 1.5\lambda$ metallic plane.

<table>
<thead>
<tr>
<th>Patch width, $W_{\text{patch}}$ (mm)</th>
<th>Antenna impedance, $Z_a$ (Ω)</th>
<th>Peak directivity</th>
<th>Peak gain</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>$12 + j139$</td>
<td>4.51</td>
<td>0.33</td>
<td>7.3</td>
</tr>
<tr>
<td>29</td>
<td>$18 + j144$</td>
<td>4.70</td>
<td>0.45</td>
<td>9.6</td>
</tr>
<tr>
<td>39</td>
<td>$15 + j136$</td>
<td>4.75</td>
<td>0.54</td>
<td>11.4</td>
</tr>
<tr>
<td>49</td>
<td>$15 + j132$</td>
<td>4.66</td>
<td>0.61</td>
<td>13.1</td>
</tr>
<tr>
<td>59</td>
<td>$18 + j145$</td>
<td>4.59</td>
<td>0.67</td>
<td>14.6</td>
</tr>
<tr>
<td>69</td>
<td>$20 + j142$</td>
<td>4.72</td>
<td>0.71</td>
<td>15.0</td>
</tr>
<tr>
<td>79</td>
<td>$17 + j144$</td>
<td>4.76</td>
<td>0.77</td>
<td>16.2</td>
</tr>
<tr>
<td>89</td>
<td>$26 + j157$</td>
<td>4.97</td>
<td>0.74</td>
<td>14.9</td>
</tr>
<tr>
<td>99</td>
<td>$16 + j143$</td>
<td>4.93</td>
<td>0.74</td>
<td>15.0</td>
</tr>
</tbody>
</table>

B.3 Remarks

- For the case when the tags are located on a $1.5\lambda \times 1.5\lambda$ metallic plane, the peak directivity and peak gain values at the direction of maximum radiation could be at an angle not normal to the patch antenna plane.

- For a wide patch antenna, there is a significant improvement in gain by introducing the $1.5\lambda \times 1.5\lambda$ metallic ground plane, but for a narrow patch antenna there is only a very slight improvement in gain brought about by the ground plane. The reasons for this are unclear, but may include the fact that the $1.5\lambda \times 1.5\lambda$ metallic ground plane being aluminium has less conductivity than the copper ground
Appendix B  Simulation Results for Patch Antennas of Various Widths

plane of the patch antenna, and is relied on more with a narrow patch antenna than with a wide patch antenna.

- Nevertheless, the $1.5\lambda \times 1.5\lambda$ metallic ground plane has improved the directivity especially for a narrow patch antenna. This can be attributed to the suppression of backward radiation, which is more severe for a narrow patch antenna.
Appendix C

Additional Result Plots for Tag in Metallic Depressions

C.1 Prediction of Read Range

C.1.1 Ratio \( \frac{(1 - p_{\text{loss},m})}{(1 - p_{\text{loss},fs})} \)

\[ \frac{(1 - p_{\text{loss},m})}{(1 - p_{\text{loss},fs})} \]

Figure C.1. Ratio \( \frac{(1 - p_{\text{loss},m})}{(1 - p_{\text{loss},fs})} \) corresponding to a tag in a circular depression. The ratio is calculated using simulated tag antenna impedance values and a chip impedance value of \( Z_{\text{chip}} = 12 - j132 \ \Omega \). The coloured lines correspond to different depths \( h \) of the depressions, as shown in the legend above the graph.
C.1 Prediction of Read Range

Figure C.2. Ratio \( \frac{1 - p_{\text{loss,m}}}{1 - p_{\text{loss,fs}}} \) corresponding to a tag in a square depression (Orientation 1). The ratio is calculated using simulated tag antenna impedance values and a chip impedance value of \( Z_{\text{chip}} = 12 - j132 \, \Omega \). The coloured lines correspond to different depths \( h \) of the depressions, as shown in the legend above the graph.

Figure C.3. Ratio \( \frac{1 - p_{\text{loss,m}}}{1 - p_{\text{loss,fs}}} \) corresponding to a tag in a square depression (Orientation 2). The ratio is calculated using simulated tag antenna impedance values and a chip impedance value of \( Z_{\text{chip}} = 12 - j132 \, \Omega \). The coloured lines correspond to different depths \( h \) of the depressions, as shown in the legend above the graph.
Figure C.4. Ratio \( \frac{1 - p_{\text{loss,m}}}{1 - p_{\text{loss,fs}}} \) corresponding to a tag in a rectangular depression (Orientation 1). The ratio is calculated using simulated tag antenna impedance values and a chip impedance value of \( Z_{\text{chip}} = 12 - j132 \ \Omega \). The coloured lines correspond to different depths \( h \) of the depressions, as shown in the legend above the graph.

Figure C.5. Ratio \( \frac{1 - p_{\text{loss,m}}}{1 - p_{\text{loss,fs}}} \) corresponding to a tag in a rectangular depression (Orientation 2). The ratio is calculated using simulated tag antenna impedance values and a chip impedance value of \( Z_{\text{chip}} = 12 - j132 \ \Omega \). The coloured lines correspond to different depths \( h \) of the depressions, as shown in the legend above the graph.
C.1 Prediction of Read Range

C.1.2 Ratio $R_{r,m} / R_{r,fs}$

![Graph showing the ratio $R_{r,m} / R_{r,fs}$ for different depression diameters.](image)

**Figure C.6.** Ratio $R_{r,m} / R_{r,fs}$ corresponding to a tag in a circular depression. The ratio is calculated using simulated tag antenna impedance values. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

![Graph showing the ratio $R_{r,m} / R_{r,fs}$ for different depression lengths.](image)

**Figure C.7.** Ratio $R_{r,m} / R_{r,fs}$ corresponding to a tag in a square depression (Orientation 1). The ratio is calculated using simulated tag antenna impedance values. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.
Appendix C  Additional Result Plots for Tag in Metallic Depressions

Figure C.8. Ratio $R_{r,m} / R_{r,fs}$ corresponding to a tag in a square depression (Orientation 2). The ratio is calculated using simulated tag antenna impedance values. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

Figure C.9. Ratio $R_{r,m} / R_{r,fs}$ corresponding to a tag in a rectangular depression (Orientation 1). The ratio is calculated using simulated tag antenna impedance values. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.
C.1 Prediction of Read Range

Figure C.10. Ratio $R_{r,m} / R_{r,fs}$ corresponding to a tag in a rectangular depression (Orientation 2). The ratio is calculated using simulated tag antenna impedance values. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

C.1.3 Ratio $|H|_{\text{min},m} / |H|_{\text{min},fs}$

Figure C.11. Ratio $|H|_{\text{min},m} / |H|_{\text{min},fs}$ corresponding to a tag in a circular depression. The plot shows that the variation of this ratio with respect to the change in size and depth of the depression is minimal. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.
Figure C.12. Ratio $|H|_{\text{min,m}} / |H|_{\text{min,fs}}$ corresponding to a tag in a square depression (Orientation 1). The plot shows that the variation of this ratio with respect to the change in size and depth of the depression is minimal. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

Figure C.13. Ratio $|H|_{\text{min,m}} / |H|_{\text{min,fs}}$ corresponding to a tag in a square depression (Orientation 2). The plot shows that the variation of this ratio with respect to the change in size and depth of the depression is minimal. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.
C.1 Prediction of Read Range

Figure C.14. Ratio $|H_{\text{min},m}|/|H_{\text{min},fs}$ corresponding to a tag in a rectangular depression (Orientation 1). The plot shows that the variation of this ratio with respect to the change in size and depth of the depression is minimal. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.

Figure C.15. Ratio $|H_{\text{min},m}|/|H_{\text{min},fs}$ corresponding to a tag in a rectangular depression (Orientation 2). The plot shows that the variation of this ratio with respect to the change in size and depth of the depression is minimal. The coloured lines correspond to different depths $h$ of the depressions, as shown in the legend above the graph.
Bibliography


Bibliography


### Bibliography


