

THEIA: RADIO FREQUENCY IDENTIFICATION
PERFORMANCE ANALYSIS TOOL

by

JASON FRANCIS PEREIRA

Presented to the Faculty of the Graduate School of
The University of Texas at Arlington in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON

December 2009

Copyright © by JASON FRANCIS PEREIRA 2009
All Rights Reserved

To my parents Joe and Evelyn, for all their love and support

To my professor Daniel Engels, who kept moving the cheese.

To all my friends for sticking by me along the way.

For those who ask the question, the answer is 42

ACKNOWLEDGEMENTS

I wish to express my gratitude to my professor and friend Dr. Daniel Engels, for his encouragement and support, for giving me the opportunity to be a little “crazy”. Daniel and I had many long conversations which always gave me a deep insight and motivation, which kept me going throughout my research. He has always inspired and motivated me to reach excellence. I hope that at least this one page is “Bloody Shakespeare”. I wish to thank him again, for being my guide, a mentor and most importantly, a friend.

I would also like to thank Dr. Stephen Gibbs for being my supervising professor and Dr. Jonathan Bredow for being on my committee.

I wish to thank my father Joe and my mother Evelyn, for their love and encouragement. My sister Jessalyn for always keeping me on my toes.

My friends in the RFID Lab, Amit, Kirti, Sheshadri, Rushikesh, Tanvi, Sai, Pranav, Nikhil and Gaurav for their constant help and support. To all my other friends who have helped me by being there for me, I will be forever grateful.

I wish to express my gratitude to the godfather and the officers of Lambda Epsilon Omega. May your values and goals live forever.

November 20, 2009

ABSTRACT

THEIA: RADIO FREQUENCY IDENTIFICATION PERFORMANCE ANALYSIS TOOL

JASON FRANCIS PEREIRA, M.S.

The University of Texas at Arlington, 2009

Supervising Professor: Daniel Engels

In recent years there has been an increase in the adoption of Radio Frequency Identification or RFID systems for most applications that deal with investment (products/people) tracking. The ideal requirements of investment tracking systems are :- lost-cost, zero maintenance and efficiency.

Although the applications are similar in nature, the scenarios and operating environments are not. This is a problem that plagues an inexperienced consumer of RFID systems. RFID systems are application specific and hence have to be properly customized to the application environment. One solution to this problem is to have the installation set up by an expert, but this is impractical due to recurring costs for each time the system is disturbed. This hinders the spreading of RFID technology. The other potential solution is to design a methodology that can be used by any RFID consumer that allows the user to gauge the efficiency of the installation of the RFID system.

This thesis focuses on determining the efficiency of the RFID system; more specifically an Ultra High Frequency RFID system. This research deals with the creation of a software that would transform a common UHF RFID reader (Sirit INfinity 510) into an RFID performance analysis tool, hence allowing a user to easily and readily determine the environmental conditions of the application that pertain to the RFID system installation.

Also presented is a metric for identifying the performance of a UHF RFID reader installation. This Reader Metric will indicate the generic read capability of a UHF RFID reader for the given reader installation.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	iv
ABSTRACT	v
LIST OF FIGURES	x
LIST OF TABLES	xiii
Chapter	Page
1. INTRODUCTION	1
1.1 Motivation	1
2. RADIO FREQUENCY IDENTIFICATION: <i>THE BASICS</i>	4
2.1 Introduction	4
2.2 A Brief History Of RFID	5
2.3 Components Of RFID Systems	8
2.3.1 The Reader	10
2.3.2 The Tag	13
2.3.3 The Information System	17
2.3.4 The RFID System	18
2.3.5 Summary	22
3. ELECTROMAGNETICS	24
3.1 Introduction	24
3.2 Fundamentals Of Electro-magnetics	26
3.2.1 The Electric Field	27
3.2.2 The Magnetic Field	28
3.2.3 Maxwell's Equations	29

3.3	Polarization	32
3.4	Laws Governing Electromagnetics	33
3.4.1	Coulomb's Law	33
3.4.2	Faraday's Law	34
3.4.3	Ampere's Law	34
3.4.4	Gauss' Law of Electric Flux and Magnetic Flux	35
3.5	Antennas	35
3.5.1	The Ideal Dipole	37
3.5.2	The Ideal Loop	39
3.6	Impedance	41
3.7	Coupling in the Far-Field	43
3.7.1	Antenna Parameters	44
3.7.2	Transmission and Reception	46
3.8	Environmental Influences	55
3.8.1	Far-Field Loss and Multipath	56
3.8.2	Other Antennas	58
3.8.3	Temperature and Humidity	58
4.	THEIA: RFID PERFORMANCE ANALYSIS TOOL	60
4.1	Introduction	60
4.2	The Sirit INfinity 510 Reader	62
4.3	The Graphical User Interface (GUI)	66
4.3.1	The Home Page	67
4.3.2	The Control Page	69
4.3.3	The Sweep Page	72
4.3.4	The Backscatter Analysis <i>a.k.a</i> The Power Sweep	75
4.4	Software Architecture	79

4.4.1	Class MainUI : Form	81
4.4.2	Class Event Handler : Form	82
4.4.3	Class Spectrum Analyzer : Form	83
4.4.4	Class CnxMgr	84
4.4.5	Class Excel	84
5.	RESEARCH METHODOLOGY	86
5.1	Introduction	86
5.2	Metric	86
5.2.1	The Gold Standard	88
5.2.2	The Gold Machine	91
5.3	The Reader Metric	95
6.	EXPERIMENTS AND RESULTS	100
6.1	Introduction	100
6.2	The Experiments	104
6.2.1	Experiment Zero	105
6.2.2	Experiment 1	106
6.2.3	Experiment 2	109
6.2.4	Experiment 3	113
7.	CONCLUSION	115
7.1	Conclusion	115
7.2	Future Work	116
8.	GLOSSARY OF TERMS	117
	REFERENCES	119
	BIOGRAPHICAL STATEMENT	125

LIST OF FIGURES

Figure	Page
2.1 The History Of RFID	7
2.2 The Main Components Of An RFID System	8
2.3 Squiggle Tag by Alien Technology	14
2.4 Bow-Tie Tag by Avery Dennison	14
2.5 The communication between Reader and Tag	15
2.6 The hand-shake between Reader and Tag	16
2.7 An RFID Tag	17
2.8 A “Basic Functionality” RFID tag	21
2.9 The RFID Network Model	21
3.1 The Electromagnetic Spectrum	24
3.2 The Radio Frequency Identification EM Spectrum	25
3.3 The Electro-Magnetic Wave	26
3.4 The Electric Field	27
3.5 The Magnetic Field	29
3.6 Polarized EM wave and Non-polarized EM wave	32
3.7 Various Polarized EM Waves	33
3.8 The Ideal Antennas	36
3.9 Impedance Plots for Ideal Dipole and Ideal Loop	42
3.10 Equivalent circuit of a far-field tag	47
4.1 Theia	60
4.2 The INfinity 510 UHF RFID Reader	62

4.3	INfinity 510 Power and I/O Connections	63
4.4	INfinity 510 LED Indicators	63
4.5	Power Consumption vs. Conducted Output Power	64
4.6	The Home Page	67
4.7	The Home Tab (Showing login and reader selection)	69
4.8	The Control Page	70
4.9	The various functionality tabs of the Control Page	71
4.10	The Event Channel Page	71
4.11	The Spectrum Analyzer	72
4.12	The Frequency Sweep Tab	73
4.13	Flowchart of the Frequency Sweep	74
4.14	The Power Sweep Tab	75
4.15	Flowchart of the Power Sweep	76
4.16	The Sweep Pages	77
4.17	The Frequency Sweep Page for Tag/Reader Metric calculation	78
4.18	The Power Sweep Page for Tag/Reader Metric calculation	79
4.19	The Reader Metric calculation	79
4.20	The INfinity 510 Communication Channels	80
5.1	The Main Components Of An RFID System	87
5.2	The Voyantic Tagformance Lite System GUI	92
5.3	The Voyantic Tagformance Lite Views	92
6.1	Repeatability Test (Frequency Sweep) on Alien Squiggle Tag using Voyantic System	106
6.2	Stand-Alone Squiggle Tag and Bow Tie Tag Frequency Sweep	107
6.3	Stand-Alone Squiggle Tag and Bow Tie Tag Power Sweep results	108
6.4	Alien Squiggle Tag Frequency Sweep results for multiple products	109

6.5	Alien Squiggle Tag Power Sweep results for multiple products	110
6.6	Bow-Tie Tag Frequency Sweep results for multiple products	111
6.7	Bow-Tie Tag Power Sweep results for multiple products	112
6.8	Bow-Tie Tag Frequency Sweep for Paper Towel	113
6.9	Bow-Tie Tag Power Sweep for Paper Towel	114

LIST OF TABLES

Table	Page
2.1 The ISO OSI network reference model	20
3.1 Log-distance Path Loss Model	58
4.1 Reader Specifications	64
4.2 Environmental Specifications	65
4.3 Power Supply Specifications	65
4.4 Ethernet LAN Specifications	65
4.5 Antenna Specifications	66
4.6 The Login Information	68
5.1 Carrier and Modulation Signals specifications	93
5.2 Backscattered Signal Waveform Parameters	93
5.3 Protocol Specifications	94
6.1 The Tag Metric: Squiggle Tag & Bow Tie Tag (Stand-Alone)	107
6.2 The Tag Metric: Squiggle Tag & Bow Tie Tag (Multiple Products)	112

CHAPTER 1

INTRODUCTION

1.1 Motivation

The need for quick, complete and efficient management of global supply chains across the vast trading partner networks in organizations has given birth to the need for Automatic Identification systems. Automatic Identification (or Auto ID for short) of objects includes a host of technologies like bar-codes, smart cards, optical character recognition, Radio Frequency Identification (RFID) and so on. The most prevalent of these various technologies are bar-codes, which have been around since the late 1960s [13]. The recent advances in silicon chip manufacturing technologies have caused drops in the cost of manufacturing and thus have given rise to an increase in popularity in RFID technologies. RFID technology represents a near perfect level of supply chain efficiency. The fact that RFID technology has no line-of-sight requirement and as well as offers far more in depth and near real-time logistics control and transparency and also allows for a method for automation of other tasks makes RFID a very viable solution both for today's and especially for tomorrow's world/s.

Realizing the acute advantages of RFID a majority of large retailers and government agencies like the Department Of Defense (DoD) issued mandates and recommendations to their suppliers to use RFID [1]. Other organizations both public and private also started encouraging the adoption of RFID because of its potential, case in point The Food and Drug Administration (FDA) asked pharmaceutical companies to use RFID [2]. These mandates and requests caused RFID to become important

to a large number of people. An estimated 14,000 companies supplying a major retailer and 50,000 suppliers to DoD had to meet aggressive time lines set by these mandates and recommendations. But, since only a few of the affected companies had the necessary in-house RF expertise to deploy the technology, noticing only the acute advantages and being obtuse about the nuances of RFID technology, lead to confusion and non-efficient systems and in some cases completely non-working RFID systems. This was not because of RFID technology but due to the time deadlines and misleading claims from RFID vendors which resulted in the wrong type of RFID systems being deployed for the task/s at hand. Thus, the majority of the companies generally resorted to outside expertise for information and help, but even as late as 2004, there were still not enough third party solution-providers with access to good information. Hence, the companies that were mandated resorted to employing the RFID vendors to investigate RFID performance in their respective environment/s. But, when companies employ vendors, there is a very obvious risk of getting biased information. For example, a leading RFID tag vendor states on a web page that “Today’s RFID tags have read rates varying from as low as 20 tags/second to over 1000 tags/second” [1]. This claim is, if looked at in the best light misleading. Even today, although there exist better third party solutions, still the risk of bias exists. Hence there is a need for unbiased, good and reliable source of information for RFID systems.

For the adoption of RFID for various applications, most importantly in supply chain management, comes the need for the choice of which high performance RFID systems should be used and in order to make this choice the end-user must have a reference of the performance capabilities of this system he is planning to use. Thus, for RFID to be easily adoptable for any situation, there **must** be a method of comparison

that defines the systems performance capabilities, under the conditions where it will be deployed.

The most cost effective (and hence highly attractive to RFID adopters) of the various RFID systems as well as the most long lasting is the passive RFID system. Passive UHF systems constantly have to operate in the edge of communications capability. This is not a problem for HF and LF RFID systems, since they communicate in the near-field, hence the interrogation zone is well defined with almost constant power level everywhere within the zone. UHF RFID systems on the other hand communicate in the far-field region and thus have large interrogation zones that depend heavily on the environment, and where inevitably there exist areas where the signal is weak. As mentioned earlier, provided time deadlines for the adoption of any RFID technology in place of whatever the currently used technologies based on the mandates have resulted in confusion among RFID end-users as well as potential RFID technology adopters. This holds true for passive UHF systems just as much and even more so as can be inferred from the above statements. Thus, for the increased adoption of Passive UHF RFID system, the system has to be optimized in both cost and efficiency. It is the focus of this thesis to create both the tools and methodology of using these tools to generate a ***“Reader Metric”*** that will characterize the performance of a UHF Gen2 RFID reader.

CHAPTER 2

RADIO FREQUENCY IDENTIFICATION: *THE BASICS*

2.1 Introduction

Since the dawn of mankind, information has been man's greatest pursuit; **“knowledge is power”**. It has been demonstrated that with the ready access to information of what products they have available, manufacturers, distributors, retailers and any other units in a supply chain have increased efficiency and consequently created tremendous savings[40].

With the turn of the millenium, came the prevalence of the internet which has given us instant access to a repository of collective worldwide knowledge. The age of information is now at the crux of its next evolution, the need to transform every physical object into its virtual counterpart. This transformation of physically embodied information to the virtual plane thus allowing human and machine access to the information presents a problem. The current solutions to this problem normally require manual intervention, which is plagued with by inefficiency and inaccuracy of information. Some other solutions require machines with sophisticated and complex vision and sensing systems. These solutions are often expensive, even for collecting basic information.

One potential solution to this problem is Radio Frequency Identification (RFID). Through the attachment of transponders (Tags) to physical objects and an infrastructure of networked reading devices (Readers), physically embodied information can automatically recorded.

Radio frequency identification systems allow for a non line-of-sight identification of an object based on the identification code assigned to the object, which is stored in the tag. This code is stored in the tag in a microchip which is attached to an antenna. An interrogator or Reader communicates with the tag, thus obtaining this information.

A class of RFID systems, Passive RFID, allows wireless powering of these tags (transponders). Passive RFID systems are a potential low cost and highly less constrained automatic data capturing system. This capability of offering lower costs and reduced operational constraints comes at a price; the constraints are now transformed into fundamental design and setup constraints. It is an objective of this thesis to discuss the creation of an RFID Performance Analysis tool and to present the methodology to use this tool to generate a numerical metric that will define the performance of the UHF RFID reader.

2.2 A Brief History Of RFID

RFID by definition has existed since for at least the past the fifty years, since World War II [46][13][23]. The Allies used a technology called Identify Friend or Foe (IFF). IFF used basic transponders installed in aircrafts. These transponders were capable of responding with an appropriate identification signal when interrogated by a signal, thus allowing the allies to identify if the aircraft asking to land was one of their own. This technology has undergone continued development and its current avatar is used in both the civilian and defense sectors and can be considered the forerunner of RFID.

RFID, as we know it today, is highly developed since its inception in World War II. This change was brought about as a means for the armed forces to safely and securely track military equipment and personnel. During the late 70's RFID technology was introduced to the private sector through Los Alamos Scientific Laboratories. The initial uses of RFID in the civilian sector included identification and temperature sensing of cattle and tracking and identification of railroad cars [57].

The early uses of RFID typically used the UHF band of frequencies *viz* 900MHz\1.9GHz. Over the course of the 80's several companies based out of the United States and Europe developed RFID technologies and systems that operated at lower frequencies, had different power sources and more memory and higher functionalities (compared to basic identification).

Towards the end of the 80's and beginning of the 90's, as large semiconductor companies became involved there was a shift towards smaller sizes, performance improvement and most importantly cost reduction.

As performance improved over the course of the 90's with subsequent cost reduction, new applications emerged. These new applications include automatic toll tags, access control and security, airline baggage handling, inventory management, asset tracking, vehicle immobilizers and the closely related smart cards [57][66][59][28].

With the wide scale development of RFID around the world there arose a need to establish rules and regulations that govern RFID. Currently, there are constant efforts to develop new standards as well as establish new standards where improving the old do not suffice or where new applications emerge. The negative aspect of standards is that standards tend to decelerate continued improvements in RFID technology and

hinder innovation. But, standards allow for increased adoption of RFID along with reduced costs.

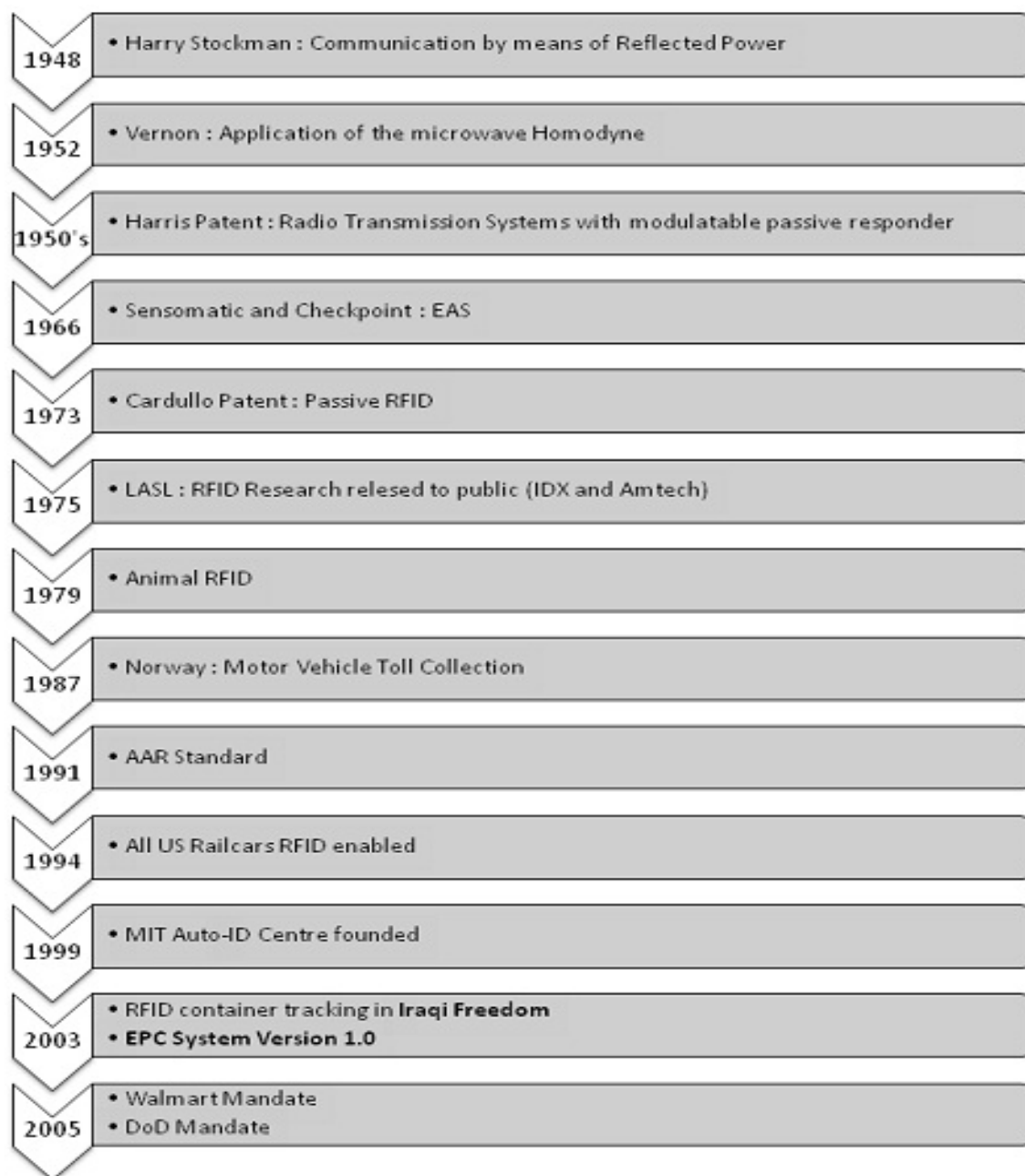


Figure 2.1. The History Of RFID.

2.3 Components Of RFID Systems

All RFID systems, varied as they may be in their applications can be reduced to a typical RFID system and as such this typical RFID system consist of three main components:-

1. The Reader
2. The Tag
3. The Information System & Middleware

The **Tag** is attached to the object that needs to be autmatically identified. The **Reader** is placed at locations where the object needs to be identified. The object is identified by reading the tag's identification number and looking up the identification number in the **Information System** (Figure 2.2).

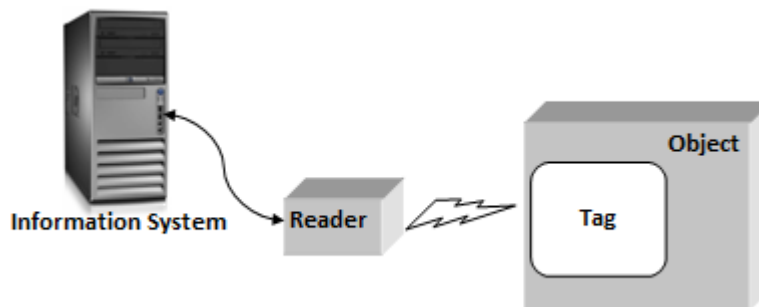


Figure 2.2. The Main Components Of An RFID System.

As RFID systems have matured, several types of systems have emerged and thus RFID systems can be classified in a myriad of ways. As mentioned earlier, all RFID systems have a reader, tags and an information system. While readers are attached to particular enviroments,tags are attached to objects and thus are burdened with the most stringent specifications. These specifications are related to performance,

size and cost and thus the various classifications of RFID systems are based around these specifications. The highest level of classification of tags is based on whether the tag is Chip or Chipless. Chip tags have an integrated circuit chip, whereas Chipless tags do not. In this thesis we will deal only with Chip tags and hence from now on throughout this thesis when I refer to RFID systems I mean Chip Tag RFID systems.

RFID systems are classified in many ways but the two fundamental classes which differentiate RFID systems are:

- Operational Frequency
- Type Of Communication

These can be further subdivided as follows:-

- Type Of Communication
 1. Passive
 2. Semi-Passive
 3. Active

Passive communication tags have no on-tag power source and no active transmitter, semi-passive communication tags have an on-tag power source, active communication tags have both on-tag power source and active transmitters.

- Operational Frequency
 1. Low Frequency (LF): 9kHz ~ 135kHz
 2. High Frequency (HF): 13.56MHz & 433MHz
 3. Ultra High Frequency (UHF): 860MHz ~ 960MHz
 4. Super High Frequency (SAW): 2.45GHz

The operation of the RFID system is decided by the frequency i.e Near field or Far field communication. Typical LF and HF RFID systems are near field communication systems, where the electromagnetic fields are reactive and quasi-static in nature and information transfer takes place by either inductive or capacitive coupling. UHF and SAW RFID systems are on the other hand far field communication systems where information transfer is achieved using transmission, propagation and reception of electromagnetic waves.

Since this thesis deals only with UHF RFID systems I will explain the functioning of these components of RFID systems along those lines. A more detailed discussion of near field and far field communication along with various other electromagnetic communication concepts can be found in Chapter 2.

2.3.1 The Reader

The RFID reader is a device that reads the information stored in an RFID tag, and then communicates it to the information system/middleware. Readers mainly consist of an antenna, a control unit and a radio frequency module [25]. Readers interrogate tags by setting up a communication channel with tags. This communication channel is established by using the antenna/s to couple with the received radio waves (electromagnetic waves). Essentially, coupling can be explained as, the antenna is designed so as to absorb/transfer maximum energy from either the electrostatic or magnetic part of the energy/electromagnetic wave.

The reader generates either amplitude modulated RF waves or frequency modulated RF waves or both depending on the type of RFID system. The antenna emits these modulated data-carrying signals in order to query the tag. The reader also acts

as an RF receiver which listens for the tag response. The received response signal from the tag is decoded, and this information is sent to the information system for further processing.

The placement of readers has to be strategic in nature i.e. depending on the application. For example, for an access control system application, the readers are placed at entry/exit points to secure areas, while for a sports timing application, readers are located at both start and finish lines for the event. Readers continuously emit interrogation signals. This interrogation signal creates an interrogation zone. Only the tags that are within the interrogation zone are read. The actual size of the interrogation zone is not just a function reader characteristics but of both tag and reader characteristics. Generally, the greater the power of the transmitted signal (interrogation signal) and the higher the frequency of operation (interrogation signal frequency), the larger is the interrogation zone. In most of my test cases, I have noticed that in the case of passive UHF RFID tags, the transmitted signal power is the more dominant factor in determining the size of the interrogation zone. In the case of active tags however, this drawback is overcome. Active tags typically have far larger read ranges than equivalent passive tags.

Since RFID became a worldwide technology, there were regulatory conditions imposed on the technology. These regulations were decided upon by certain regulatory bodies specific to the region of implementation of RFID technology. In Europe the regulatory body is ETSI (European Telecommunications Standards Institute), in the United States the body is FCC (Federal Communications Commission) [27][26]. The regulatory bodies specify the governing standards like security, spectrum allocation and safe power levels to name a few.

The FCC specifies that a radio device that operates in the ISM band 902MHz - 928MHz in the United States (*viz.* UHF RFID) is required to frequency hop every 0.4 seconds [27]. In Europe the ETSI specifies that an RFID reader is required to listen for any communication in the specified frequency range before initializing their communication. This is known as Listen Before Talk (LBT) [26]. These regulations impose restrictions on the RFID reader and hence affect the performance parameters of an RFID system, like maximum operable range and back-scatter signal strength significantly.

Since the operation of an RFID systems is highly restricted it is very important that every aspect of the system design is as efficient as possible. An important part of the reader system is the antenna. The antenna plays a vital role in the transmission and reception of the electromagnetic waves, hence the reader antenna must have high gain and directivity. Commonly used antennas for a UHF RFID reader are patch antennas [14][43]. The directivity of an antenna is defined as the ratio the radiation intensity in a given direction from the antenna to the radiation intensity averages over all direction [17]. In simple terms, the directivity of an antenna is quite literally what it says it makes the antenna more sensitive in a certain direction. It is very important to have highly directional antenna for both transmission and reception as the signal transmitted and received by the reader needs to be focused on a specific area for reasons that include increased read range, localization of the tag in 3D space and decrease in spurious/ghost reads. Another important parameter of an antenna is the gain. Although gain of an antenna is closely related to the directivity, it is a parameter that takes into account the efficiency of the antenna as well as its directional capabilities. This can be mathematically stated as shown in Equation 2.1.

$$gain = \frac{Efficiency}{Directivity} \quad (2.1)$$

Another definition of gain is in terms of the radiation intensity and the total input power, generally referred to as absolute gain. Equation 2.2 shows the mathematical form of gain.

$$gain = 4\pi \frac{radiationintensity}{totalinput(accepted)power} = 4\pi \frac{U(\Theta, \Phi)}{P_{in}} \quad (2.2)$$

In order to increase the gain of an antenna, separate transmit and receive antennas can be used for the reader, this is referred to as a bi-static antenna system, while a single antenna cycling through transmit and receive cycles is referred to as a mono-static antenna system.

Polarization of the antenna is yet another important parameter. The reader antenna polarization and tag antenna polarization must match for communication to take place. These concepts of antennas and electromagnetic communication are further discussed in Chapter 2.

The control unit of a reader is nothing more than a processing system that implements the various higher-level functions which in turn are constituted of lower-level operations. Thus, the front-end of a reader communicates with a tag/s while the back-end communicates with the information system.

2.3.2 The Tag

The tag or transponder is attached to the object that is to be tracked or traced. RFID tags mainly consist of an antenna and a microchip (*a.k.a* integrated circuit chip). Based on the functioning of the tag and/or the object that is tagged they are allocated into five classes :-

1. Passive Tags

2. Passive Tags with Sensors
3. Semi-Passive Tags
4. Active/Ad-Hoc tags
5. Readers

The first four of the above mentioned classes of tags are more thoroughly discussed in later sections (RFID Communication Types). The reason a reader is also included in this classification is that a reader is essentially a tag with access to an information system.



Figure 2.3. Squiggle Tag by Alien Technology.

Tags “talk” to the reader by encoding/decoding the RF signal. The tag antenna performs the function of coupling to the EM field generated by the reader antenna, and thus establishes a wireless channel of communication. The microchip controls the functioning of the antenna as well as executing the hardcoded communication algorithm thus allowing data transfer.



Figure 2.4. Bow-Tie Tag by Avery Dennison.

In Passive UHF RFID systems the Tag has no power supply , hence they have unlimited lifetime. Since the tags are passive, the power is supplied to the tags by the reader itself, along with the timing and commands (Figure 2.5).

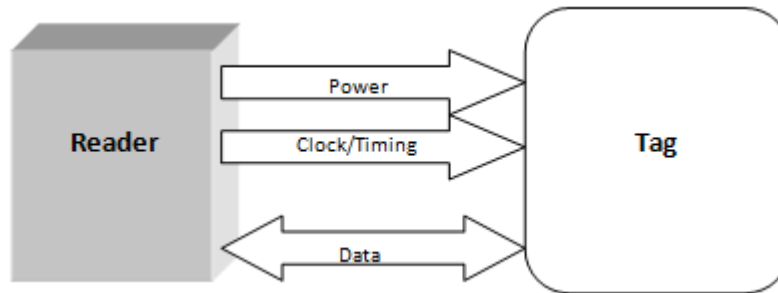


Figure 2.5. The communication between Reader and Tag.

Once the tag receives the power, commands and clock from the reader, the tag responds (based on the reader's command, if it be so) by modulating the receiver's signal. The reader generates a carrier, whose fundamental frequency is used to create digital pulses which act as a clock, or which is used to derive the clock by frequency division. In a basic sense this can be explained as, the tag selectively shunts a capacitance which would electro-statically couple with the electric component of the reader's signal when in range. This results in a change in impedance of the antenna, and hence in effect a change in the antenna's cross-sectional area of reflection. Thus resulting in decrease in the power of the reflected (back-scattered) wave. This change in the signal power levels is monitored by the reader and through sophisticated algorithms interpreted as the required data. This is called back-scattering (further explained in Chapter 2). Besides, the signal modulation the digital data is also data encoded. This refers to an alteration of the data from the chip's memory array before transmission

so that it improves the reliability of communication. The typical flowchart for the handshake between reader and tag is shown below (Figure 2.6).

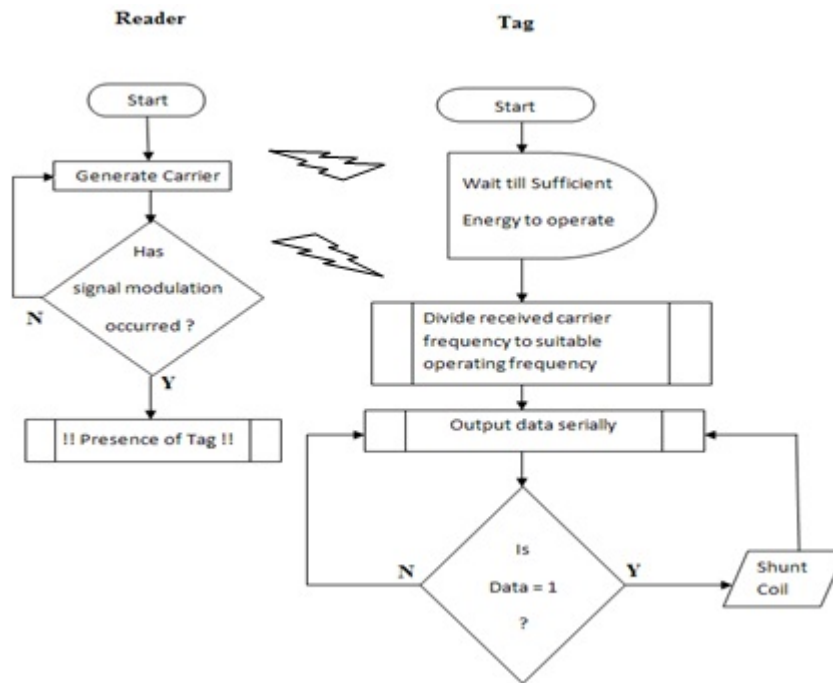


Figure 2.6. The hand-shake between Reader and Tag.

The Tag is essentially a RF transponder and thus consists of a microchip which may be Write once Read many (WORM) or Write many Read many (WORM). Since UHF RFID operates in the UHF range, a small dipolar antenna is enough (Figure 2.7), though this means that it works well for electrostatic coupling only.

Passive UHF RFID operates mainly in the far-field. When in the read range, passive RFID tags are powered by the minute electrical current induced in the antenna by the incoming electromagnetic signal. Thus the antenna is designed both to absorb power from the incoming signal and also to transmit the outgoing backscatter signal

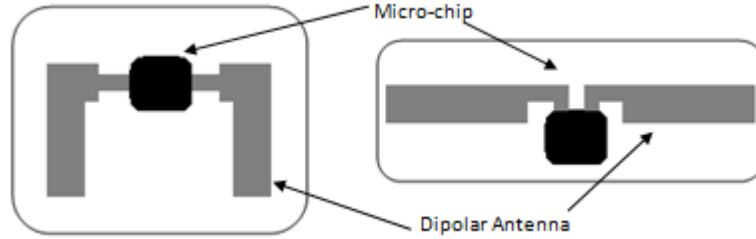


Figure 2.7. An RFID Tag.

(data). In the field, passive tags have read ranges varying from 10 cm to a few metres, depending on the antenna size and frequency and bandwidth of operation. In UHF ISO 180006-C protocol (*a.k.a* Geneneration 2 protocol or just Gen 2 protocol) the reader tag communication takes place using ASK modulation with either FM0 or Miller 2,4,8 coding schemes [7][63][25].

2.3.3 The Information System

The information system & Middleware are the most vital parts of an RFID system. The data of the tag that is read by the reader is sent to and processed by the information system/middleware. It is the information system & middleware that transforms the raw data collected by the reader into useful/coherent information.

The information system has various application specific porograms which integrate the reader data and in turn trigger application specific events.

The Middleware resides between reader and the information system. The Middleware performs the tasks of data collection from the reader and the transformation of this data by the process of reduction of data redundancy. This transformed data is what is presented to the Information system. The challenges faced by the middleware include filtering of unwanted data or ghost reads and data mining and sorting, thus

making the middleware customizable for every reader. The other important functions of the middleware are processing the raw data from the reader/s, providing an interface to manage multiple readers and encapsulating all the data so that the same data can be presented to the various applications.

The Middleware is responsible for providing the reader management hence resulting in easy customization and deployment of RFID readers. The middleware can be customized for integration with sensors or other data acquisition sources. Management of data is highly critical as if not done will increase the data traffic to the information system. The Middleware **must** filter out all redundant and hence undesirable data as well as route data to the appropriate destinations.

There are various implementations of the middleware. EPC Global specifications for Application Level Events (ALE) provide for a standard interface for obtaining filtered, consolidated EPC data from RFID readers as well as other data sources [30]. The specifications for the ALE provides flexible mechanisms to filter and group raw RFID data, which in turn creates a means to isolate and focus specific applications [16].

2.3.4 The RFID System

The working of the entire RFID system can be described with reference to the ISO networking models,i.e. the network layers within tag and reader that model the system's basic functionality.

RFID tags are purely the carriers for a unique identification number that helps identify the object that has been tagged [58]. The tag performs certain basic functions which collectively aid in achieving this objective. We can explain the basic

functionality by devolving it into its component functions and explaining how these functions are done by hardware/software in the tag.

The tag both receives and rectifies the incoming signal for the extraction of energy and information. The extracted energy is utilised to power the tag (in case of passive tags) while the extracted information is used to generate a clocking signal which drives the digital circuitry. This circuitry processes the extracted information and makes appropriate modulations in the reader's signal through load modulation or back scattering, thus establishing communication (data transfer) with the reader [58].

In order to achieve reliable communication with the reader, since RFID implementation deals with reader broadcast and multiple tags replies, there must be anti-collision protocols running and as with all wireless digital communication there has to be coding and modulation.

Thus, we have an RF (hardware) front-end that performs task of modulation and demodulation (extraction of data) along with extraction of energy for powering the tag and creating a clocking signal.

“The RF front end is responsible for the bi directional interfacing between the antenna and other functional blocks of the tag” [58].

The digital circuitry of the tag consists mainly of memory for storing the UID (ROM/WORM in case of read only tags) and minute processing capabilities which allow it to execute command recognition and response/reply by load modulation or backscattering. As mentioned earlier, in order to prevent loss of data since the reader may be in the presence of multiple tags, an anti-collision scheme is run in the tag. This anti-collision in the tag is mainly a method of smart framing, as intelligent

Table 2.1. The ISO OSI network reference model

#	Layer	Data Units	Function
7	Application	Data	Semantics of application
6	Presentation	Data	Data representation and Encryption
5	Session	Data	Inter-host communication
4	Transport	Segment	End to End connection and reliability
3	Network	Packets	Logical addressing (IP)
2	Data-Link	Frames	Physical addressing
1	Physical	Bits	Binary data transmission

sensing (and therefore high computational requirements) algorithms cannot be run due to the tags low power (in case of passive tags) and low processing capabilities.

Now that the tasks have been clearly defined as to how they are implemented, let us now consider the ISO OSI network reference model (Table 2.1).

“The OSI reference model is an abstract description of inter process communication” [21].

The OSI model (Figure 2.1) defines the **Physical layer** as the layer that provides the mechanical, electrical, functional and procedural standards to access the physical medium. The physical layer deals with only bits/bit-stream. The **Data Link layer** is the layer that provides the functional and procedural means to transfer data between network entities. It is also responsible for detecting and correcting errors present in the physical layer. The Data Link layer deals with only frames [21][30].

Thus, when we map the *basic functions* of the tag into abstract layers based on the OSI definitions, we see that the tags require only two layers across which their entire *basic functionality* can be mapped: - The **Physical Layer** and the **Data Link Layer** (Figure 2.8).

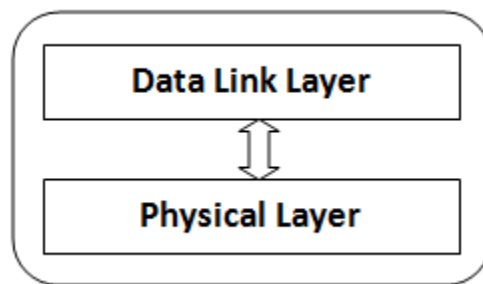


Figure 2.8. A “Basic Functionality” RFID tag.

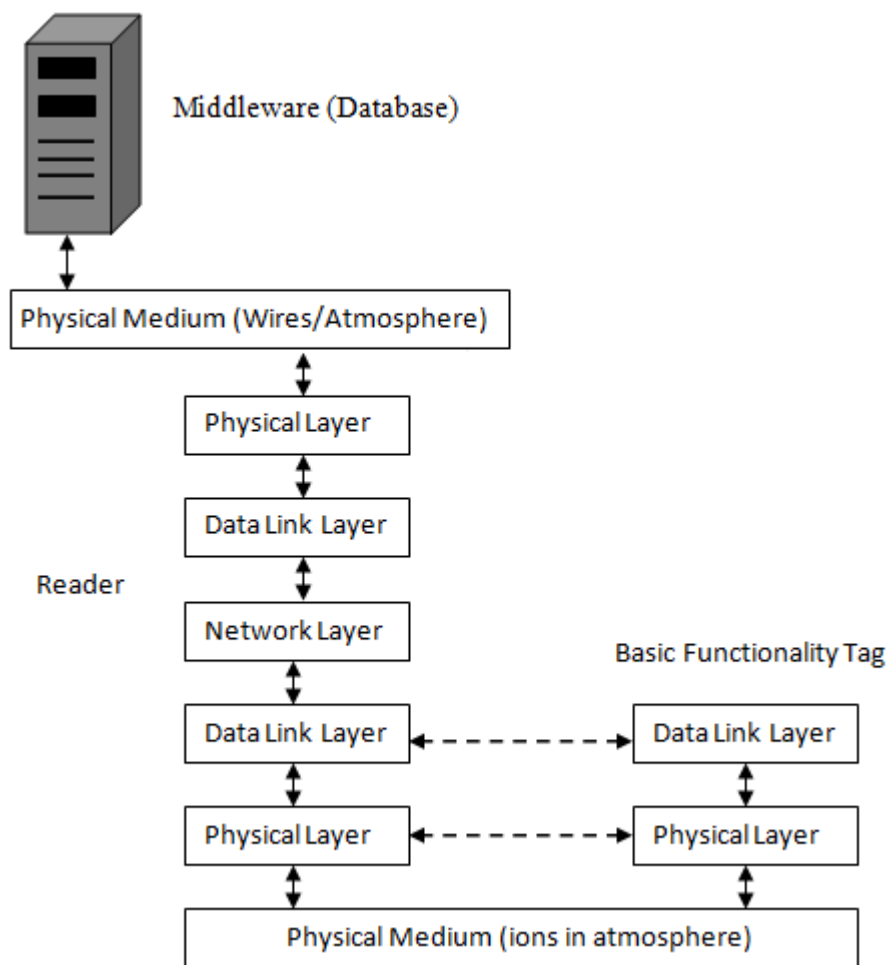


Figure 2.9. The RFID Network Model.

Thus, we can describe the network model of an RFID system (Figure 2.9). The RFID network model describes the tag (basic functionality) as having only two ab-

strat layers (Physical and Data Link) since at maximum the tag handles only data frames. The Reader is described as having an additional layer (network) as this is required to interface with the RFID middleware (Information System) [58][21][25]. The Information System is simply a network entity, with all seven OSI network layers.

2.3.5 Summary

To Summarize, the operations of a tag and reader are complementary in nature. The operations of both tag and reader together constitute a means of identifying a tag or a set of tags. These operations include command protocols and higher-level algorithms. The commands are based around anti-collision algorithms since anti-collision algorithms aim to reduce the occurrence of multiple simultaneous (and therefore colliding) responses to a reader's search signal (*viz.* query) [58][25].

The higher-level commands are made up of interface operations which in turn are made up of necessary lower-level functions. The reader transmits power, information and clock. The clock is generated directly from the carrier wave or from division of the carrier wave. The clock is necessary for driving the digital circuitry of the tag [25][58].

The tag receives and processes the power, information and clock from the reader-transmitted signal. After the higher-level processing of received information the tag transmits information (usually its identification code or portions of the identification code) back to the reader. In passive RFID tags, this is done by modulating the reader's signal. The reader senses/receives this modulated signal/information which is then processed by the reader's higher-level functions [25][58].

The design and implementation of the various functions of an RFID system is determined by both specifications and fundamental constraints. These constraints include electromagnetics and communications constraints which define the methods by which tags and a reader communicate, and regulation and hardware constraints, which impose limits on these methods [25][58].

In Chapter 2, I will discuss the physics behind electro-magnetics. This will include how electromagnetic fields and waves are created using antennas and how their characteristics and hence behavior are varied with frequency and distance. In this chapter I will also discuss and describe how RFID systems achieve communication (information transfer by coupling) by exploiting these characteristics.

CHAPTER 3

ELECTROMAGNETICS

3.1 Introduction

RFID systems consists of a reader and tags that communicate over the air (use EM waves) at a particular frequency i.e. readers are linked to tags by electromagnetic fields and waves occupying or propagating through the environment. Electromagnetic waves or just EM waves include radio waves, microwaves, visible light, Ultra-violet radiation, X-rays, gamma rays and cosmic rays. These collectively form the electromagnetic spectrum, shown in Figure 3.1.

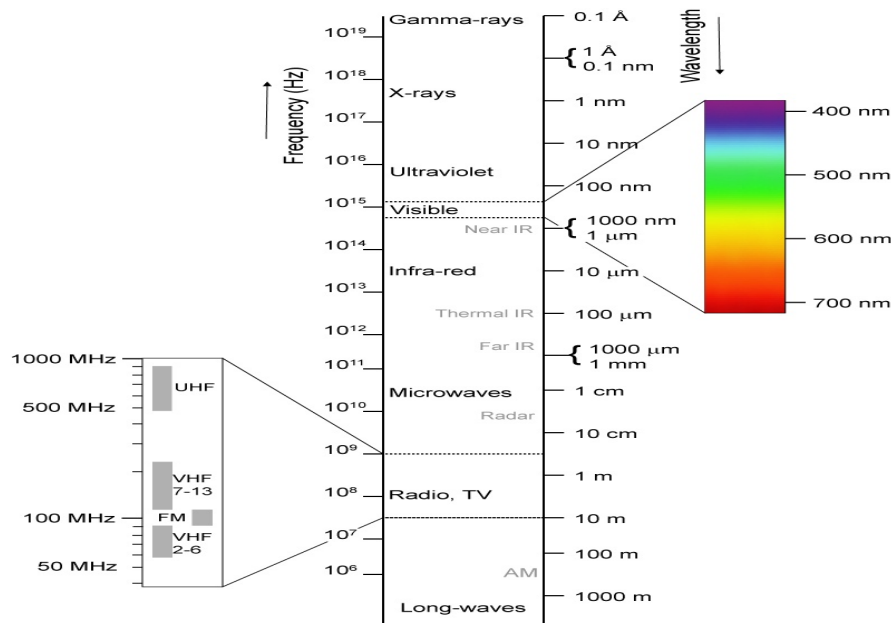


Figure 3.1. The Electromagnetic Spectrum.

In the case of any RF wireless communication, the portion of the electromagnetic spectrum used is shown below (Figure 3.2).

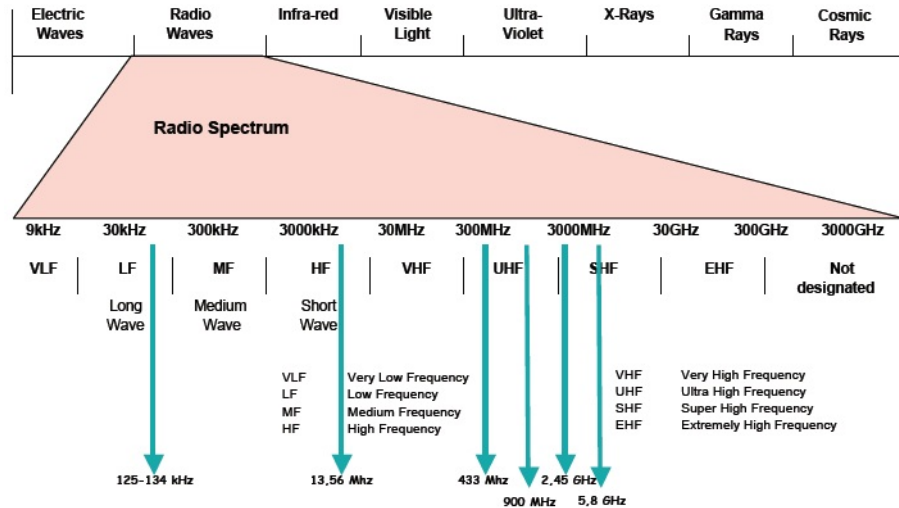


Figure 3.2. The Radio Frequency Identification EM Spectrum.

As the working of RFID systems are dependent on electromagnetic wave and field propagation, it is necessary that we understand the fundamental physics electromagnetics. By understanding these “physics” of the system, we gain insight on how data is transferred in an RFID system and how the power harvesting in the tag takes place. Also, in order to understand how RFID systems are designed, we must learn how these fields are created, manipulated and received.

In this chapter we seek to understand, How fields are created, their size, their available power, their variation with angle, orientation and polarization. How they are transmitted and received. How the antenna type, size and shape can have a bearing on the properties of these fields. How we can maximize the reception of power and

information through the process of tuning and matching. How reactive and radiating link conditions vary with the channel and the environment of the channel.

The answers to the above mentioned questions will aid us in understanding the physical constraints on RFID systems; as well as the fundamentals governing their function.

3.2 Fundamentals Of Electro-magnetics

The foundations of all wireless communication lies in the understanding of *Electromagnetic Field Theory*. Regardless of the type of wireless communication, wireless communication is based on the fundamental laws of physics. An electromagnetic wave comprises of two (2) time varying waves, namely an electric wave and a magnetic wave, that are orthogonal to each other (Figure 3.3). These two waves form the mathematical basis for electromagnetic wave propagation.

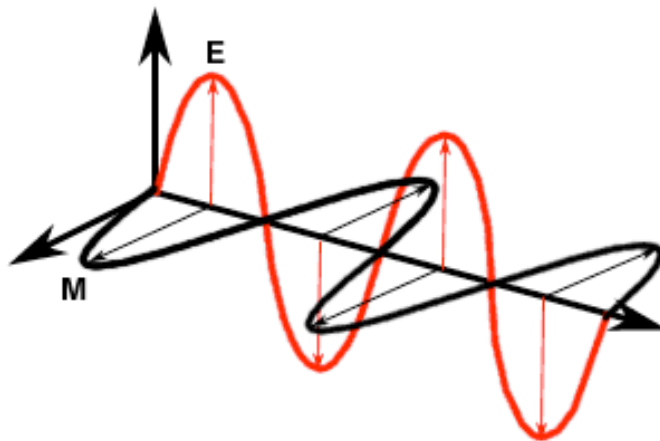


Figure 3.3. The Electro-Magnetic Wave.

3.2.1 The Electric Field

An electrical wave or electrical field is generated/radiated when a single static electrical charge is accelerated in some direction. The electric field is defined as the vector force exerted on this unit charge. The unit of electric field is Newton per coulomb (N/C) which is equivalently volts per meter (V/m). The strength of the electric field is given by, the ratio of the electric force on a charge at a point, to the magnitude of the electric charge placed at that point. Thus, a stationary charged particle in an electric field experiences a force that is proportional to its charge. The electric field is dependent on the amount of flux, or flux density and the permittivity of the material (Figure 3.4).

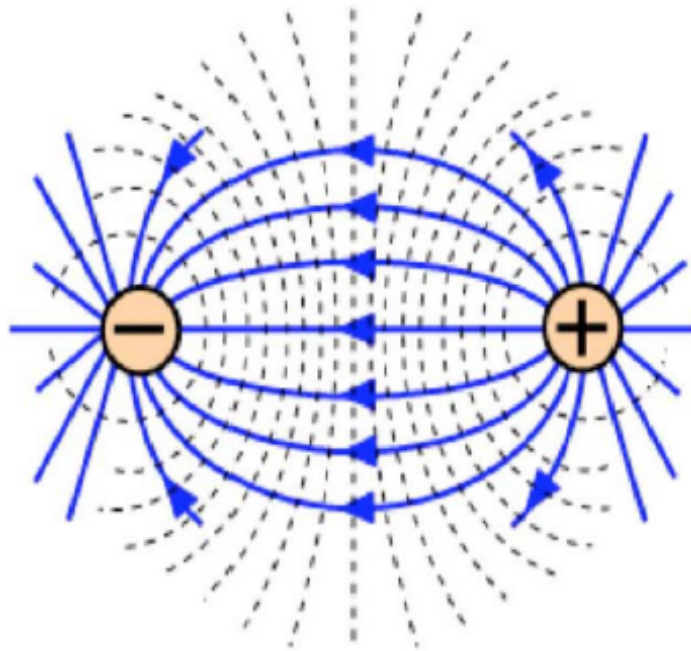


Figure 3.4. The Electric Field [3].

$$E = \varepsilon D \quad (3.1)$$

Where, permittivity ε is expressed with respect to the permittivity of the free space and the relative permittivity or the dielectric constant of the material i.e.

$$\varepsilon = \varepsilon_o \varepsilon_r \quad (3.2)$$

where, $\varepsilon_o = 8.854 \times 10^{-12}$.

Consequently, the energy stored by an electric field is given by

$$U = \frac{1}{2} \varepsilon E^2 \quad (3.3)$$

3.2.2 The Magnetic Field

A magnetic field is generated by steady current flow through conductor or by magnetic materials. A magnetic field can be expressed as a magnetic field strength (B) and magnetic flux density (H). The attraction and the repulsion property of a magnetic field is similar to electrical force between the charges, the only difference is electric charges can be separated but magnetic poles always exists in pairs. The unit of magnetic field strength is amperes per meter (A/m) and the unit for magnetic flux density is weber per square meter (Wb/m^2).

The magnetic field strength and magnetic flux density are related by permeability of the material (μ), and is given by following equation.

$$B = \mu H \quad (3.4)$$

Where, the unit of permeability μ is Henries per meter.

Permeability is expressed relative to the permeability of free space (μ_0)

$$\mu = \mu_0 \mu_r \quad (3.5)$$

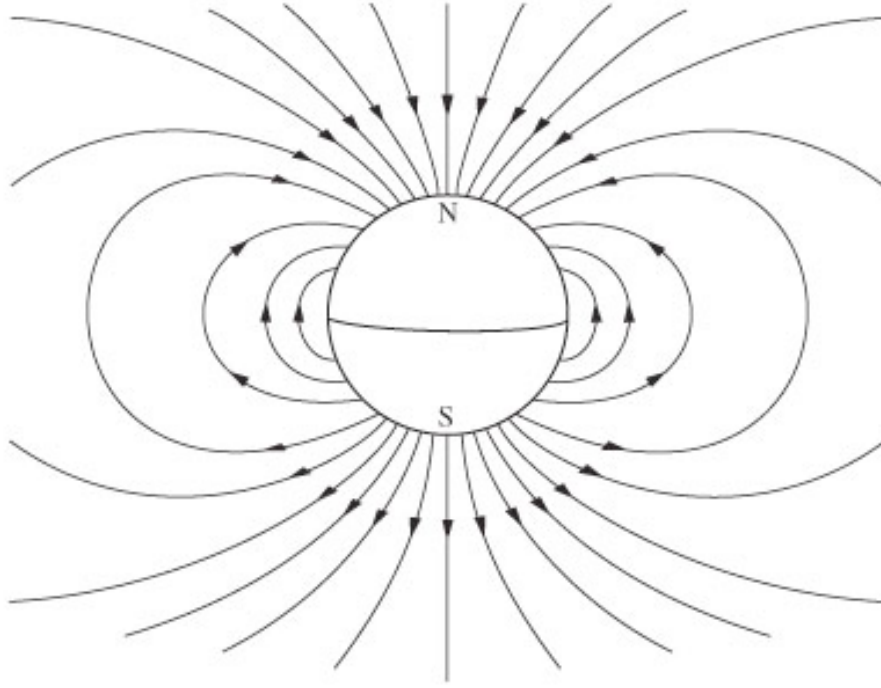


Figure 3.5. The Magnetic Field [5].

Where, $\mu_0 = 4\pi \times 10^{-7}$ H/m.

The Biot-Savart Law (also known as Amperes law) quantifies the relationship between the electric current flowing through the conductor and magnetic flux (Equation 3.6).

$$H = \frac{I}{4\pi} \int \frac{dl \times R}{R^3} \quad (3.6)$$

3.2.3 Maxwell's Equations

Every space-time varying electric field has an associated magnetic field. The behavior of these EM fields at every point in space and at any instant in time relative

to the position and motion of charged particles, is described by Maxwell's equations [61]. These equations are stated mathematically below (Equations 3.7 - 3.10)

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (3.7)$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \quad (3.8)$$

$$\nabla \cdot D = \rho \quad (3.9)$$

$$\nabla \cdot B = 0 \quad (3.10)$$

We can also represent these equations in time-harmonic (sinusoidal) form with frequency ω , through the relationship $\partial/\partial t = -j\omega$

$$\nabla \times E = j\omega B \quad (3.11)$$

$$\nabla \times H = J - \partial\omega D \quad (3.12)$$

$$\nabla \cdot D = \rho \quad (3.13)$$

$$\nabla \cdot B = 0 \quad (3.14)$$

Where,

E is the electric field strength (V/m)

D is the electric flux density (C/m^2)

H is the magnetic field strength (A/m)

B is the magnetic flux density (Wb/m^2)

J is the electric current density (A/m^2)

ρ is the electric charge density (C/m^3)

And where,

Equation 3.7 is known as **Faraday's Law**,

Equation 3.8 is known as **Ampere's Law**

Equation 3.9 is known as **Gauss' Law for electric field**

Equation 3.10 is known as **Gauss' Law for magnetic field** The continuity equation for the conservation of charge and current is given as

$$j\omega\rho + \nabla \cdot J = 0 \quad (3.15)$$

Together with Maxwell's equations, they form the fundamental equation of electromagnetics. The time averaged power per unit area delivered through a surface by electric and magnetic fields is given by Poynting's vector :

$$S = \frac{1}{2} \text{Re}\{E \times H^*\} \quad (3.16)$$

Where,

H^* is the complex conjugate of H

S is the power density (W/m^2)

Further in this chapter we will use several other parameters besides Maxwell's equations to describe fields and waves. Of the parameters available, we will focus on the parameters for lossless media and free space. The free space wave-number is given by :

$$k_0 = \omega\sqrt{\mu_0\epsilon_0} = \frac{\omega}{c} = \frac{2\pi}{\lambda_0} = \beta \quad (3.17)$$

Where,

c is the speed of light $\cong 3 \times 10^8 (m/s)$

ϵ is the permittivity of free space $= 8.8542 \times 10^{-12} (F/m)$

μ_0 is the permeability of free space $= 4\pi \times 10^{-7} (H/m)$

And the free-space impedance is:

$$\eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \quad (3.18)$$

3.3 Polarization

The polarization of an antenna is defined as the orientation of the electric field vector of the electromagnetic wave from the antenna. In the most general case, the locus of the electric field is an ellipse and the electromagnetic wave is said to be an elliptical polarized wave (Figure 3.7(b)).

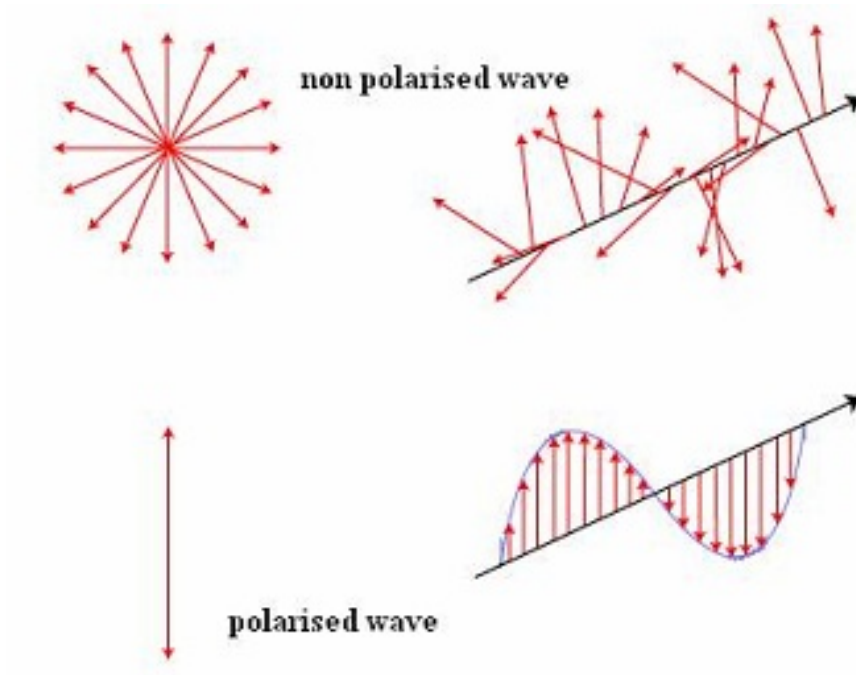


Figure 3.6. A Polarized EM wave and A Non-polarized EM wave [4].

Under certain circumstances, the ellipse may degrade/deform to a circle or a straight line, in those cases the polarization is then referred to as circular (Figure 3.7(a)) or linear respectively (Figure 3.7(c)). The linearly polarized wave has the angle between E_x and E_y either 0° or 180° . Whereas the circular polarized wave is either right handed or left handed.

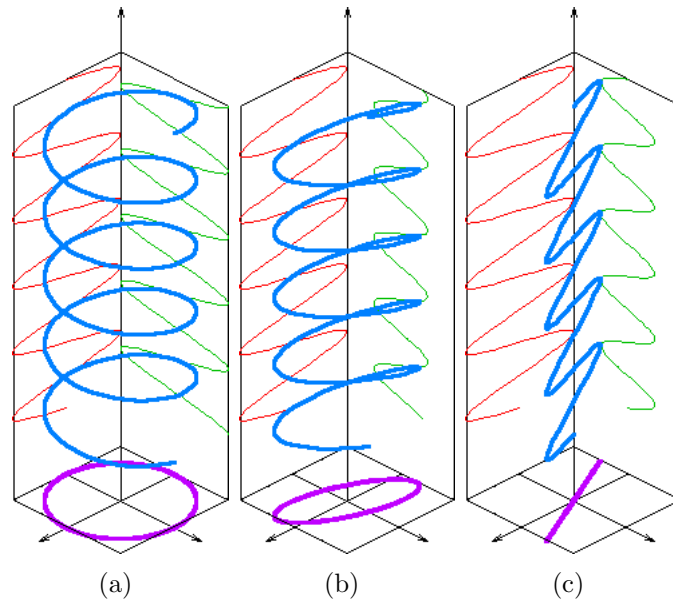


Figure 3.7. Various Polarized EM waves (a)Circular Polarized Wave (b)Elliptically Polarized Wave (c)Linear Polarized Wave [2].

3.4 Laws Governing Electromagnetics

In order to proceed further, it is important to understand the laws governing electromagnetics so that we may understand the physics behind RFID systems. Coulomb's Law, Faraday's Law, Gauss's Law and Ampere's Law will be discussed in the following section.

3.4.1 Coulomb's Law

The magnitude of the electromagnetic force between two point charges is directly proportional to the product of the magnitudes of each charge and inversely proportional to the square of the distance between the charges.

$$F = \frac{1}{4\pi\epsilon_o} \frac{q_1 q_2}{r^2} \quad (3.19)$$

where,

F is the electrostatic force,

q_1, q_2 are the point charges,
 r is the distance between the point charges
 and ε_o is the permittivity of free space.

3.4.2 Faraday's Law

Faraday's law states that the induced electromotive force in a closed loop is directly proportional to the time rate of change of magnetic flux through the closed loop.

$$E = -N \frac{d\phi_B}{dt} \quad (3.20)$$

where,

E is the electromotive force,
 N is the number turns in the wire
 and B is the magnetic flux.

The circulation of the electric field vector E around a closed contour is equal to minus the time rate of change of magnetic flux through a surface bounded by that contour. The positive direction of the surface being related to the positive direction of the contour by the **Right-Hand rule**.

3.4.3 Ampere's Law

Ampere's law relates the magnetic field around a closed loop to the electric current passing through the loop. The circulation of the magnetic field vector H around a closed contour is equal to the sum of the conduction current and the displacement current passing through a surface bounded by that contour, once again the right hand rule relating the senses of the contour and the surface.

$$\nabla \times B = \mu_o J + \varepsilon_o \mu_o \frac{\partial E}{\partial t} \quad (3.21)$$

The displacement current was added to the Ampere's Law by Maxwell. The corrected law is stated in the unified Maxwell's Equations on electromagnetic theory.

3.4.4 Gauss' Law of Electric Flux and Magnetic Flux

Gauss' law is based on the electrostatic application of the generalized Gauss's theorem. Thus Gauss' Law gives the equivalence relation between any flux and electric charges enclosed within a closed surface. The differential form of Gauss's law is the basis of Maxwell's equations. The total electric flux (defined in terms of the D vector) emerging from a closed surface is equal to the total conduction charge contained within the volume bounded by that surface.

$$\phi = \oint_s E \cdot dA \quad (3.22)$$

The total magnetic flux (defined in terms of the B vector) emerging from any closed surface is zero.

3.5 Antennas

An antenna is the a means for radiating or receiving radio waves [17]. Essentially an antenna is a guiding device that will transport the electromagnetic energy from the transmitting source to the radiating element and/or from the receiving element to the load. Reflected waves from the interface, along with the traveling waves from the source towards the antenna, create constructive and destructive interference patterns , referred as standing waves. The field of antenna is vigorous and dynamic and it plays a very important role in RFID. The Reader antenna must me highly sensitive and very directional, while tag antenna must me wide-band in order to universal. A few types of antennas are listed below :-

- Reflector Antennas

- Lens Antennas
- Fractal Antennas
- Wire Antennas
- Aperture Antennas
- Array Antennas
- Micro-strip Antennas

The basic principle in creating radiation is that there must be a time-varying current or an acceleration of the charge in the radiating element (transmitting antenna) and vice-versa at the receiving antenna.

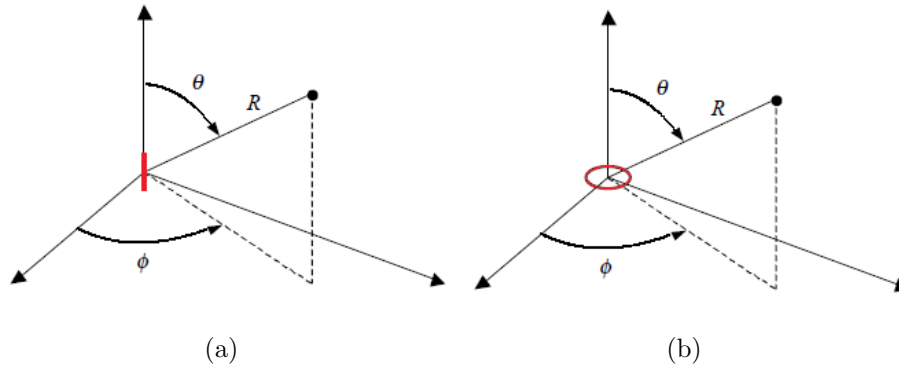


Figure 3.8. The Ideal Antennas (a)An Ideal Dipole (b)An Ideal Loop [58].

For a better understanding of the relationship between electromagnetic fields and waves, it is helpful to examine how they are formed by an antenna. We can derive the electric and magnetic fields created and radiated by any antenna using the previously discussed Maxwells equations. For purposes of illustration, we will consider two antennas considered to be electrically small, in that their maximum dimension is much less than the wavelength *viz.*, we will consider the ideal dipole, also known

as a Hertzian dipole (Figure 3.8(a)), and the small loop (Figure 3.8(b)) [62]. The ideal dipole is an infinitesimally small element that carries current with a uniform amplitude and phase over its length. The small loop is a closed current loop with a perimeter of less than about a quarter of the wavelength.

The approach to deriving the radiated electric and magnetic fields, involves first calculating a vector potential based on the current density. The electric field is then found from the vector potential and the magnetic field is subsequently found from the electric field.

3.5.1 The Ideal Dipole

The fields created by an oscillating ideal dipole with length dl can be written as [18] :-

$$E = -\frac{Idl}{4\pi}\eta_0\beta^2 2\cos\theta \left[\frac{1}{(j\beta r)^2} + \frac{1}{(j\beta r)^3} \right] e^{-j\beta r} \hat{r} - \frac{Idl}{4\pi}\eta\beta^2 \sin\theta \left[\frac{1}{j\beta r} + \frac{1}{(j\beta r)^2} + \frac{1}{(j\beta r)^3} \right] e^{-j\beta r} \hat{\theta} \quad (3.23)$$

$$H = -\frac{Idl}{4\pi}\beta^2 \sin\theta \left[\frac{1}{j\beta r} + \frac{1}{(j\phi r)^2} \right] e^{-j\beta r} \hat{\phi} \quad (3.24)$$

On examining the electric and magnetic field equations, we can see the dependence on distance r from the antenna.

- When, $\beta r \ll 1$ (or, $r \ll \lambda/2\pi$), the third order terms dominate. At this distance:- the electric field strength decays as $1/r^3$, and the magnetic field strength decays as $1/r^2$. This region is referred to as the **near-field**.
- When, the distance r is much greater than $\lambda/2\pi$, the first order terms dominate, and both the electric field and magnetic field strengths decay as $1/r$. This region is referred to as the **far-field**.

Examining the equations further, we notice that in the near-field where $\beta r \ll 1$, not only does the third order term dominate, but $e^{-j\beta r}$ also approaches 1. Thus, the electric and magnetic fields reduce to

$$E^{nf} = j \frac{Idl}{4\pi\beta r^3} \eta_0 \left(2\cos\theta \hat{r} + \sin\theta \hat{\theta} \right) \quad (3.25)$$

$$H^{nf} = \frac{Idl}{4\pi r^2} \sin\theta \hat{\phi} \quad (3.26)$$

Aside from the dissimilar relationship with distance r indicating different levels of decay, we note that the electric field is imaginary, indicating it is $\lambda/4$ (90 degrees) out of phase with the magnetic field, thus indicating it is a reactive field. In a reactive field, energy is essentially stored and released between the two fields. Evaluation of the Poynting vector for this case, reveals that there is no real power flow. The electromagnetic fields in the near-field are in essence decoupled from each other and quasi-static. Further simplification of the equations reveals that the small dipole essentially behaves as a static electric dipole.

In considering the far-field where $\beta r \gg 1$, the first order terms dominate and the field equations reduce to :-

$$E^{ff} = j \frac{Idl}{4\pi r} \eta_0 \beta e^{-j\beta r} \sin\theta \hat{\theta} \quad (3.27)$$

$$H^{ff} = j \frac{Idl}{4\pi} \beta e^{-j\beta r} \sin\theta \hat{\phi} \quad (3.28)$$

$$(3.29)$$

Thus, we see that in the far field, the electric and magnetic fields are in phase, orthogonal in polarization, and related in magnitude by $E_\theta/H_\phi = \eta_0$, the intrinsic impedance of free space. Both fields decay as $1/r$. Evaluation of the Poynting vector reveals a real power density, indicating propagation through a surface. The electromagnetic fields in the far-field constitute an electromagnetic wave.

3.5.2 The Ideal Loop

The fields created by an ideal loop can be written as [18] :-

$$E = \frac{Idl}{4\pi} \eta_0 \beta^2 \sin\theta \left[\frac{1}{j\beta r} + \frac{1}{(j\beta r)^2} \right] e^{-j\beta r} \hat{\phi} \quad (3.30)$$

$$H = -\frac{Idl}{4\pi} \beta^2 2\cos\theta \left[\frac{1}{(j\beta r)^2} + \frac{1}{(j\beta r)^3} \right] e^{-j\beta r} \hat{r} - \frac{Idl}{4\pi} \beta^2 \sin\theta \left[\frac{1}{j\beta r} + \frac{1}{(j\beta r)^2} + \frac{1}{(j\beta r)^3} \right] e^{-j\beta r} \hat{\theta} \quad (3.31)$$

In the near field the electric and magnetic fields reduce to :-

$$E^{nf} = -\frac{Idl}{4\pi r^2} \eta_0 \sin\theta \hat{\phi} \quad (3.32)$$

$$H^{nf} = j \frac{Idl}{4\pi \beta r^3} \left(2\cos\theta \hat{r} + \sin\theta \hat{\theta} \right) \quad (3.33)$$

In considering the far-field where $\beta r \gg 1$, the field equations reduce to :-

$$E^{ff} = -j \frac{Idl}{4\pi r} \eta_0 \beta e^{-j\beta r} \sin\theta \hat{\phi} \quad (3.34)$$

$$H^{ff} = j \frac{Idl}{4\pi r} \beta e^{-j\beta r} \sin\theta \hat{\theta} \quad (3.35)$$

The similarities between the ideal dipole and the small loop field equations reveal that the small loop is the dual of the ideal dipole.

Before proceeding with the further dicussion regarding antennas and waves, there is yet another region is of concern, often called the Rayleigh region. This region is given by

$$r > \frac{2D^2}{\lambda} \quad (3.36)$$

Where,

r is the distance from the antenna and

D is the length of a radiating line source

In this region, we can reasonably approximate a spherical electromagnetic wave as a uniform plane wave.

“Plane waves are those with an electric field with the same direction, magnitude, and phase in infinite planes, perpendicular to the direction of propagation [58].”

Plane waves do not exist in practice, as they would require infinitely sized sources. However, at a distance far enough from the source, this approximation is reasonable. From here on, when we discuss electromagnetic waves, we will not only assume we are in the far-field, but also in the Rayleigh region.

From these equations we see that electromagnetic fields exhibit radically different behavior in the near-field zone as compared with the far-field zone. In the near-field, fields are reactive and quasi-static, while in the far-field they constitute radiated waves. This result is particularly important to RFID systems. RFID systems operating at lower frequencies where the near-field encompasses the operating range, must achieve coupling through the quasi-static fields, while RFID systems operating at higher frequencies typically operate in the far field and achieve coupling through electromagnetic waves. In this research work as we deal only with Passive RFID Systems which operate in the far-field, in the further sections of this chapter we will further our understanding of the physics of RFID by dealing only with those functions of electro-magnetics that are relevant to Passive Ultra High Frequency (UHF) RFID Systems.

An important factor to note, is that the transition point between near-field and far-field is actually dependent on the geometry of the antenna, but we will use the transition point of $\lambda/2\pi$ as the standard definition.

3.6 Impedance

Before further analyzing the behavior of RFID systems operating in the near-field and far-field, it is helpful to first discuss the concept of impedance as it relates to free-space, antennas, and circuits. Generally, impedance describes the relationship between an effort and a flow. In electromagnetic field and wave theory, impedance is the relationship between the electric field and the magnetic field.

$$Z = \frac{E}{H} \quad (3.37)$$

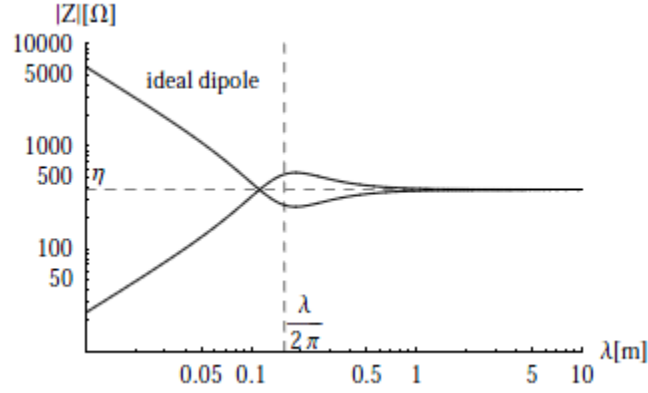
In the case of electrical circuits and antennas, it is given by the relationship between voltage and current.

$$Z = \frac{V}{I} \quad (3.38)$$

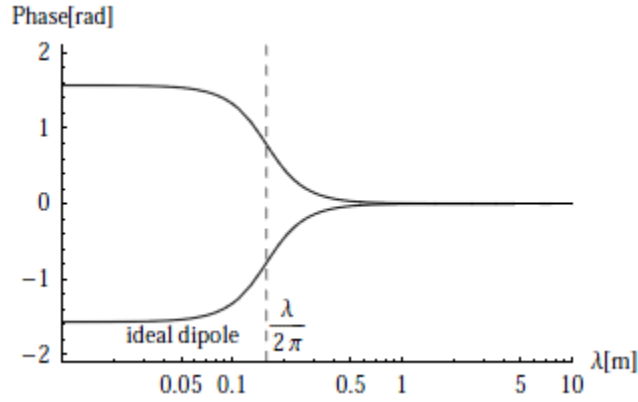
Regardless of the domain, impedance is an extremely useful parameter; it is capable of characterizing the behavior of fields and waves, radiation and reaction of an antenna and power transfer between an antenna, transmission line and a load.

The figure below (Figure 3.9(a)) shows the magnitude of the free space impedance of the fields generated by both an ideal dipole, and a small loop. We can see that at the near-field to far-field transition point ($\lambda/2\pi$), the impedances converge and become constant. In the far field, the impedances of the two different antennas are identical and equal to the intrinsic impedance of free space, η ; but, in the near-field they are different. Figure 3.9(b) shows the phase of the impedances of the two antennas. In the near-field, the phases are opposite at positive and negative $\pi/2$, while in the far-field they converge to 0.

We must note that the antennas themselves have an input impedance at their terminals. The real portion represents a combination of actual radiation R_{rad} and



(a)



(b)

Figure 3.9. Impedance Plots for Ideal Dipole and Ideal Loop (a)Plot of impedance magnitude versus wavelength (b)Plot of impedance phase versus wavelength [58] (The ideal dipole impedance is labeled; the small loop impedance is unlabeled).

ohmic losses R_{ohmic} , while the reactive portion X indicates energy stored in the field around the antenna.

$$Z_{in} = R_{rad} + R_{ohmic} + jX \quad (3.39)$$

Thus we see, the smaller the antenna relative to a wavelength, the lower the radiation resistive component, and the higher the reactive component (This characterizes an inefficient radiator). Referring back to Figure 3.9 showing the impedance magnitude and phase of the fields produced by the ideal dipole and the small loop, we see

that the small loop has a large positive reactive component, while the ideal dipole has a large negative reactive component. A positive reactive component represents inductance, while a negative reactive component represents capacitance.

Now, as the antenna size increases relative to the wavelength, the radiation resistance component increases, while the reactive component decreases. At the length or perimeter of a half-wavelength the reactive component approaches zero while the resistive component reaches its maximum. At this dimension, the antenna is resonant and radiates efficiently. Far-field systems typically use resonant antennas [58]. Increasing the size of the antenna further, results in an increase in the reactive component and a decrease in the resistive component, until at a dimension of one wavelength, the impedance is similar to what it was at an infinitesimal dimension. This cycle repeats for every multiple of a wavelength.

Transmission lines and electric circuits have an impedance also. As described by transmission line theory, for maximum power transfer, impedances must be conjugate matches. Real components should be equal, while reactive components should be equal and opposite. In the following sections we will discuss how this affects the operation of RFID systems.

3.7 Coupling in the Far-Field

Coupling in wireless systems operating in the far-field is achieved through transmission, propagation, and reception of electromagnetic waves. In the following section/s, first discussed will be some useful relations for electromagnetic fields, then the performance parameters necessary for describing the radiating properties of an antenna,

and finally the transmission and reception of electromagnetic waves - focusing on the power available to a receiving antenna and its attached load.

3.7.1 Antenna Parameters

We have already discussed electrically small dipole and loop antennas. These antennas are noted for their high reactance (whether it be capacitive or inductive), inefficient radiation characteristics, and difficulty in matching. While suitable for operation in the near-field, electrically small antennas are generally not suitable for far-field operation where transmission, and particularly, reception should be efficient. For this reason, resonant antennas characterized by a dimension on the order of one half the wavelength of transmitted frequency, are commonly used for far-field communication. These resonant antennas offer far more efficient radiation and reduced reactivity. The bandwidth however, can be narrow. Types commonly used in RFID systems include half-wave dipole and micro-strip patch antennas.

The waves radiated by all antennas consist of electric and magnetic fields related by the impedance of free-space. The field magnitudes vary with antenna type and output power, but both decay with the inverse of distance from the source. However, the angular distribution of radiation, varies with the type of antenna.

We can use the radiation pattern to describe the angular distribution of an antenna's radiation. The radiation pattern of an antenna is given in terms of the normalized electric field distribution over a constant distance r . For the case where a z -directed source has an electric field with only a θ component, the radiation pattern can be given as:-

$$F(\theta, \phi) = \frac{E_\theta}{E_{\theta_{max}}} \quad (3.40)$$

Antennas may be designed to concentrate their fields into a narrower beam of radiation, thus increasing the power density relative to distance; allowing transmission at longer ranges. The term **directivity** is used to describe how an antenna concentrates its energy in one direction as compared to every other direction. It is defined as the ratio of radiation intensity in a certain direction to the average radiation intensity. Directivity is based solely on an antennas radiation pattern.

It is also useful, however, to describe not only the directive properties of an antenna but its efficiency in transforming some input power to radiated output power. The term **Gain** quantifies this. Typically, Gain, is defined as 4π times the ratio of radiation intensity in a given direction to the net power input of the antenna.

$$G(\theta, \phi) = \frac{4\pi U(\theta, \phi)}{P_{in}} \quad (3.41)$$

Gain is often described by comparing the maximum radiation intensity of one antenna to the maximum radiation intensity of some standard reference antenna. An antennas gain is typically described relative to an isotropic radiator (that radiates energy in all directions uniformly). Gain can also be described relative to a half-wave dipole. Gain is given in units of decibels (dB). An isotropic radiator has a gain of 0 dB, while a half-wave dipole antenna has a gain of 2.15 dB. When describing the gain relative to an isotropic radiator we describe this by units of dBi. When describing gain relative to a half-wave dipole antenna, we use units of dBd. If we consider an antenna with a gain of 6 dB, it can be described by a gain of 6 dBi, or 3.85 dBd [62].

Similarly, just as gain can be described relative to some standard reference antenna, so to can we describe the radiated power. We often use effective (or equivalent)

isotropically radiated power, EIRP. EIRP is defined as the net input power to an antenna multiplied by its gain relative to an isotropic antenna.

$$EIRP = G_t P_t \quad (3.42)$$

We may also use effective radiated power, ERP, which is simply the net input power to an antenna multiplied by its gain relative to a half-wave dipole antenna.

$$ERP = P_t G_{td} \quad (3.43)$$

EIRP is related to ERP by,

$$EIRP = ERP \times 1.64 \quad (3.44)$$

With antenna parameters understood, we can now consider the transmission and reception of waves.

3.7.2 Transmission and Reception

In considering the operation of RFID tags, we must firstly determine the power available at the tag antenna. The tag absorbs some of this “available power” for powering itself. It also scatters some of this “available power” for transmitting information back to the reader. To understand this process, we will firstly determine the power available to the tag, given the transmitted power and gain at the reader. Next, we will determine the power delivered to the tags load. Finally, we will consider the scattering of power back to the reader for communication purposes.

3.7.2.1 Reader to Tag Transmission

Given an electromagnetic wave incident on a receiving antenna, the electric field will induce a voltage V_A across the receiving antenna,

$$V_A = E^i \times h^* \quad (3.45)$$

Where,

E^i is the incident electric field

h is the antenna vector effective length, and

h^* is it's complex conjugate

The tag will generally store charge and use it when necessary. However, there must be sufficient power available at the antenna to keep the tag charge storage full. If sufficient power is not available at a given distance, range will be reduced [58].

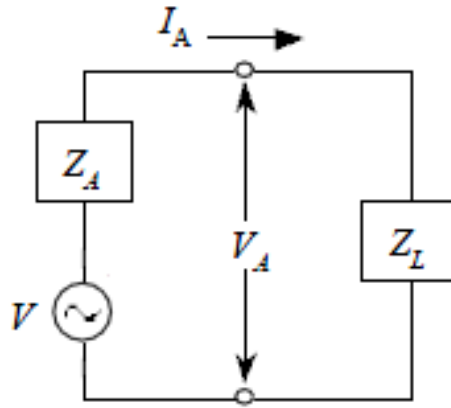


Figure 3.10. Equivalent circuit of a far-field tag [58] (We model the antenna as a voltage source and impedance).

If we consider a transmitter that sends power P_t through an antenna whose gain is G_t , we can compute the power density S incident on a receiving antenna at some distance R from the transmitting antenna by using Poynting's vector as:-

$$S = \frac{G_t P_t}{4\pi R^2} \quad (3.46)$$

From this power density, we can define an effective aperture A_e , which is based on the antennas own gain. Effective aperture A_e , essentially can be thought of as a power capture area. Thus we define A_e as :-

$$A_e(\theta, \phi) = \frac{\lambda^2}{4\pi} G(\theta, \phi) \quad (3.47)$$

When denoted just as A_e , i.e. without dependence on angle, Effective aperture represents the maximum effective area.

Thus, simply multiplying the effective aperture by the power density should give us the power received by the receiving antenna. However, we must also consider potential polarization mismatch issues. Essentially, if the antenna has some polarization that is different from that of the incoming wave, only a fraction of the transmitted power will be received. For this reason, we must also define a polarization mismatch factor, p , to account for the potential polarization mismatch [58]. Polarization mismatch factor, p , can be written as :-

$$p = \frac{|E^i \cdot h^*|^2}{|E^i|^2 |h|^2} \quad (3.48)$$

Where,

E^i is the incident electric field

h is the antenna vector effective length, and

h^* is it's complex conjugate

Note: When there is no polarization mismatch, $p = 1$.

Having defined p , we can now compute the power received by the receiving antenna as :-

$$P_r = p S A_{er}(\theta, \phi) = p \frac{G_t P_t A_{er}(\theta, \phi)}{4\pi R^2} \quad (3.49)$$

Substituting for A_{er} in terms of G_r using Eqn. 3.47, we get:-

$$P_r = pP_t \frac{G_t G_r \lambda^2}{(4\pi R)^2} \quad (3.50)$$

This gives the power received by the antenna, yet as there is some load in the attached circuitry, we must also consider the power available to the load. For maximum power transfer from the antenna to the load, we must match the impedance of the antenna with the load equivalent impedance. In those cases where a conjugate match between the load and antenna impedances is achieved, the power available to the load is that received by the antenna. In all other cases however we include an impedance mismatch factor q . Where q can be given as:-

$$q = \frac{P_D}{P_{D_{max}}} = \frac{4R_A R_L}{(R_A + R_L)^2 + (X_A + X_L)^2} \quad (3.51)$$

When a conjugate match is achieved between the antenna impedance Z_A and the load impedance Z_L , q becomes 1.

Thus, with q we can find the power delivered to the load resistance R_L as:

$$P_D = qP_r = qpP_t \frac{G_t G_r \lambda^2}{(4\pi R)^2} \quad (3.52)$$

Hence, the fraction of P_t not delivered to the load $(1 - q)$ is scattered.

3.7.2.2 Scattering

When an electromagnetic wave is incident on irregularities in a medium, the wave may be randomly dispersed. This phenomenon is called scattering. In sensor systems like radar and RFID, a transmitter will transmit a radio-frequency electromagnetic wave and a receiver will detect an object's scattered response. When the receiver is collocated with the transmitter, scattering is referred to as monostatic, or backscatter [58].

In UHF RFID systems, the tags communicate with the reader through a process called backscattering. Backscatter involves variation of the tags load impedance, which in turn causes an intended mismatch in impedance between the tags antenna and load. This causes some power to be reflected back through the antenna and scattered, in essence much like the tag antenna is radiating its own signal. The return scattered signal is detected and decoded by the reader. This form of communication is called Backscatter modulation. Modulated backscatter RFID systems achieve communications through controlled changes of a tags backscatter response [58].

A very useful representation of an object's monostatic scattering characteristics is its backscattering cross section or radar cross section (RCS). Before describing the basic principles of modulated backscatter in the context of RFID systems, we will briefly review the definition of scattering and radar cross-section. Then, in more detail, the factors influencing RFID tag and reader design [58].

Scattering in radio wave propagation can be defined as: "A process in which the energy of a traveling wave is dispersed in direction due to interaction with inhomogeneities of the medium" [1]. Scattering is caused when electromagnetic waves impinge upon an object and induce oscillating charges and currents within the object and on its surface and hence an electromagnetic field. These scattered fields can be determined through numerical or analytical evaluation of the induced surface charges and currents, or through the use of the tangential field approximation as used in physical optics [44]. Generally, the spatial distribution of the scattered energy depends on size, shape, and composition of the object, and the waveform, and direction of its arrival.

The Radar Cross-section (RCS), is defined as a measure of power scattered in a given direction. RCS is expressed as an area, much like an antennas effective aperture.

The IEEE defines RCS as :

... 4π times ratio of the power per unit solid angle scattered in a specified direction to the power per unit area in a plane wave incident on the scatterer from a specified direction. More precisely, it is the limit of that ratio as the distance from the scatterer to the point where the scattered power is measured approaches infinity..[1]

There are three cases that can be considered:

1. monostatic or backscattering RCS, where, incident and pertinent scattering directions are coincident but opposite in sense
2. The two directions and senses are the same
3. Bistatic RCS, where, the two directions are different

When not specified as otherwise, RCS is assumed to be monostatic. RCS is a function of frequency, transmitting and receiving polarizations, and target aspect angle. It can be represented symbolically as [1]:

$$\sigma = \lim_{R \rightarrow \infty} 4^2 \frac{|E^{scat}|^2}{|E^{inc}|^2} \quad (3.53)$$

Where,

E_{scat} is the scattered electric field

E_{inc} is the incident electric field and

R is the distance from the target

We can also represent RCS symbolically as:

$$\sigma = 4^2 \frac{P_s}{P_i} \quad (3.54)$$

Where,

P_s is the scattered power

P_i is the incident power

Based on the ratio of wavelength λ to body size L , scattering can be classified into three regimes:

A. The Rayleigh region(not to be confused with the far-field plane wave region):

Here, the wavelength is much greater than the body size so there is little variation in phase over the length of the body. The body essentially sees a quasi-static field; hence, a dipole moment is induced resulting in a scattered field [44].

B. The Resonant region: Here, the wavelength is of the order of the body size, typically the body size is taken to be between 1 and 10 wavelengths. In this region, the electromagnetic energy shows a tendency to stay attached to the surface of the body; thus creating surface waves including traveling waves, creeping waves, and edge traveling waves [44].

C. The Optics region: Here, the wavelength is much less than the body size. Thus, the dominating scattering mechanisms are specular scattering, end-region scattering, diffraction, and multiple reflections [44]

As we are concerned with backscatter from antennas with size on the order of a wavelength, we are principally concerned with scattering in the resonant region where surface wave scattering dominates. We cannot use the tangential plane approximation, as it is essentially only useful for evaluation of specular scattering. Instead we must use the induced surface currents and charges to solve for the scattered field. As an analytical solution to this can be difficult, the various methods, including the method of moments can provide a numerical solution [44].

In analyzing modulated backscatter tags, we will concern ourselves with the scattering characteristics of the tags antenna. Since antennas are designed to transmit and receive radiation, they are generally regarded as having two modes of scattering:

- 1. The Structural mode:** is the scattering that occurs because a given antenna is a certain shape, size, and material
- 2. The Antenna mode:** is the scattering that occurs because the antenna was designed to transmit RF energy and has a specific radiation pattern.

(To be noted is that there are no formal definitions of these modes, and variations exist)[44].

There are several models for the field scattered from an antenna [32][31]. We will use the one presented by Green [31]. Referring back to Figure 3.10, the scattered field as a function of load impedance Z_L is given by:

$$E(Z_L) = E(Z_A^* + \Gamma I(Z_A^*))E^r \quad (3.55)$$

Where,

Γ is the modified reflection coefficient, given by: $\Gamma = \frac{Z_A^* - Z_L}{Z_A^* + Z_L}$

E^r is the far-field electric field when the antenna is excited by a unit current source, given by: $E^r = -j\frac{\eta\beta}{4\pi r} \exp^{-j\beta r} h$

Comparing the equation above with that of the ideal dipole electric field in the far field (Equation 3.29), we see that $h = dl\sin\theta\hat{\theta}$ in the case of the ideal dipole. This value will be different for practical antennas. Note that the negative sign represents the reflection. $E(Z_A^*)$ and $I(Z_A^*)$ in Equation 3.55 represent the scattered field and antenna current when the load impedance is a conjugate match of the antenna impedance, respectively. The second term of Equation 3.55 is the antenna mode scattering. The antenna mode scattering term is related directly to the load impedance

connected to the antenna. Thus, when the load impedance is matched with the antenna impedance, this term goes to zero; leaving the first term called the structural mode scattering. Using familiar antenna parameters, we can write the RCS of the antenna mode scattering as:

$$\sigma_{ant} = p\Gamma^2 G^2(\theta, \phi) \frac{\lambda^2}{4\pi} \quad (3.56)$$

Where,

p is the polarization mismatch factor (discussed earlier) between the incident field and the scattering antenna.

Green also additionally considers the case where the load is switched between two different loads with modified reflection coefficients Γ_1 and Γ_2 . In effect, this cancels the static structural mode, and the modulation of the scattered field becomes:

$$\Delta E = -j \frac{\eta_0}{4\lambda R_A} h(h \cdot E^{inc})(\Gamma_1 - \Gamma_2) \frac{e^{-j\beta r}}{r} \quad (3.57)$$

And the associated Radar Cross Section (RCS) thus becomes:

$$\sigma_{\Delta} = p^2 |\Gamma_1 - \Gamma_2|^2 G^2(\theta, \phi) \frac{\lambda^2}{4\pi} \quad (3.58)$$

The above equations show the basics behind backscatter modulation. Thus, by varying the load impedance, the tags are able to modulate the amplitude and phase of the backscattered field and hence communicate information back to the reader.

Earlier on we discussed that some of the received power is delivered to the load, while the rest is scattered. The fraction delivered to the load is q , while $1 - q$ is reflected back towards the transmitting antenna. The modified reflection coefficient Γ can be related to q by:

$$1 - q = |\Gamma|^2$$

From the antenna mode RCS, we can find the power radiated back to the reader. Essentially, the power transmitted by the reader antenna is captured by the antenna mode RCS and then radiated isotropically. Using a basic form of the radar range equation :

$$P_{TX} = p_t \frac{P_t G_t^2 \lambda^2}{(4\pi)^3 R^4} \sigma \quad (3.59)$$

Where,

p_t is a polarization mismatch factor between the scattered wave and the final receiver.

Thus, the backscattered power received by the reader antenna becomes:

$$P_{TX} = pp_t \Gamma^2 \frac{P_t G_t^2 G_r^2 \lambda^4}{(4)^2} \quad (3.59)$$

Applying the relationship between Γ and q from Equation ??, we get:

$$P_{TX} = pp_t (1 - q) \frac{P_t G_t^2 G_r^2 \lambda^4}{(4\pi R)^4} \quad (3.59)$$

Thus, from the above equation (Equation 3.59), we see the relationship between power delivered to the tag load and backscattered power from the tag received by the reader are related.

3.8 Environmental Influences

IN the previous sections, we have purely considered the behavior of electromagnetic fields and waves in free space. Under such conditions, the atmosphere is uniform and non-absorbing, and no objects surround or interfere with transmission and reception. In practice however, the environment differs dramatically from free space. Properties of the channel media, like temperature, humidity and interactions with

various materials are particularly important. This section will briefly discuss these issues.

3.8.1 Far-Field Loss and Multipath

Radiated electromagnetic waves propagate through the environment in the far-field. The Field strengths decay as $1/r$, thus, long ranges are more easily achieved. However, the consequence of the free radiation and low decay is increased susceptibility to interference from radiation from the same and/or other sources due to scattering, reflection, and diffraction.

The Far-field losses can be characterized by large-scale affects and small-scale affects. The Large-scale affects are those variations of field strength that happen over larger distances, while the Small-scale affects are characterized by rapid fluctuations over short distances.

Small-scale affects include the multi-path phenomenon, where waves from a single source, having traveled different paths, can constructively and destructively interfere.

Large-scale path loss models and small scale fading models describe these affects respectively [56]. The Large-scale path loss models describe how power is attenuated with distance from a transmitter. These models, modify the typical inverse square law relationship for free space (Equation 3.49) and provide for the attenuation due to atmosphere and material interaction. Thus, we get:

$$PL(R) = \left(\frac{\lambda}{4\pi R} \right)^n \quad (3.59)$$

Where,

for free space, $n = 2$.

Combining equations 3.59 and 3.8.1, we get:

$$P_r = pP_t G_t G_r PL(R) \quad (3.59)$$

Usually, for estimating path loss in indoor environments, a commonly used path loss model is the Log-distance Path Loss Model [56].

$$PL(R)[dB] = PL(R_0) + 10n \log\left(\frac{R}{R_0}\right) + X_\sigma \quad (3.59)$$

Where,

n depends on the surroundings.

X_σ represents a normal random variable with standard deviation of sigma dB.

R_0 is a reference distance (from which to base the path loss measurements). It is usually taken to be 1 meter in indoor environments.

The table below (Table 3.1) shows the values for n and X_σ for various environments at various frequencies. Note: Low values of X_σ represent a more accurate model.

Small-scale fading models describe the multipath phenomenon. Multipath causes large fluctuations in both amplitude and phase over short distances, random frequency modulations, and time dispersion (due to delays). In those environments that contain metals and other reflective objects, multipath can be highly severe. Various statistical models are used to describe multipath; a common measure is the root-mean-square (RMS) delay spread. Buildings with few metals and hard partitions usually have small RMS delay spreads in the range of 30 to 60 ns. Larger buildings with a lot more metal and open aisles can have delay spreads as large as 400 ns. Many techniques are employed to lessen the effects of multipath, these include equalization, diversity and channel coding.

Table 3.1. Log-distance Path Loss Model parameters n and σ for indoor wave propagation

Building	Frequency (MHz)	n	σ
Retail Stores	914	2.2	8.7
Grocery Store	914	1.8	5.2
Office, hard partition	1500	3.0	7.0
Office, soft partition	900	2.4	9.6
Office, soft partition	1900	2.6	14.1
Factory LOS			
Textile/chemical	1300	2.0	3.0
Textile/chemical	4000	2.1	7.0
Paper/cereals	1300	1.8	6.0
Metalworking	1300	1.6	5.8
Suburban Home			
Indoor to street	900	3.0	7.0
Factory OBS			
Textile/chemical	4000	2.1	9.7
Metalworking	1300	3.3	6.8

In RFID, readers usually employ antenna diversity and equalization techniques; Tags, however, due to severe constraints on size, complexity and cost typically do not employ any of these techniques.

3.8.2 Other Antennas

When multiple tags are within close range, coupling between antennas can have detrimental effects on the transfer of power. In the far-field, radiation patterns are usually severely distorted, and power transfer efficiency is subsequently reduced.

3.8.3 Temperature and Humidity

Temperature variations can cause variations in the parameters of matching circuits and subsequent inefficiencies in transferring power. Those systems with high quality factors can suffer serious performance degradation and detuning due to a shift in the

resonant frequency because of changes in the temperature of the environment. Thus, components with low temperature coefficients should be used when possible.

Humidity can also degrade performance. The effects are generally more detrimental at higher frequencies.

CHAPTER 4

THEIA: RFID PERFORMANCE ANALYSIS TOOL

4.1 Introduction

Theia is used to test the performance of RFID Systems in a variety of scenarios. It implements the EPC Class 1 Gen 2 protocol to detect all parameters of the tag. The software operates throughout the entire frequency range of INfinity 510 *viz* 860MHz to 960MHz [35].

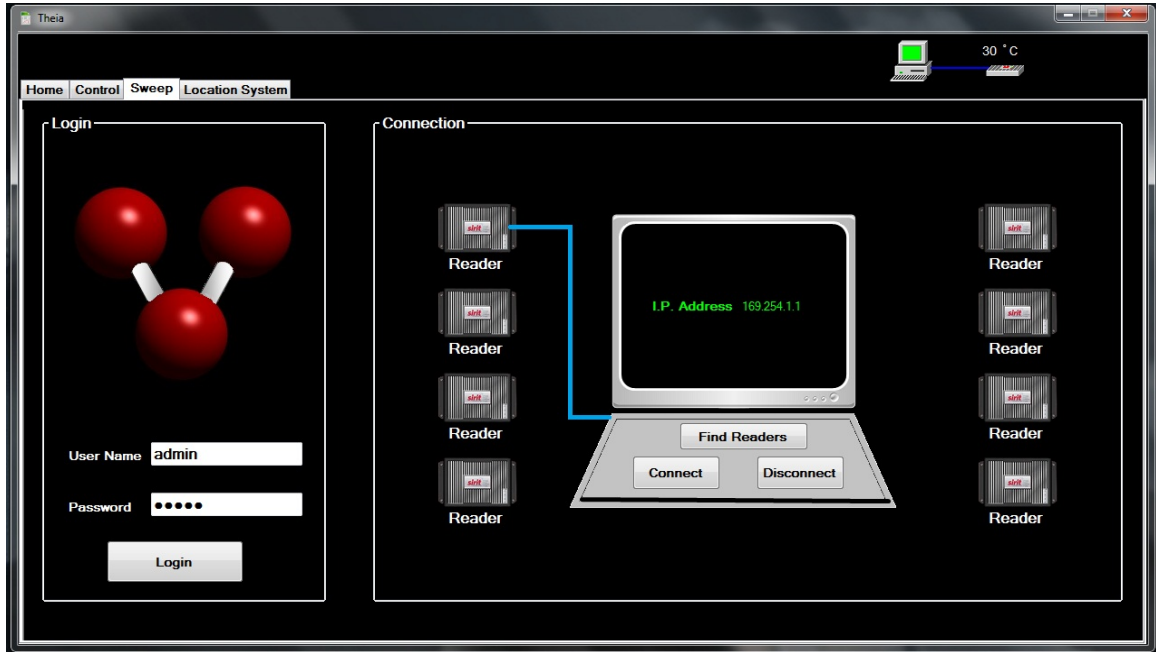


Figure 4.1. Theia.

The software/code was created using Microsoft's Visual C# 2008. *“C# (pronounced “C Sharp”) is a multi-paradigm programming language encompassing imperative, functional, generic, object-oriented (class-based), and component-oriented programming disciplines. It was developed by Microsoft within the .NET initiative and later approved as a standard by Ecma (ECMA-334) and ISO (ISO/IEC 23270)”* [48].

Using C# I created code that accessed the Sirit INfinity 510's configuration and control functions. Essentially, the software is based around the RAPID API, which provides an application a high level interface to the Sirit INfinity 510's data layer.

“RAPID (RFID Application Programming Interface for Developers) is an API that allows system developers to extend the functionality of the INfinity 510 reader by providing server-side access to the readers configuration and control functions.

Currently, the INfinity 510 supports a command and control protocol that provides an interface to the readers connectivity layer. RAPID provides the application developer with a high level interface to the readers data layer [38].”

The software architecture of Theia is based on the .NET framework 2.0, with provisions to directly map the data gathered to an Microsoft Excel workbook, thus allowing for easy data viewing in tabular for as well as advanced data manipulation and graphing. The requirements for Theia to be run can be listed as follows:-

- Hardware Requirements
 - IBM Standard PC, with Ethernet capabilities (RJ45 type)
 - Sirit INfinity 510
 - Four Patch Antennas, with 50 ohm termination
 - Required RF and power cables &

- Software Requirements
 - Microsoft Windows XP upwards, with .NET 2.0 &
 - Microsoft Excel 2003 upwards

4.2 The Sirit INfinity 510 Reader

Before we proceed with the description of Theia, we must understand the Sirit INfinity 510 reader and its capabilities. The Sirit INfinity 510 reader is a multi-protocol, multi-regional Radio Frequency Identification (RFID) reader that can operate in the 860 to 960 MHz UHF band (Figure 4.2) [36].



Figure 4.2. The INfinity 510 UHF RFID Reader.

As shown in Figure 4.3, this reader supports upto four Tx/Rx antennas and one Listen before Talk (LBT) antenna and is equipped with both serial and Ethernet interface ports. Discrete digital inputs and outputs are also provided

[36].

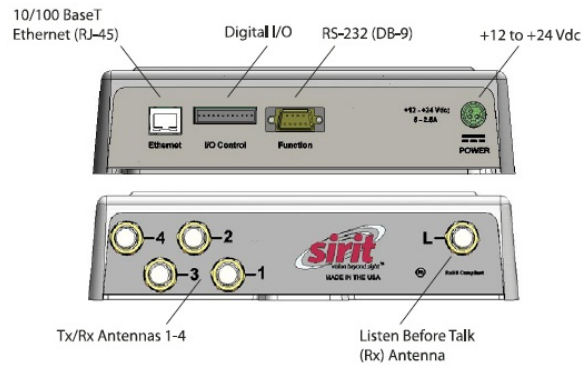


Figure 4.3. INfinity 510 Power and I/O Connections.

The Sirit also has four (4) Light Emitting Diodes (LEDs) located on the top which indicate the current status/task of the reader (Figure 4.4) [35]. The four LEDs are :-

1. Sense - This LED indicates reader has detected a tag in the RF field.
2. Transmit - This LED indicates the reader's transmitter is operating (RF on).
3. Fault - This LED indicates that a fault has occurred or is occurring.
4. Power - This LED indicates that power is applied to the reader.



Figure 4.4. INfinity 510 LED Indicators.

The following tables (Table 4.1 - Table 4.5) and figure (Figure 4.5) provide a quick look at the reader specifications and operating conditions that were relevant for this research work.

Table 4.1. Reader Specifications [36]

Frequency	860 MHz - 960 MHz
RF Power	10 mW - 1000 mW conducted (30 dBm)
Power Consumption	13W (typical while idle) 34W (typical at 1W conducted output power) 40W (maximum at 1W conducted output power)
Connections	RS-232, Digital I/O, Ethernet LAN
Input Voltage	12 VDC - 24 VDC, 60W
Input Current	2.5A maximum at 24 VDC 5.0A maximum at 12 VDC

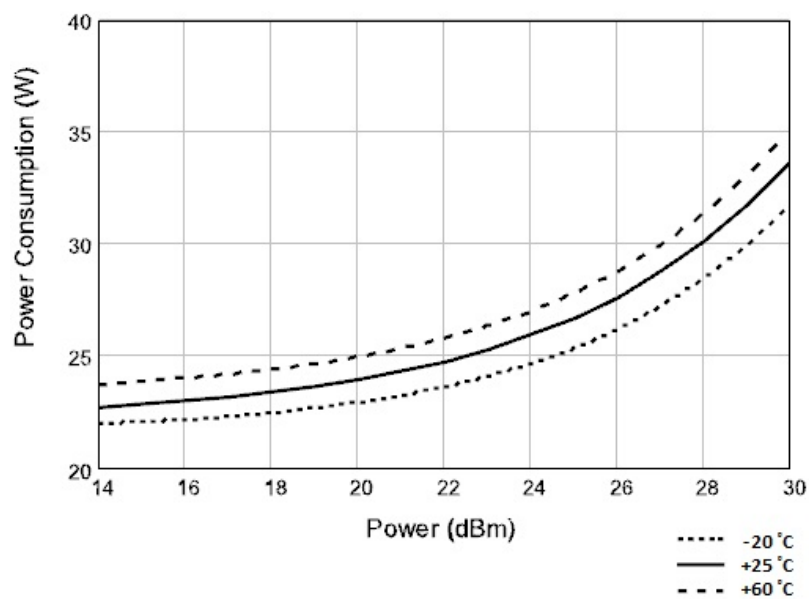


Figure 4.5. Typical Power Consumption versus Conducted Output Power (910 MHz) [36].

Table 4.2. Environmental Specifications [36]

Operating Temperature	-20 C - +55 C
Storage Temperature	-40 C - +85 C
Maximum Shock	0.3m drop to any corner
Relative Humidity	5% - 95% non-condensing
Case Material	Aluminum
Case Dimensions	220 mm x 300 mm x 56 mm
Weight	3.0 Kg

Table 4.3. Power Supply Specifications [36]

Input Voltage	100 VAC - 240 VAC
Input Consumption	60W maximum
Input Frequency	50Hz - 60Hz
Output Voltage	15 VDC
Output Current	4A maximum

Table 4.4. Ethernet LAN Specifications [36]

Connector	RJ-45
Ethernet	10/100 Base T
Indicators	Yellow - Link is operational Green - Network traffic detected
Signals	Pin 1 - TXD+ (Transmit Data +) Pin 2 - TXD- (Transmit Data -) Pin 3 - RXD+ (Receive Data +) Pin 4 - NC Pin 5 - NC Pin 6 - RXD- (Receive Data -) Pin 7 - NC Pin 8 - NC

Table 4.5. Antenna Specifications [36]

Type	Patch
Frequency(FCC)	860 MHz - 960 MHz
Polarization	Circular
Gain	7 dBi \pm 1 dBi, maximum
VSWR, maximum	1.3:1 or less
Axial Ratio	1 dB or less
Input Impedence	50 Ohm (nominal)
Power Handling	10 W
Size	245 mm x 235 mm x 40 mm
Weight	470g

Sirit also designed the INfinity 510 with an API called RAPID (RFID Application Programming Interface for Developers). The API allows the extension of the reader's functionality by providing server-side access to the readers configuration and control functions [36].

“RAPID provides the application developer with a high level interface to the readers data layer” [38].

Thus, with knowledge of RAPID, I was able to access the reader's data layer, by creating a program using MS Visual C# to create an application, code-named Theia.

4.3 The Graphical User Interface (GUI)

The system is currently composed of three main sections. These three sections are contained within the tabs on the top left hand side of the page. The user can go from one section to the other by clicking on these tabs. The first tab is the **Home** tab (Figure 4.7), which is the login, connection/disconnection, and reader selection page. The second tab is the **Control** tab which sets various operating modes and shows the

events channel and the commands sent by the user and responses of the reader (shown in Figure 4.8). The third tab goes to the **Sweep** page which is shown in figure 4.16. In this page the frequency and power sweep operations will be run, and plots will be made to represent the electromagnetic threshold analysis, and backscatter analysis.

4.3.1 The Home Page

The Home Page has different login levels in order to abstract the functionalities offered by Theia for both safety and upgrade issues. Theia has three distinct login levels (Figure 4.6):-



Figure 4.6. The Home Page.

User/Guest login level : This provides only the basic reader functions to the user. To login at this level, User name : user, Password : user.

Table 4.6. The Login Information

Login Level	User Names	Passwords	Color
User/Guest	user	user	Red
Administrator	admin	admin	Green
Support/Programmer	support	xxxx	Green

Administrator login level : This provides the user with the advanced functionalities required for performing experiments like backscatter analysis and electromagnetic threshold analysis. To login at this level, User name : admin, Password : admin.

Support/Programmer login level : This provides the user with the advanced functionalities as well as raw view of the data as it is captured, this login level is for debugging purposes only. To login at this level, User name : support, Password : xxxx.

Once a user has successfully logged on, Theia then displays a new box, the screen shown below (Figure 4.7) as compared to earlier (Figure 4.6). In this new box (Connection), the user is allowed to select which reader they want to connect to. The more readers that are connected to the network, the more that will display. Theia has the ability to allow for a collection of upto eight (8) readers. By selecting a reader the user's PC is directed to establish a connection with the selected reader.

The top right hand corner of the screen displays the current status of the connection. Based on the color of the screen of the PC icon a user can judge at what login level they are currently at. The connection line between the PC icon and the reader icon shows whether the connection between reader and PC is active. Once a connec-

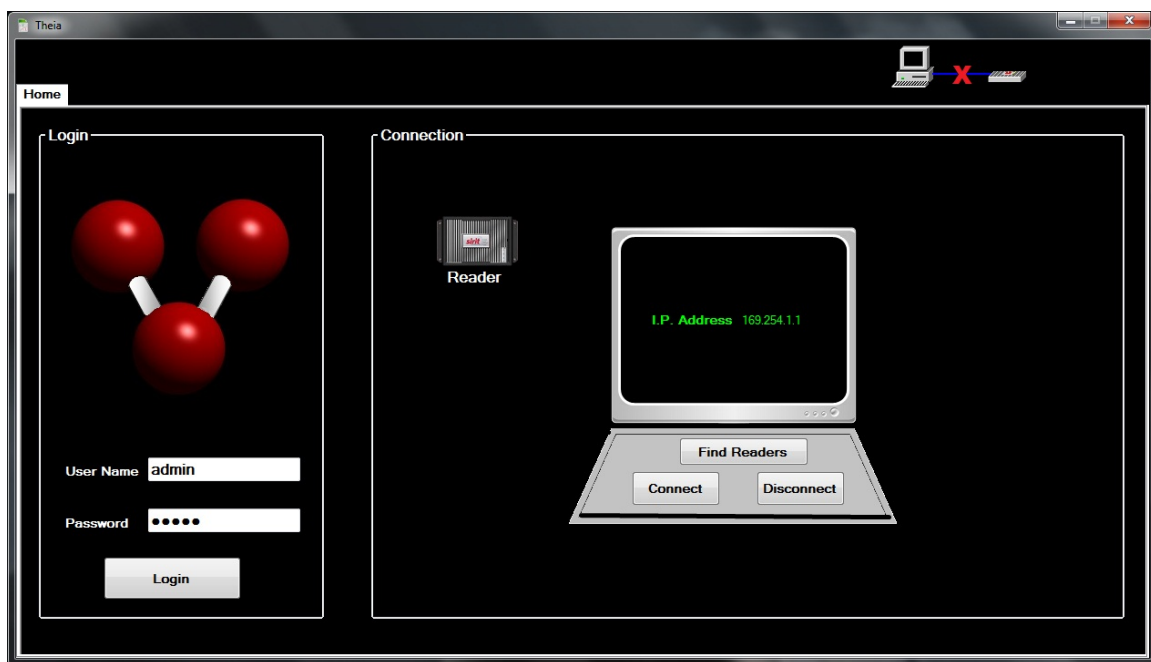


Figure 4.7. The Home Tab (Showing login and reader selection).

tion is established and is active, Theia displays the remaining tabs, allowing the user to access the various functionalities offered by Theia depending on the access/login level. **Please Note**, from this point on the right hand top corner of the screen, shall be referred to as the Indicator Icon/ Status Icon.

4.3.2 The Control Page

The Control Page has the the common reader functions as well as the advanced functions that are required for the analysis operations like, The Carrier Wave, Find All Tags in Interrogation Zone, Event Channel (Figure 4.10) and The Spectrum Analyzer.

Typically in a reader/tag communication the reader generates a carrier that powers up the tag, and sends the tag various commands by modulating this carrier signal. The tag communicates back to the reader by modulating the signal reflecting from it. The Theia system measures the various properties of the tag during the communica-

tion process. Thus Theia keeps track of the generated RF carrier and the modulated carrier. The System allows for the option to generate the carrier wave even when no communication is taking place, thus the tags within the field can optionally be kept powered even when no communication is taking place (Figure 4.8). The following figures (Figure 4.8 - Figure 4.9) show the various extended functionalities offered on the control page.

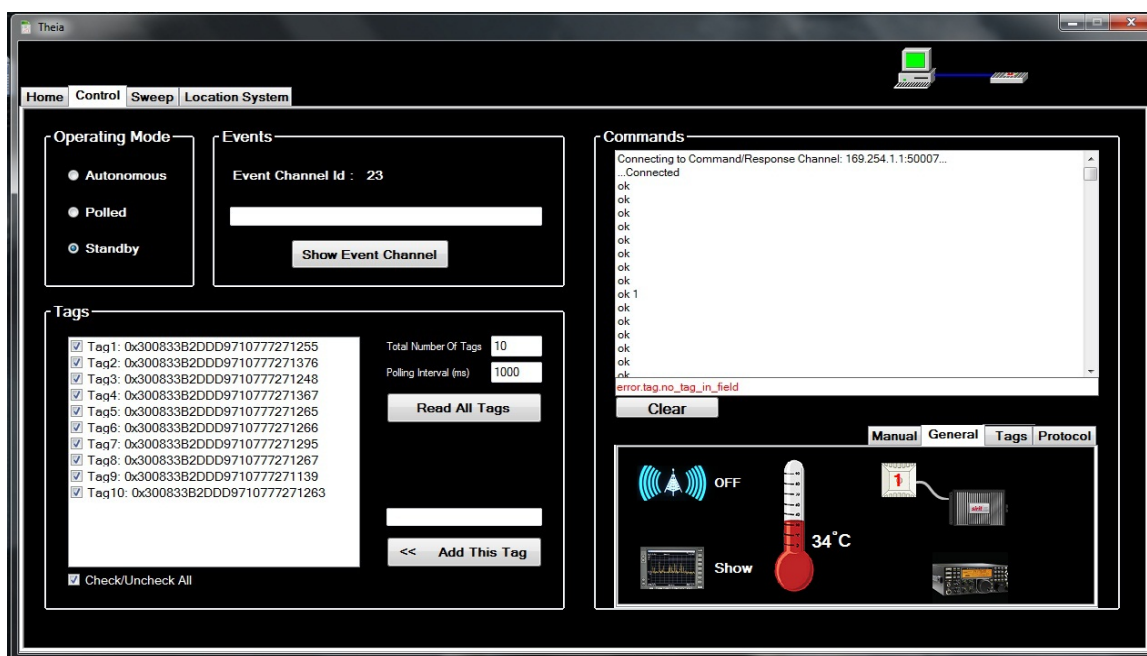


Figure 4.8. The Control Page.

Additional parameters that one can control with this software vary from tag fields that can be read, to number of inventory rounds. Also provided is a Spectrum Analyzer with frequency span of upto 6.4MHz for the frequency range of 860MHz to 960MHz and resolution of upto 5kHz (Figure 4.11).

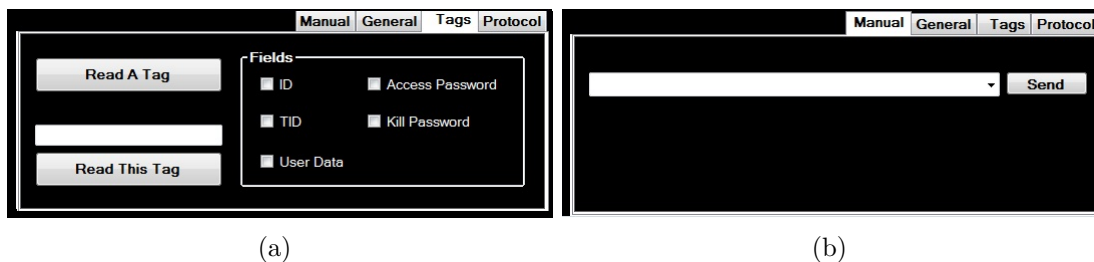


Figure 4.9. The various functionality tabs of the Control Page (a)The Tag Controls Tab (b)The Manual Controls Tab.

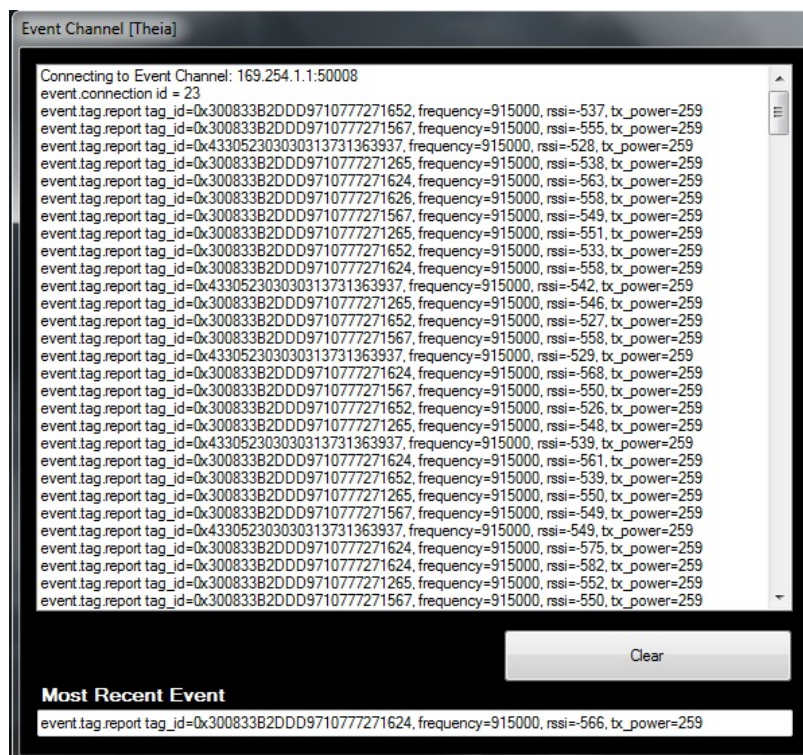


Figure 4.10. The Event Channel Page.

The spectrum analyzer shows the current RF energy present within the read zone of the INfinity 510's antennas. Although not as sensitive as a stand alone system, this functionality is provided to allow a user a quick look at the RF noise in the area (read zone) should the need arise.



Figure 4.11. The Spectrum Analyzer.

4.3.3 The Sweep Page

The Sweep Page provides the functions necessary to perform an analysis of the reader to tag and tag to reader communication. The analysis of the communication is performed by doing two “Sweeps”.

Theia allows for the selection of a single specific tag, or multiple tags simultaneously (Figure 4.8 and Figure 4.16). Theia can then sweep over the entire frequency range with power ramp-up at each frequency, hence allowing us to measure the “**Turn-On**” power of the tag/tags. Similarly the tag sensitivity to various power levels at a known fixed frequency is determined by doing a power sweep where for each power level the tag’s reflected power is plotted. The power of the backscatter signal is measured from recording the tags response to a command. This information will be calculated while reading the tag using the Gen2 protocol. The Theia system has a power range of

0dBm to 30dBm(1mW to 1W) with tenth of a dBm steps allowed, and a frequency range from 860MHz to 960MHz with kHz steps allowed.

4.3.3.1 Electromagnetic Threshold Analysis *a.k.a.* The Frequency Sweep

The Frequency Sweep is performed by choosing a range of frequency between 860MHz and 960MHz. This range selection is done by specifying the following values

1. The upper value of the frequency range (Upper Frequency).
2. The lower value of the frequency range (Lower Frequency).
3. The value of increment of frequency (Frequency Step).
4. The value of increment of power (Power Step).

Figure 4.12. The Frequency Sweep Tab.

This sweep also allows a user to choose the antenna which is to be used to perform the analysis (Figure 4.12). The frequency sweep measures the “Turn-On” power for each tag, i.e. The minimum power of the transmitted signal of the reader that is

required for the tag to give a valid read. The algorithm that is used by the system can be best explained and understood by the use of a flowchart (Figure 4.13).

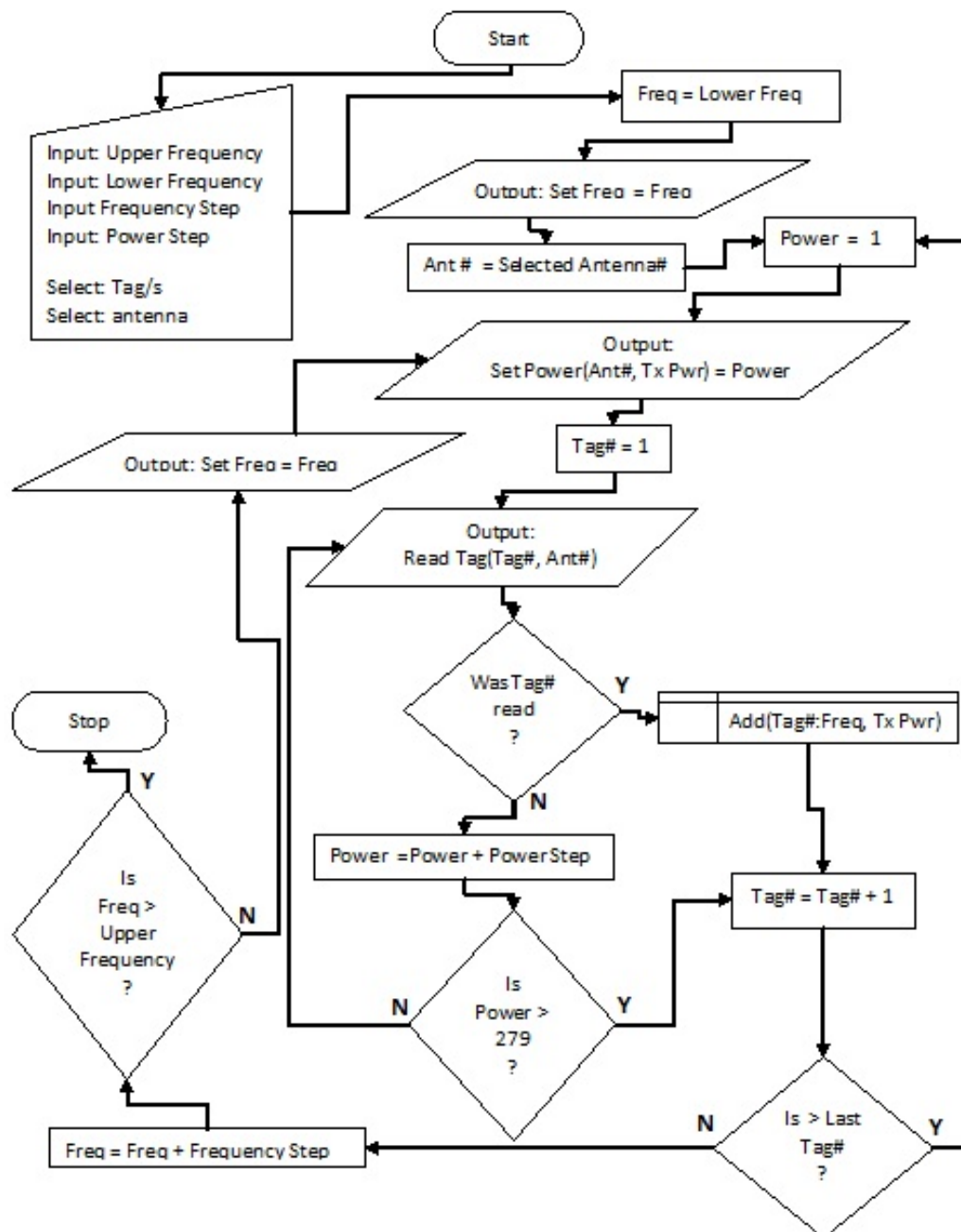


Figure 4.13. Flowchart of the Frequency Sweep.

4.3.4 The Backscatter Analysis *a.k.a* The Power Sweep

paragraph The Power Sweep is performed by selecting a range of power between 0.1dBm and 27.9dBm. The term ddBm that is used in the software is used to denote a tenth of a dBm. The values that have to be specified for a power sweep are:-

1. The upper value of the power range (Upper Power).
2. The lower value of the power range (Lower Power).
3. The value of increment of power (Power Step).
4. The frequency of operation (Frequency).

Figure 4.14. The Power Sweep Tab.

For this sweep a user has also to choose the antenna/s which is/are to be used to perform the analysis (Figure 4.14). The power sweep measures the tag sensitivity to various power levels at a known fixed frequency for each tag. This is done by measuring the power level of reply (backscattered) signal of a tag. The algorithm

that is used by the system can be best explained and understood by the use of a flowchart (Figure 4.15).

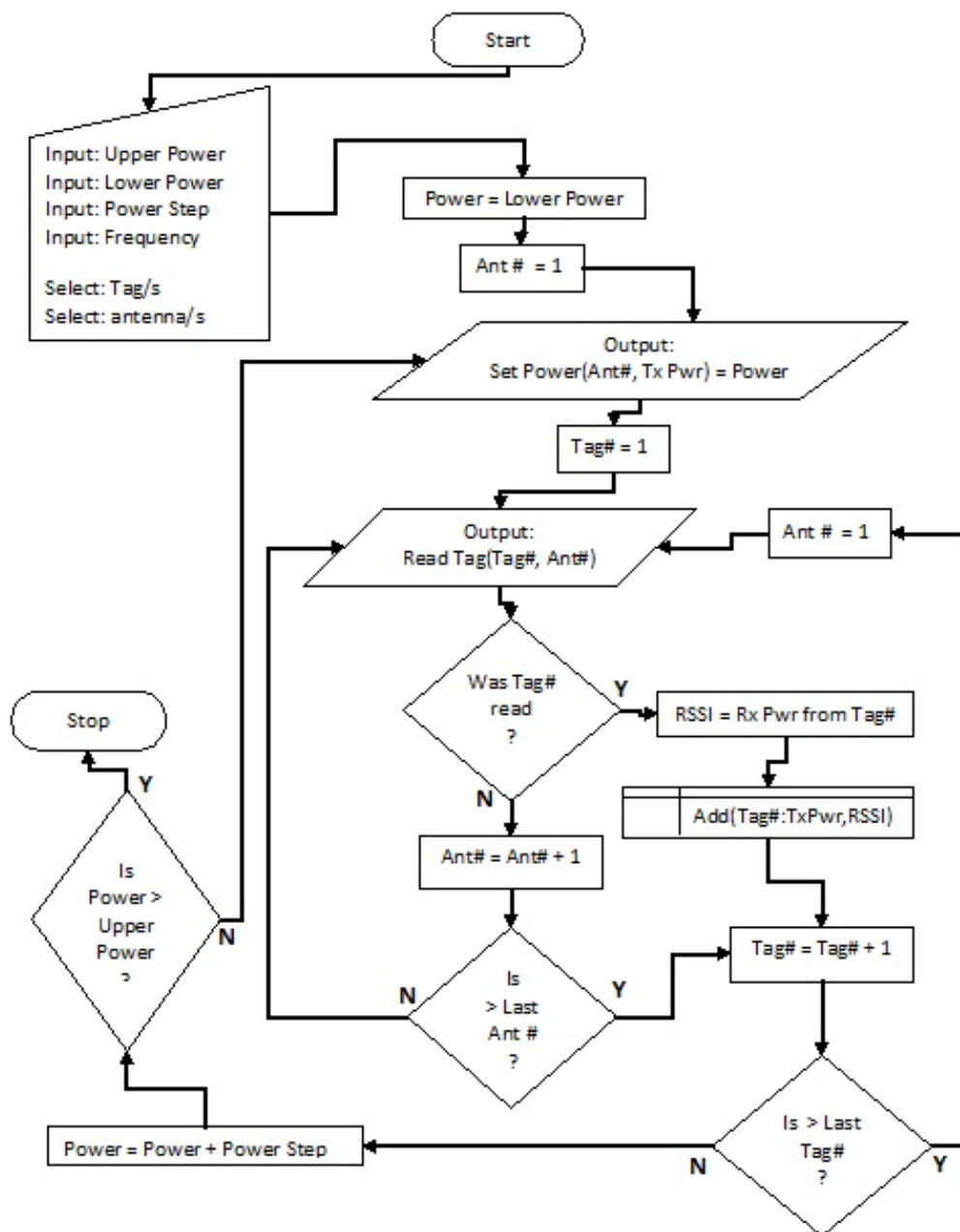
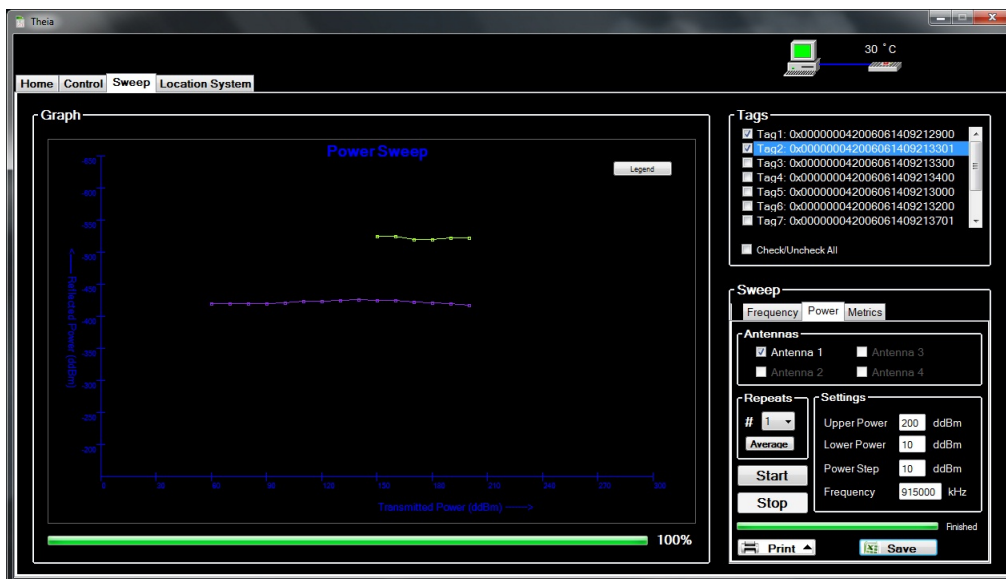
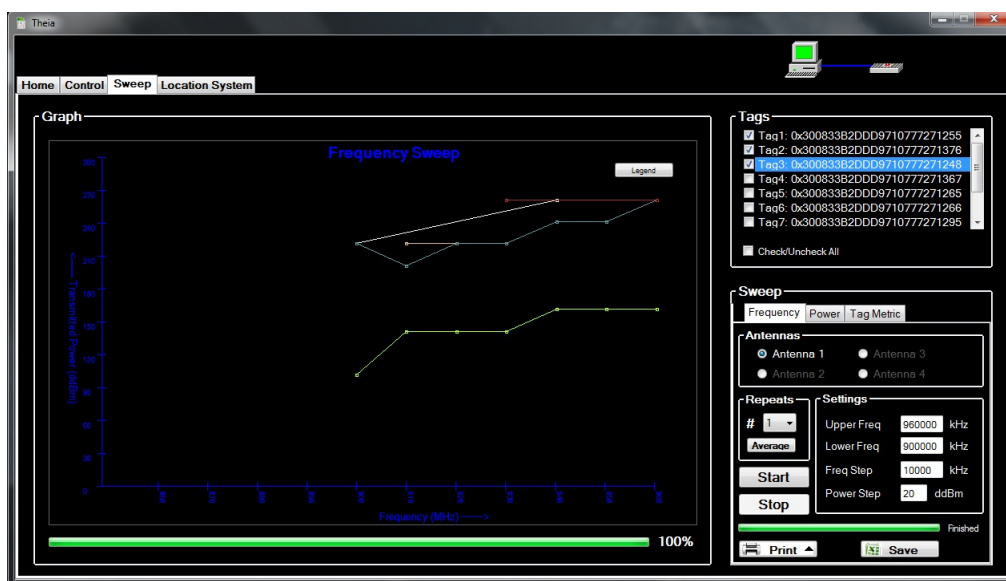


Figure 4.15. Flowchart of the Power Sweep.

The figures below show the power and frequency sweep graphs that were produced in real time.



(a)



(b)

Figure 4.16. The Sweep Pages (a)The Power Sweep Page (b)The Frequency Sweep Page.

Further on in this paper(Chapter 4), the procedure of obtaining tag metrics using the frequency and power sweep functionalities will be discussed. In this chapter and specifically this section, the tag metric and reader metric calculation functionality is covered. The reason for this, is that, Theia automates the methods for the Tag Metric and Reader Metric calculation. These functions are seen in the following figures (Figure 4.17 - Figure 4.19).

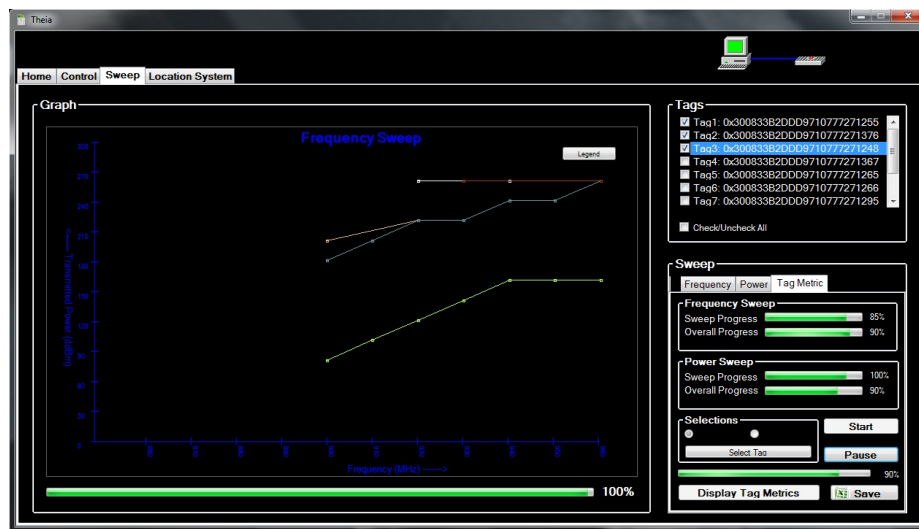


Figure 4.17. The Frequency Sweep Page for Tag/Reader Metric calculation.

The tabs to be noted in the figures (Figure 4.17 - Figure 4.19) are the “Tag Metric” tab and the “Reader Metric” tab. The reader metric, since it is dependent on the tag metric, will only be accessible after calculating the tag metric. Thus, the Reader Metric tab will appear only after the Tag Metric calculation is done.

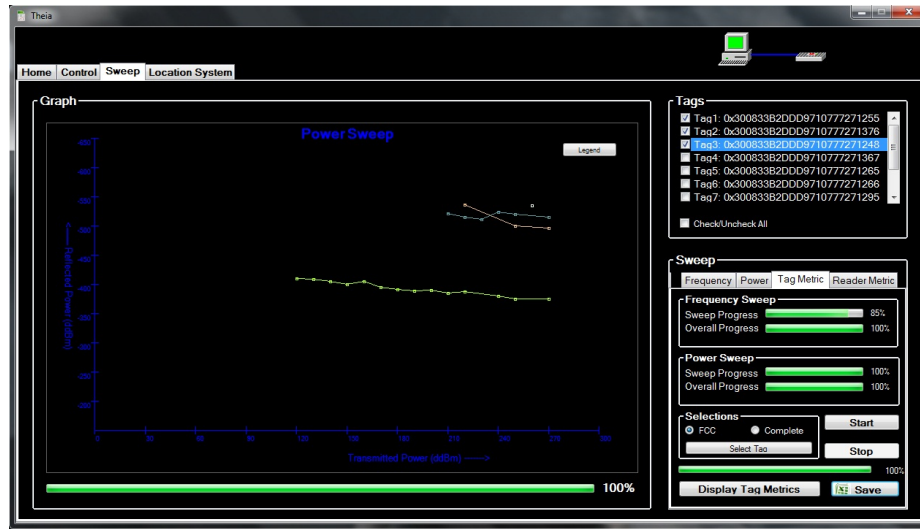


Figure 4.18. The Power Sweep Page for Tag/Reader Metric calculation.

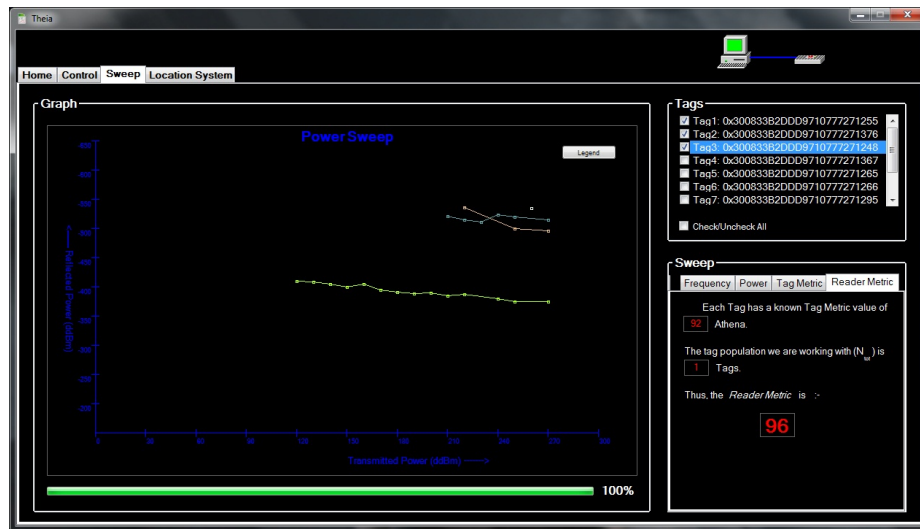


Figure 4.19. The Reader Metric calculation.

4.4 Software Architecture

Logically following the discussions and subsequent understanding of both the Sirit INfinity 510 and the graphical user interface of Theia, we can now proceed with the explanation of the software architecture of Theia, that is, a brief overview of the inner constructs that make up “*Theia: RFID performance analysis tool*”. The first

task of this software is to establish a communication channel/s over the Ethernet port with the Sirit INfinity 510 reader. Based on the specifications provided in the Sirit documentation, this communication channel can be setup using TCP protocol and using TCP IP ports 50007 for the command channel and 50008 for the event channel. The command channel is a bidirectional(full duplex) interface for sending commands and receiving responses. The event channel is a unidirectional channel directed towards the PC, i.e. the event channel simply sends asynchronous events such as errors, tag arrival and digital output triggers (Figure 4.20) [37].

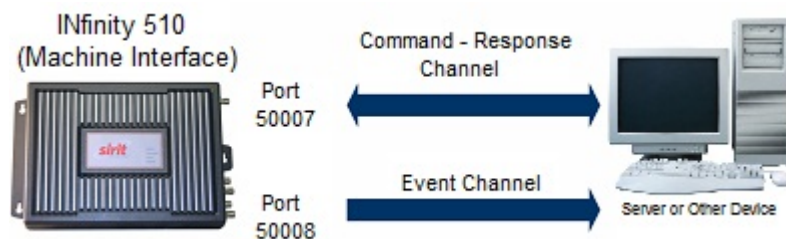


Figure 4.20. The INfinity 510 Communication Channels.

In order to perform the required tasks as well as provide abstraction of subtasks for current, as well as future work, the code can be considered to contain five(5) basic classes :-

- Main
- Excel
- CnxMgr
- Spectrum Analyzer
- Event Handler

4.4.1 Class MainUI : Form

The main class is the starting point for the application. This class defines the GUI of the opening form, from which the other forms that constitute the application are launched. The main creates two connection objects (instances of the CnxMgr class), one for the command/response channel and one for the event channel. In order to maintain responsiveness of the GUI since the task of performing the sweeps is time intensive, there are five(5) background worker threads defined in this class:-

backgroundWorkerp : runs the algorithm necessary for controlling the power sweep functions, these include :

- The checks for the correctness of the manually entered values for upper power, lower power, power step, and frequency of operation.
- The start of sweep, stop of sweep, pausing the sweep.
- The calls to the methods that start bw_graph_p.
- The creation of an excel workbook and the saving of the captured data to it.

bw_graph_p : performs the task of drawing a graph of the power sweep data, as well as maintaining the legend and the progress bar.

backgroundWorkerf : runs the algorithm that controls the frequency sweep.

The tasks that are performed by this thread are :

- The checks for the correctness of the manually entered values for upper frequency, lower frequency, frequency step, and power step.
- The start of sweep, stop of sweep, pausing the sweep.
- The calls to the methods that start bw_graph.f.
- The creation of an excel workbook and the saving of the captured data to it.

bw_graph_f : performs the task of drawing a graph of the frequency sweep data, as well as maintaining the legend and the progress bar.

backgroundWorkerm : runs the algorithm that controls the metric calculation by in turning controlling the frequency and power sweeps. The tasks that are performed by this thread are :

- The checks for the correctness of the manually entered values for upper frequency, lower frequency, frequency step, and power step.
- The checks for the correctness of the manually entered values for upper power, lower power, power step, and frequency of operation.
- The start of sweeps, stop of sweeps, pausing the sweeps.
- The calls to the methods that start bw_graph_f and bw_graph_p.
- The creation of an excel workbook and the saving of the captured data to it.

Aside from the above mentioned threads MainUI also has other timer threads that perform the time scheduled tasks like temperature monitoring and event data updating. MainUI also performs the tasks of the login password checks and task/s abstraction based on the the login level. The MainUI class/form is the most important part of the application.

4.4.2 Class Event Handler : Form

The Event Handler class/form can be considered as the next most important class/form of the software/application. Within the Event Handler class/form there is a single minded task carried out. A task with drive and clarity of vision. The task is to monitor the event channel/port 50008 for asynchronous data from the connected reader and as soon as it is received dissect it and present it to the rest of

the application. The reason for this is that data is in the form of a string, hence the need to dissect it. The Event Handler dissects or sorts the data into the following types:-

- Tag Identification Number i.e. the Identification number stored in the tag's memory
- Transmit Power i.e. the value of transmitted power from the reader antenna
- Frequency i.e. the value of frequency of operation of the reader
- Received Signal Strength Indicator (RSSI) i.e. the value that indicates the power level of the received power/backscattered power from the tag.
- Tag Number i.e the identification number for the tag, the number that identifies the tag, not the product

The Event Handler form also maintains a collection, a list of the event strings sent from the reader in order of reception. This list can be viewed by the user, as well as cleared. The most recent event string is always sent to MainUI and is always displayed in the Event Handler form.

4.4.3 Class Spectrum Analyzer : Form

The Spectrum Analyzer class/form is another functionality offered by Theia. In this form is displayed the current RF energy levels present in the read-zone of the Infinity 510's antennas. The Spectrum Analyzer allows the user to examine the spectral composition of the radio waves in your surrounding environment. This functionality provides a graphical representation of the current spectral RF noise in units of dBm. The spectrum analyzer has a range of 0 to -120 dBm. This feature is intended for expert users to verify RF environmental conditions during testing an installation

procedures. The user can customize this graphical display and the sensitivity. The parameters excepted form the user to this form/class are as follows :-

- Center Frequency - The user is allowed to specify the center frequency. If not specified the current frequency is used
- Resolution Bandwidth - This allow the user to specify the bandwidth resolution.
- Frequency Span - The user has to specify the span of the spectrum analysis.
- Coherent Scaling On/Off - This allow the user to enable/disable coherent scaling.
- Output Frequency - The user can choose to focus on the RF spectral component at a single frequency only.

The results of this function are scaled to account for all system gains.

4.4.4 Class CnxMgr

This class has the variables and methods necessary for the creation of connection objects. These connection objects are for the purposes of establishing connections with the reader over the Ethernet LAN using the TCP/IP sockets protocols.

4.4.5 Class Excel

The excel class has the singular purpose of creating objects that are related to the creation and data mining/embedding to and from excel workbooks. The reason for this is that Microsoft excel is a very powerful tool for the purposes of data handling, manipulation and graphing. The excel objects (instances of the excel objects) are accessed/created only by the MainUI and spectrum analyzer classes. Recalling the functionalities offered by the afore mentioned classes we see that only they present

the user with tabular data, hence only these two classes have need of providing excel functionality to the user.

CHAPTER 5

RESEARCH METHODOLOGY

5.1 Introduction

In this chapter we will cover what is a metric, the equipment that was used and the procedural steps that were used to generate the Reader Metric and how these steps were derived.

5.2 Metric

A metric is the measurement of a particular characteristic of a system's performance.

In the case of a business scenario we can define a business metric as “*A business metric is any type of measurement used to gauge some quantifiable component of a company's performance, such as return on investment (ROI), employee and customer churn rates, revenues, EBITDA, and so on. Business metrics are part of the broad area of business intelligence, which comprises a wide variety of applications and technologies for gathering, storing, analyzing, and providing access to data to help enterprise users make better business decisions. Systematic approaches, such as the balanced scorecard methodology, can be employed to transform an organization's mission statement and business strategy into specific and quantifiable goals, and to monitor the organization's performance in terms of achieving those goals*” [15].

To elucidate, we can use the analogy of the octane rating i.e. we can say a metric is similar to the octane value of gasoline. The Octane number of gasoline is a

measure of its resistance to knock. This octane number/value is defined in terms of two parameters, Iso-octane and n-Heptane. Isooctane is given an octane value of 100 while n-Heptane is given octane value of 0. Thus, gasoline with an octane value of 'X' can be interpreted as having same anti-knocking property as the gasoline with X% of Isooctane and (100 - X)% of n- Heptane. The speed at which the engine is running has an impact on the Octane rating and thus, often the Octane rating is calculated as the average of two values. One of the values is the research octane number (RON), which is determined with a test engine running at a low speed of 600 rpm, the other value is the motor octane number (MON), which is determined with a test engine running at a higher speed of 900 rpm. Thus the Octane rating is given by the formula

$$OctaneNumber = \frac{RON + MON}{2} \quad (5.0)$$

Now that we have an understanding of what a metric is, we can proceed with discussing the theory behind and involved with the calculation of the reader metric.

We start with a recap of an RFID system's operation. An RFID system basically consists of three components; A Tag, A Reader and An Information System/Middleware. The interaction between these components can be seen in figure 5.1.

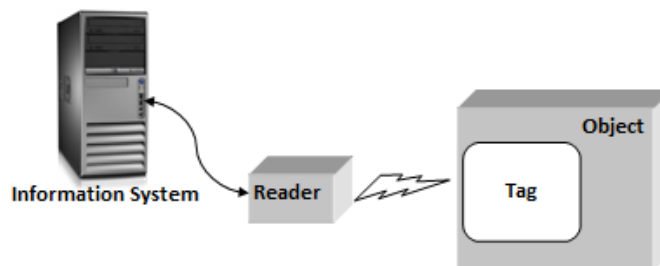


Figure 5.1. The Main Components Of An RFID System.

As this thesis deals with the performance of a reader, hence we only need to consider the interactions between the reader and the tag/tags. The performance of reader we can thus define very simply as, *The better the read ability of a reader, the better it is performing*. Thus, we what is needed to calculate a reader metric is to have a comparison of the read ability of the given reader to an ideal reader. An ideal reader being a system with the best possible read performance under a given set of conditions, hence establishing a Gold Standard.

The reader metric can thus be defined as the comparison of the given/test reader's tag read ability to that of the gold reader's tag read ability. Since the reader's read ability depends on how well it is reading a tag, it is thus easily deducible, that in order to have a reader metric we must firstly have a tag metric. This tag metric that we choose will form the **Gold Standard** and the equipment/reader used to obtain the metric will become the **Gold Machine**.

5.2.1 The Gold Standard

Work in the area of tag metrics has been plentiful. Researchers have tried to define the performance of tags based on the various tag parameters, but so far they have done so by only taking these various parameters individually [39]. The various tag parameters that have been used so far to define tag performance include :-

1. Minimum required reader transmitted power, for reading a tag at a set distance, at a particular frequency
2. Frequency read variability
3. Orientation sensitivity
4. Read distance of tag
5. Effect of tagged object on tag (i.e. effect of water and metal on tags)

Of the various work done in the area of tag metrics, the tag metric that was chosen as the *Gold Standard* was the *Athena “Tag” Metric*. The Athena Tag Metric takes into account all the above mentioned parameters when calculating the metric that defines the tag performance [39]. The Athena Tag Metric (or Tag Metric from now on in this paper), allows a consumer to choose the best tag depending on the requirement. The tag metric ranges between 1 and 100, with a higher value indicating a better performing tag. The tag metric value tells the consumer how efficient a given tag is, for a given set of conditions, for a given application. In essence, the higher the tag metric, the higher is the probability of the given tag being read and thus, higher is the efficiency of the overall system under the given conditions [39]. The **Tag Metric** is calculated based on the following parameters :-

- Frequency Of Operation
- Transmitted Power from the Reader
- Orientation of the Tag with respect to Reader Antenna &
- Environmental Conditions

In this discussion however (as provided for by the Athena Tag Metric), we will consider the **Tag Metric** under constant orientation, with minimal effect of environmental conditions [39]. Thus, the **Tag Metric** is calculated by using the backscattered power at a particular frequency, in the ideal case and hence the case we will use as the reference from now on 915MHz [39]. The formula below gives the value of the tag metric (Equation 5.2.1):-

$$Metric = -\frac{7}{2} \left(\frac{1}{\ln(-\frac{1}{P_b})} \right) \times (112 - P_{TX}) \quad (5.0)$$

Where,

P_b is the backscattered power of the tag, at minimum value of P_{TX} .

P_{TX} is the transmitted power from the reader at which P_b is chosen.

With the above formula, we can thus calculate the tag metric. The unit of the tag metric is “Athena”. For example, let us consider two types of UHF Gen2 tags under a similar set of test conditions and calculate the metric for them:-

Example 5.1 *The Alien Squiggle tag*

Here, $P_b = -45.153$ dBm and thus,

$$\begin{aligned}
 Tm &= -3.5\left(\frac{1}{\ln\left(-\frac{1}{-45.153}\right)}\right) \times 100 \\
 &= -3.5\left(\frac{1}{\ln(0.022155754)}\right) \times 100 \\
 &= -3.5\left(\frac{1}{-3.809657999}\right) \times 100 \\
 &= -3.5(-0.262490753) \times 100 \\
 &= 0.918717638 \times 100
 \end{aligned}$$

\therefore Tag Metric = 92 Athena

Example 5.2 *The Bow-Tie tag* Here, $P_b = -40.351$ dBm and thus,

$$\begin{aligned}
 Tm &= -3.5\left(\frac{1}{\ln\left(-\frac{1}{-40.351}\right)}\right) \times 100 \\
 &= -3.5\left(\frac{1}{\ln(0.024782533)}\right) \times 100 \\
 &= -3.5\left(\frac{1}{-3.697616178}\right) \times 100 \\
 &= -3.5(-0.270444511) \times 100 \\
 &= 0.946555789 \times 100
 \end{aligned}$$

\therefore Tag Metric = 95 Athena

Thus we can say that for our given test conditions, since the Bow-Tie tag has a higher tag metric value compared to the Squiggle tag, the Bow-Tie tag will have a better performance.

Having understood the formula used to calculate the Tag Metric, we must delve further into the procedure behind the acquisition of the tag metric that was used. The procedural steps are as follows :-

For a given set of test conditions,

1. Perform an **Electromagnetic Threshold Analysis / Frequency Sweep**
2. Choose F_{PS} (from the data collected), the frequency at which the value of P_{TX} is minimum for the given tag
3. Using F_{PS} as the frequency, perform a **Backscatter Analysis**.
4. Choose P_b (from the data collected), the received power/backscattered power, at which the value of P_{TX} is minimum

5.2.2 The Gold Machine

Having established the tag metric that we will use, we can continue our discussion with the description of the “Gold Machine”. In research that was conducted to create the Athena Tag Metrics, the *gold machine* was the *Voyantic TagformanceLite Measurement System* by Voyantic Ltd (hereafter referred to as the Voyantic System) (Figure 5.3)[39]. Thus, the Voyantic becomes the gold machine and the data (Tag Metric Values), that was generated using this system becomes our **“Gold Standard”**.

The voyantic system is specifically designed to measure the performance of an *EPC Class 1 Gen 2 'passive UHF RFID tag'*. The Voyantic Tagformance Lite is designed

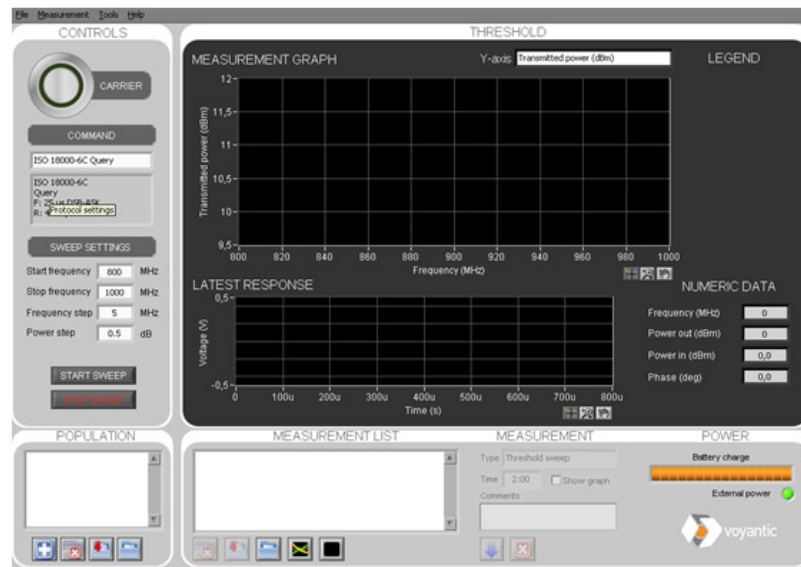


Figure 5.2. The Voyantic Tagformance Lite System GUI.



Figure 5.3. The Voyantic Tagformance Lite Views (a)The Voyantic System Front (b)The Voyantic System Back.

for indoor use only. The voyantic has a typical warm-up time of 10 minutes, and is rated to work best within the temperature range of $0^{\circ}C$ - $40^{\circ}C$, at a non-condensing relative humidity of 0% - 95%. The tables below (Tables 5.1 - 5.3) give a brief overview of the specifications of the Voyantic Tagformance Lite System.

The measurement unit of the Voyantic System, consists of a RF generator unit that is used both for generating the RF carrier signal and modulating it with an arbitrary waveform. The specifications of the carrier and the modulation signal are shown in the table below :-

Table 5.1. Carrier and Modulation Signals specifications

Carrier Specifications Parameter	Typical Value	Unit
Frequency Range (Standard)	860 to 960	MHz
Frequency Range (Extended)	800 to 1000	MHz
Frequency Resolution	100	kHz
Frequency Accuracy	± 10	ppm
Output Power	0 to +27	dBm
Output Power Resolution	± 0.1	dB
Output Power Absolute Accuracy	± 1	dB
Output Power Uniformity	± 0.5	dB
Output Impedance	50	Ω
Modulation Modes	DSB-ASK and PR-ASK	-
Modulation Depth	0 to 30	dB
Modulation Waveform Resolution	16-bit (non-linear)	-
Modulation Waveform Sample Rate	1000	kS/s

The Voyantic's RF receiver includes the ability for retrieving the backscattered signal waveform from the reflected carrier. The detailed specifications are presented below:-

Table 5.2. Backscattered Signal Waveform Parameters

Parameter	Typical Value	Unit
Usable Linear Dynamic Range	-80 to +10	dBm
Absolute Maximum Input Power	+30	dBm
Sensitivity	-80	dBm
Backscattered Waveform Resolution	16 bit	-
Backscattered Waveform Sample Rate	1000	kS/s
Input Impedance	50	Ω

The working of the system is as follows, an RF carrier signal is generated, modulated and is sent to the tag by the transmitter of the Voyantic, the Voyantic receiver

Table 5.3. Protocol Specifications

Parameter	Value
Supported Protocol	ISO 18000-6C (EPC Class 1 Gen2)
Forward Link	DSB-ASK, $T_{\text{ari}} = 25\mu s$
Return Link	FM0, $f_d = 40$ Kbps
Supported Commands	Full Command Set
Receiver Sensitivity	-80 dBm

listens and receives the backscatter from the tag, which is stored and is displayed as acquired waveform (response). The sensitivity and the strength of the backscatter signal are the two most important performance parameters that a tag produces. The sensitivity of a tag is measured by determining the minimum required power to be transmitted by the reader antenna, for the tag to be able to respond to a command. The backscatter signal (The modulated reader signal returning from the tag), is measured by recording the tag's response to the readers command [47].

The Voyantic gives the user ability to perform two kinds of measurements; *viz.* The Electromagnetic Threshold Analysis and The Backscatter Analysis. The Electromagnetic Threshold Analysis corresponds to the sensitivity parameter of the tag. It plots the graph of different measurement values taking operational frequency of the Voyantic as the base axis (hence, this is a Frequency Sweep). The Backscatter Analysis gives the backscattered-signal analysis, where the base axis is the transmitted power of the Voyantic(hence, this is a Power Sweep).

The graphical user interface of the Voyantic System is shown in the figure above (Figure 5.2). The *Measurement Graph* area in this figure shows the frequency sweep over the extended frequency range of 800MHz - 1000MHz. The *Latest Response* graph-area shows waveforms corresponding to any activity on the antenna. This

graph area shows the waveform for the transmitted signal as well as for the response. The Voyantic System has a frequency range of 800 MHz to 1000MHz, but the ranges which were relevant to this research work are :- between 860 to 960 MHz and the FCC approved range in US (902 to 928 MHz).

Just as was described earlier on in this work, under the section “The Method”, the procedure followed to obtain the tag metrics was performed on th Voyantic System. In case of the frequency sweep, the range used was 860 to 960 MHz, with the frequency step of 5 MHz. The power step used is 0.5 dBm. For each value of frequency the system tries to read the tag at minimum power and increases the power in step of 0.5 dBm. It saves the minimum value of power at which the tag is read and then jumps to the next frequency.

For the power sweep, the frequency at which the power sweep was carried out was obtained from the prior frequency sweep. In the power sweep the system calculates the received power at the reader antenna from the tags response for each value of transmitted power. The transmitted power range for the system was 0 - 27dBm. The power step was 0.5 dBm here as well. For each transmitted power value the reader looks for the tag response, logs it, and jumps to the next value of transmitted power.

5.3 The Reader Metric

Before we proceed with discussing the methods to obtain the *Reader Metric*, we will first enumerate the requirements of a metric. The requirements of a metric define what we want the reader metric to be; in other words what are the rules the Reader Metric must conform to. The requirements that the Reader Metric should meet are :-

1. The Reader Metric should work for all Passive UHF Gen2 readers.
2. The Reader Metric should be between 1 and 100.
3. The Reader Metric should be universal.
4. The Reader Metric should be repeatable on a similar system in a similar environment.
5. The Reader Metric should define the generic read performance of the reader.
6. The Reader Metric should be a real natural number that is easily understood/interpreted by the user.

With these rules of The Reader Metric clearly defined, we now proceed to the methods used to obtain the *Reader Metric*.

The method used to calculate the Reader metric was mentioned earlier on in this chapter. We, will now continue with the discussion of this method in detail.

Since, Theia can perform the same functionalities as the Voyantic and beyond, we can thus calculate the Tag Metric using Theia (on The Sirit Infinity 510) as well. Thus, using Theia, we can calculate a tag metric and compare this value with the actual Tag Metric value, hence creating a “Reader Metric”. To make the calculation of the reader metric clear, we will summarize the previous sections including this section, and also provide two examples, *exempli gratia*, so that we will have “The steps used to calculate the **Reader Metric**”:-

1. For the given set of conditions, get the Tag Metric.
2. Under the same conditions, using Theia (on the Sirit INfinity 510) calculate the tag metric.
3. Calculate the Reader Metric using the formulas used in the following example

Example 5.3 *A Single Tag*

Let us consider we are working with a single tag “A”, and let us consider this Tag Metric value to be 80 Athena.

Now, let us assume that performing the same procedure for calculation of the Tag Metric outlined above using a test system, we get :

$$A = 78Athena \quad (5.-10)$$

Thus, we use the formula, $\frac{CalculatedTagMetricvalue}{ExpectedTagMetricvalue} \times 100$, which gives us,

$$IndividualMetricVariance\%, X_i = \frac{TM_{calc}}{TM_{Exp}} \times 100 \quad (5.-10)$$

$$\therefore X_A = 97.5\%$$

We, now calculate the average of these values to get the *Reader Metric*, i.e.

$$ReaderMetric = \frac{Sum_{X_i}}{N_{tot}} = 98 \quad (5.-10)$$

Where,

$$Sum_{X_i} = \sum_{i=1}^N X_i$$

Example 5.4 *Multiple Tags*

Let us consider we are working with a tag population consisting of ten (10) tags, A,B,C,D,E,F,G,H,I & J (So $N_{tot} = 10$). Each of these tags is the same type and is used to tag the same type of object, thus we have the same tag metric value for each of these tags, let us consider this Tag Metric value to be 80 Athena.

A = 80 Athena F = 80 Athena

B = 80 Athena G = 80 Athena

C = 80 Athena H = 80 Athena

D = 80 Athena I = 80 Athena

E = 80 Athena J = 80 Athena

Now, let us assume that performing the same procedure for calculation of the Tag

Metric outlined above using a test system, we get :-

A = 79 Athena F = 72 Athena

B = 78 Athena G = 73 Athena

C = 78 Athena H = 76 Athena Thus, we use the formula, $\frac{\text{CalculatedtagMetricvalue}}{\text{ExpectedTagMetricvalue}} \times$

D = 66 Athena I = 69 Athena

E = Not Read J = 81 Athena

100, which gives us:

$$\text{IndividualMetricVariance}\%, X_i = \frac{TM_{calc}}{TM_{Exp}} \times 100 \quad (5.-10)$$

A = 98.75% F = 90.00%

B = 97.50% G = 91.25%

C = 97.50% H = 95.00%

D = 82.50% I = 86.25%

E = 0% J = 101.25%

We, now calculate the average of these values to get the *Reader Metric*, i.e.

$$\text{ReaderMetric} = \frac{\text{Sum}_{X_i}}{N_{tot}} = 84 \quad (5.-10)$$

Where,

$$\text{Sum}_{X_i} = \sum_{i=1}^N X_i$$

Thus, having understood the method of calculation of the Reader Metric using the Athena Tag Metric formula, we can now discuss the further restriction of the degrees of freedom of these calculated Reader Metric values by applying the other requisites that the metric must meet so as to polish down the procedure of obtaining a *Reader Metric*.

We, will first consider the fact that the Metric must represent a generic read capability of a reader, hence in order for the metric to conform to this we must define a **Gold Product**. This Gold Product will be chosen by analyzing the **Gold Standard** on the **Gold Machine**. Thus, using this fixed tag-product-machine scheme we will have now defined the Reader Metric completely. The next chapter will cover the experiments carried out in order to choose the **Golden Tag-Product** combination.

CHAPTER 6

EXPERIMENTS AND RESULTS

6.1 Introduction

As this work aims to develop the reader metric as a generic read ability indication, it is necessary that the experiments were based such that the data collected would create the largest reader metric variance and thus present to an observer a wide perspective of the metric. Hence, in order to get a large difference in the reader metric we must test the system along the parameters that affect it, thus we first need to understand the parameters that effect the reader metric [39][52]. The main parameters that effect the tag/reader metric are listed below :-

A. Power Transmitted by the Reader In order to power on a passive tag it has to receive power from the reader's signal. The reader signal is a powerful electromagnetic wave, which creates an electromagnetic field that powers the tag. When the time varying electromagnetic field is incident on the tag's antenna, it creates an electrical current that flows through the antenna, generating a standing wave which is rectified and used to charge the tag's internal power storage. The power storage provides the direct current and voltage which is used to drive the tag's internal circuitry. Once powered up, the tag modulates and backscatters the reader's signal. This backscattered power is dependent on many factors, such as, the tags antenna gain, transmitted power by the reader, distance between the reader and the tag, environment etc. The readability of the tag depends on the power received at the

tag's antenna and the tag's efficiency to harvest that power which ultimately effects read rate [39][52][25].

B. Frequency Of Operation of the Reader The operational frequency plays an important role in wireless communication. It can affect aspects of the system such as operating range and line of sight requirements. Different frequencied electromagnetic waves have very different behaviors (absorption and travel distance) in different environments. Hence, the various RFID systems are classified by their frequency of operation *viz.*

- Low Frequency (30 kHz to 500 kHz) systems have short reading ranges and are commonly used in security access, asset-tracking, and animal identification applications [39][28].
- High Frequency (13.56 MHz) systems, have longer read ranges (greater than 90 feet) and high reading speed and are used for applications such as railroad, car tracking and automated toll collection. However, the better performing high-frequency RFID systems incur higher system costs.
- Ultra High Frequency RFID systems use bands that vary in different countries these are included between 860 MHz and 960 MHz (EPC global standard). In the USA 902-928 MHz UHF backscatter coupling with 4 W EIRP spread spectrum is used [52][39][28][25].

C. Tagged Product The product that is tagged causes one of the most profound effects on the read rates because of the variation of the properties of different frequencied electromagnetic waves in different environments. We can generally classify the environments as :-

- Liquids: mostly absorb RFID radiations but some tend to be permeable. Those liquids that absorb RFID radiations (especially water) effect the performance of the tag and in turn makes it difficult for the reader to read the tag. This problem is not only limited to liquids but is also seen in items that contain liquid in some suspended form *e.g.* fruits & vegetables.
- Metals: demonstrate either absorption or reflection of RFID radiations. A Tag attached to a metal box or to a box containing metallic objects such as foils, tools, and gear boxes are significantly affected. Using a metallic box is not always bad though; an RFID tag (with a relatively thin layer of dielectric insulation) when attached directly to metal, can cause the metal to turn into an antenna thereby improving the performance. Also, the metal surface antenna will reflect back the RF signal to the reader, instead of just the tag antenna radiating the signal. Apart from this, materials having high mineral metal content, like rice & lentils (which have iron) can also affect the tag's performance.
- Wood: provides the same challenge for RFID communication as products containing water, because of its moisture content.
- Paper: contains wood as well as water in the form of moisture, thus, indirectly becoming an RFID absorber and affecting tag performance and thereby affecting the metric value.

It is therefore recommended that any RFID the system being developed should have consideration for these factors which will maximize read range and detection speed. Placing tags on plastic caps, instead of the liquid, metals, may resolve the problem to some extent [39][28][52][25].

D. Distance between Tag and Reader Antenna This parameter takes into account the maximum distance between reader and the tag at which the tag is

readable. With the variation in distance i.e. if increased/decreased, the reader may not be able to read the tag at certain points due to dead spots and thus readability becomes zero, thus preventing detection. Hence, the tag distance from the reader antenna plays a significant role in determining the Metrics.

E. Orientation of Tag (w.r.t.) Reader Antenna Orientation of a tag can be considered in two different ways; firstly the physical orientation, which refers to the angle which the tag makes with the reader antenna and secondly the polarization orientation, which depends on the polarization of tag's and the reader's antenna. In this thesis work, we take into consideration a linearly polarized antenna, so that the effects of polarization orientation are minimized and thus can be neglected. In the ideal scenario, the tag and the reader lie in the same plane i.e. the angle between the tag and the reader is zero so that the tag's response is maximized, but in real world scenarios the tagged object orientation is typically at a random angle with respect to the reader's antenna while being read, and therefore the readability of tag is affected significantly which in turn affects the Metric value.

F. RF Noise in the environment During the course of typical RFID operation, tags are subjected to a number of RF interfering signals from electrical equipment such as, cell phones, mobile radios, fluorescent lights etc. All the mentioned sources interfere in the communication between the reader and the tag, producing adverse effects [54]. The interference from the environment can also be due to other RFID readers in the vicinity of the tag. Since tags are Broadband receivers, they may not be able distinguish between the RF signal of the desired reader and other readers. RF noise in the environment attenuates the signal of the desired reader, thereby decreasing the signal strength; as a result, the power received at the tag's

antenna is decreased, which in turn reduces the probability of the tag's response to the query of the desired reader. The capability of a tag that allows it to respond to just desired reader signals and reject the signal from all other sources is known as Interference Rejection. The Interference rejection ability can be incorporated into the tag by using proper circuitry. If the interference rejection is not good enough, the tag cannot understand which reader to respond to and thus causes the system to fail miserably.

Having covered the parameters that effect the the read ability of the reader, we can thus move on the experiments that were performed.

6.2 The Experiments

With the steps taken towards calculating the Reader Metric clear, we will further this paper with a discussion of the various experiments that will be conducted using the Voyantic System, and calculating the Tag Metrics from the data acquired in these various scenarios. From these data sets the Gold Tag-Product combination will be chosen, as was mentioned earlier.

The tags we will use for these experiments will be

1. The Alien Squiggle Tag
2. The Bow-Tie Tag &

The tests that we will conduct will be on six (6) different products *viz.:-*

1. Wood
2. Foam
3. Water
4. Oil

5. Paper

6. Metal

In the case of all the following mentioned experiments the first test that was carried out was a test for a tag free environment and then a test to account for environmental conditions. This can be considered as experiment zero (0).

6.2.1 Experiment Zero

It should be taken care that the environment where testing is to be carried out is free from other UHF RFID tags. For this a frequency sweep and a power sweep are run without placing any tag in front of the antenna and the outputs are observed. The system ideally should not give any reads/output. If it does, the nearby area is scrutinized for any other tag present and if found is removed from the environment. The test is carried out 4 to 5 time to make sure that there is no interfering tag present.

Next, the tag/s to be tested are placed in front of the antenna and a frequency sweep was carried out to account for environmental conditions thus making them invariable; this test also makes sure the reader system is not faulty. This test is run multiple times and will be referred to as a repeatability test. The frequency sweep was carried out on the same tag for 10 times and test result shows that all the graphs are overlapping throughout the range except at few frequency points. The figure below (Figure 6.1) shows the environment characterization in free space.

The results that can be inferred from the above figure are, that the environment effects are constant and there is not much Electromagnetic interference in the environment.

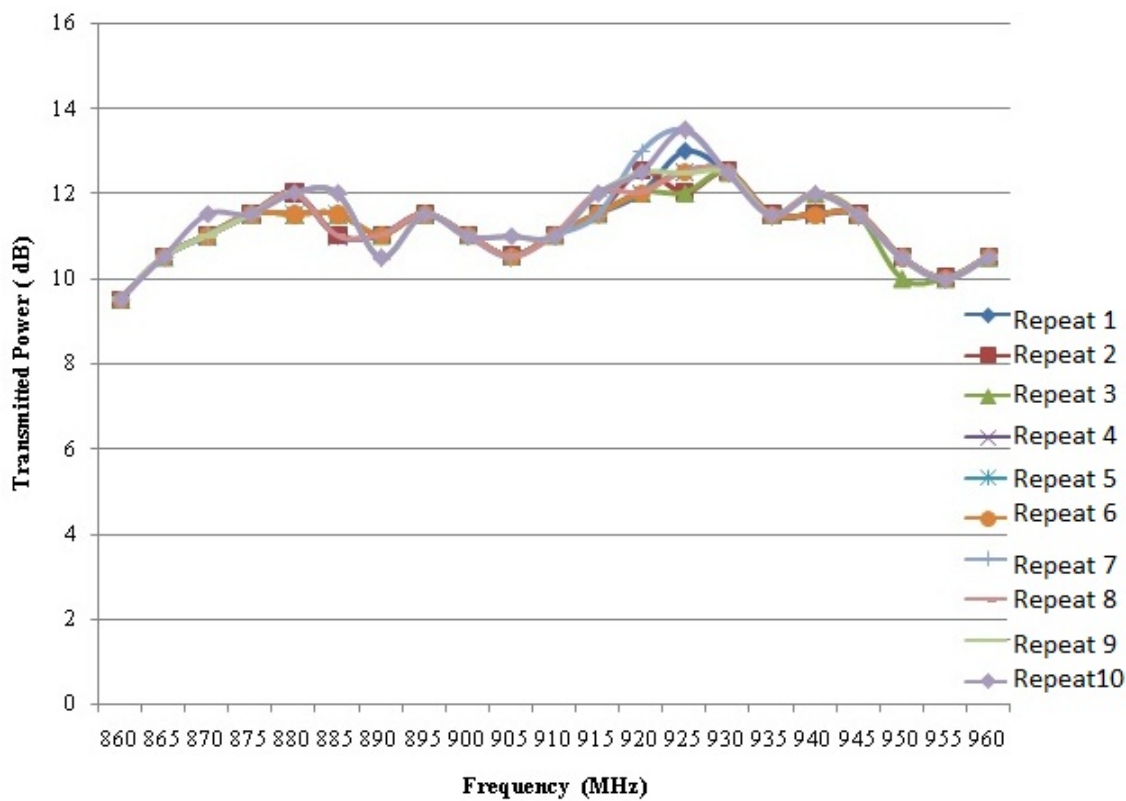


Figure 6.1. Repeatability Test (Frequency Sweep) on Alien Squiggle Tag using Voy-antic System.

6.2.2 Experiment 1

In this experiment the tests (Frequency Sweep and Power Sweep) were carried out individually on both the the Alien Squiggle Tag and the Bow Tie Tag. The tags were tested without any products, hence referred to as Stand-Alone. The tags were suspended in front of the antenna at a distance of one (1) meter. This test is done to give a clear idea of the tags' performance when there is no effect due to the products. The figures/graphs below show the frequency sweeps and power sweeps results for an Alien Squiggle (A.S.) and the Avery Dennison Bow Tie (B.T.) tag.

Frequency Sweep

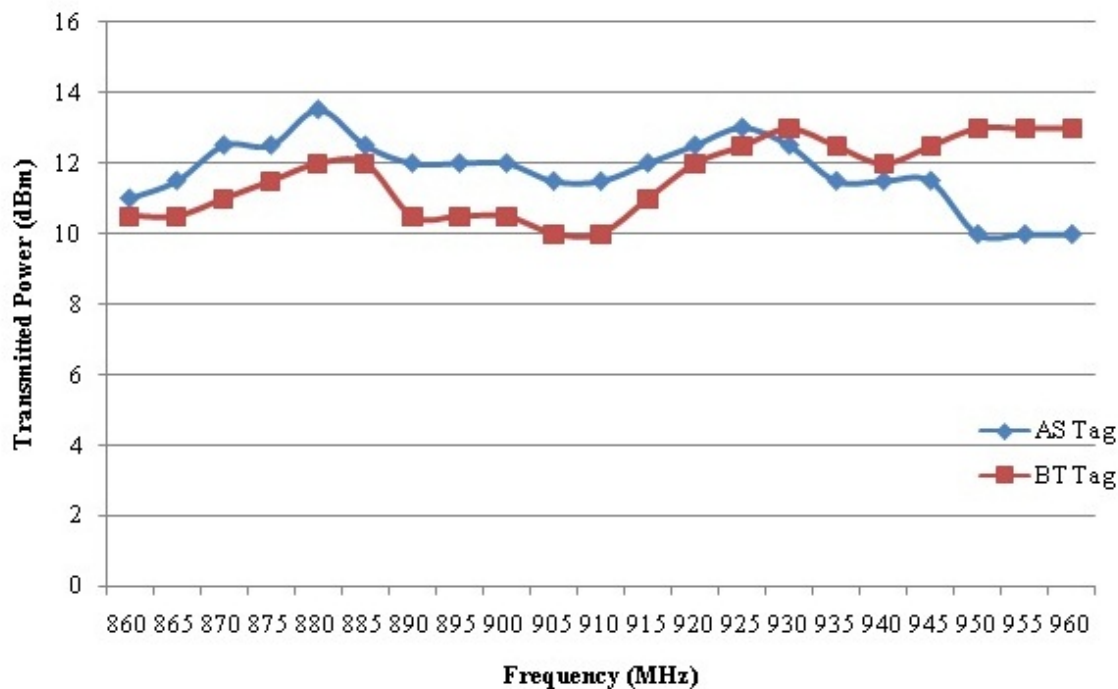


Figure 6.2. Stand-Alone Squiggle Tag and Bow Tie Tag Frequency Sweep results.

The results indicate that the Bow Tie tag is read at comparatively lower power level when compared to the Squiggle Tag for the entire FCC range. The Power Sweep results show that the Bow Tie tag has a quicker response compared to the Squiggle Tag. From the data gathered the Tag metric calculated was :-

Table 6.1. The Tag Metric for Alien Squiggle Tag and Bow Tie Tag, Stand-Alone

Tags (Stand Alone)	Metric
Alien Squiggle Tag	95
Bow Tie Tag	97

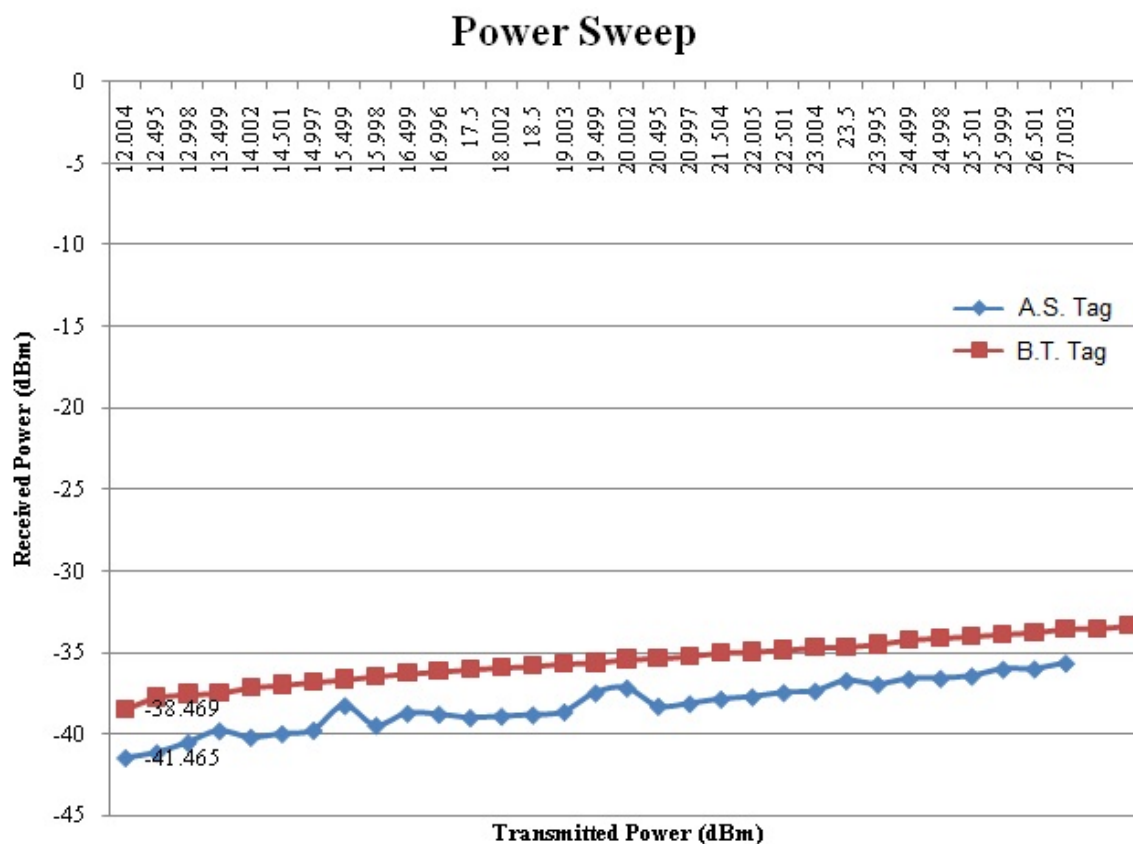


Figure 6.3. Stand-Alone Squiggle Tag and Bow Tie Tag Power Sweep results.

The metric for Alien Squiggle at 1 meter distance turns out to be 95 and the Metric for the Avery Dennison Bow Tie tag is 97. This gives a comparison of the two tags and shows that the Bow Tie Tag works better than the Squiggle Tag. It can be observed that the received signal strength of the Alien Squiggle Tag has a 3dBm difference as compared to the Bow tie Tag. Also to be noted is that the Alien Squiggle Tag starts reading 1 dBm after the Bow Tie Tag. These two factors together account for the difference in the metric values.

6.2.3 Experiment 2

In this experiment the tests (Frequency Sweep and Power Sweep) were carried out individually on both the the Alien Squiggle Tag and the Bow Tie Tag. The tags were tested on all the afore mentioned products. The tagged products were placed in front of the antenna at a distance of one (1) meter. The test method used for these tests was as discussed before, first a frequency sweep is performed to find the best frequency suited for the power sweep operation then a power sweep is carried out. From the results of the power sweep the Tag Metric Value is calculated. The figures/graphs below show the frequency sweeps and power sweeps results for an Alien Squiggle (A.S.) and the Avery Dennison Bow Tie (B.T.) tag.

6.2.3.1 The Alien Squiggle Tag

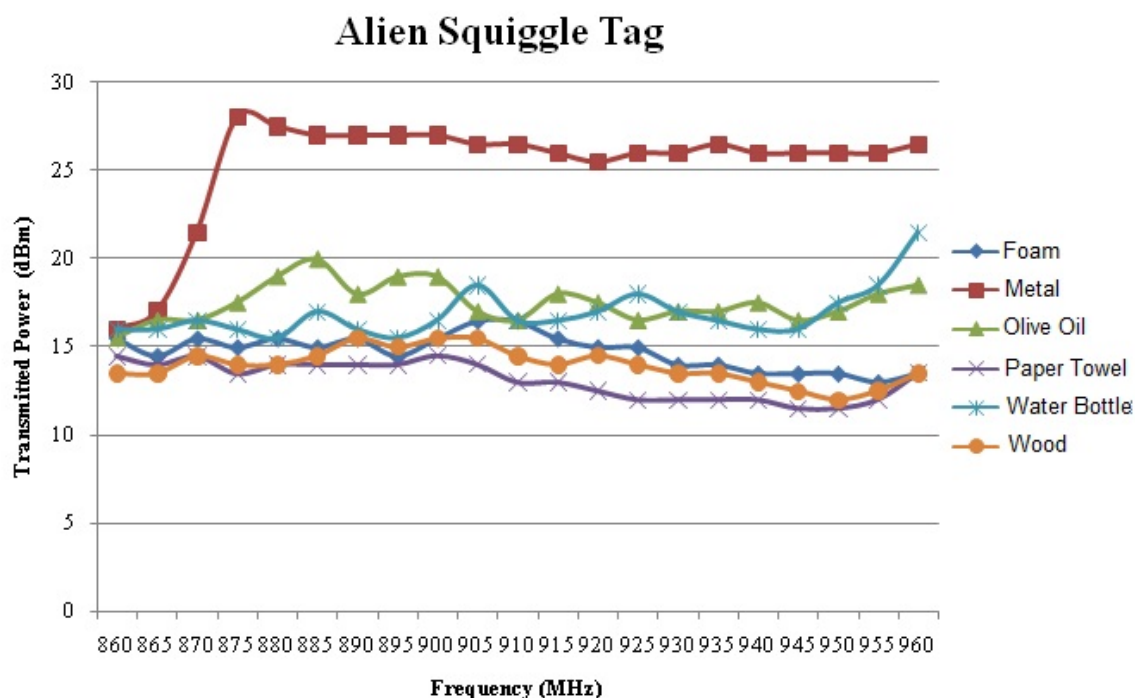


Figure 6.4. Alien Squiggle Tag Frequency Sweep results for multiple products.

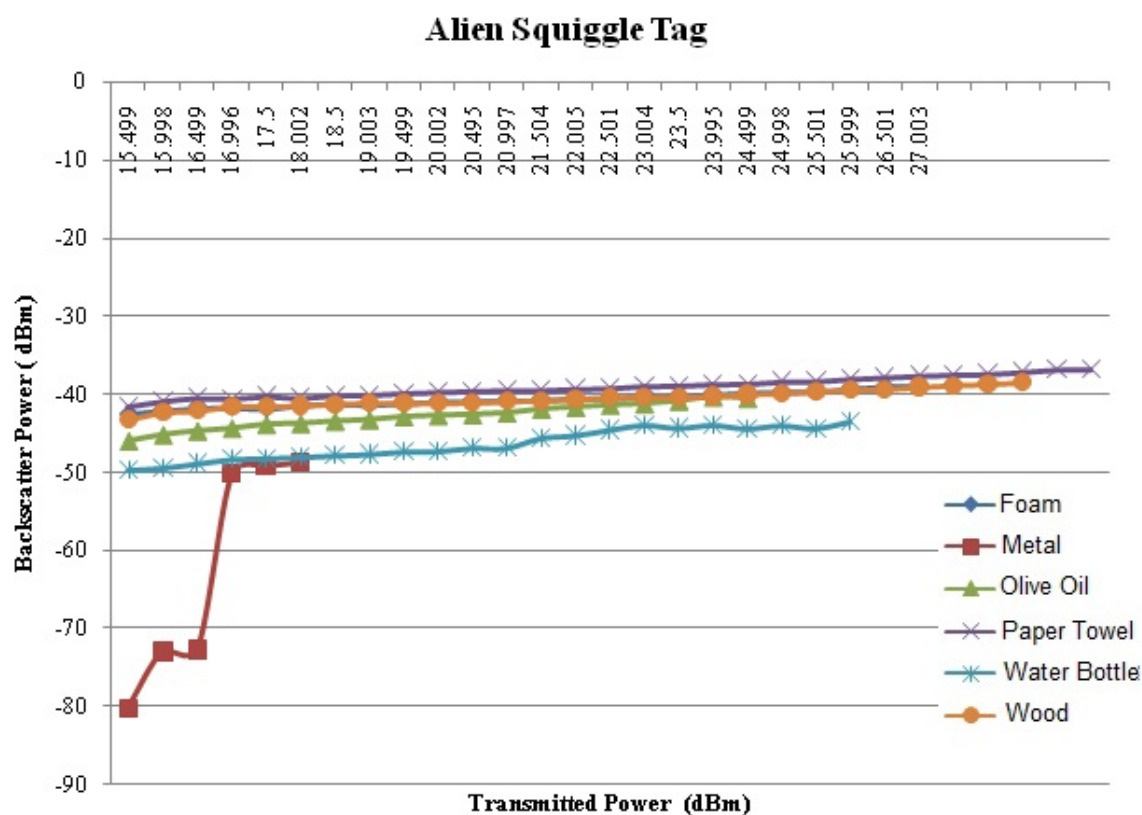


Figure 6.5. Alien Squiggle Tag Power Sweep results for multiple products.

From the above graphs it can clearly be observed that tagged objects cause the tag to require a higher transmitted power for the tag to be able to respond to the reader query. We can also note that for the whole frequency range Metal has the worst results; it is read at very high power level. The Paper towel shows the best performance in the frequency sweep followed by the wood.

In the power sweep graph, a huge difference can be noticed in the power levels at which the tag replies to the reader query. The paper towel followed by the wood

have the best results and thus higher metrics than the other products. The tag when attached to the metal or the water bottle does not exhibit a good performance.

6.2.3.2 The Bow-Tie Tag

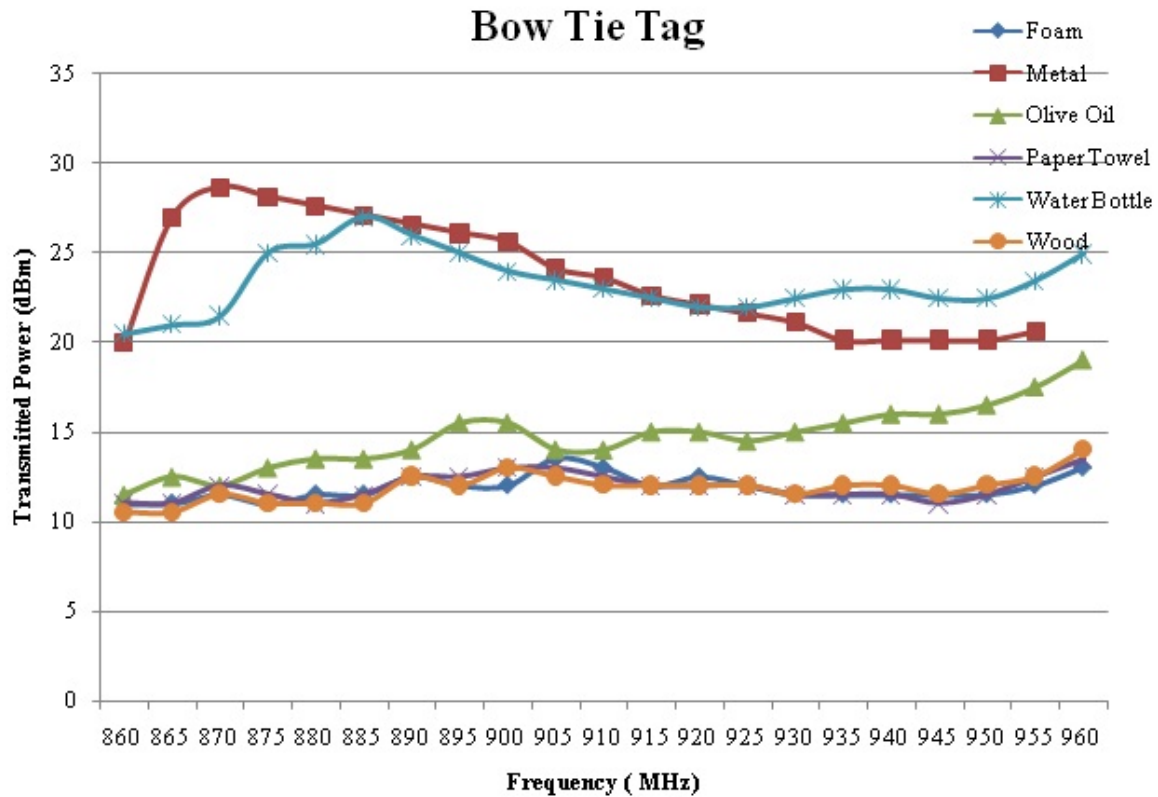


Figure 6.6. Bow-Tie Tag Frequency Sweep results for multiple products.

The results in the case of the Bow-Tie Tag are very similar to the Alien Squiggle Tag frequency. The only major difference was in case of water, the frequency sweep of water is much like the results for metal, that is, the performance of the Bow Tie tag is bad with water.

Bow -Tie Tag

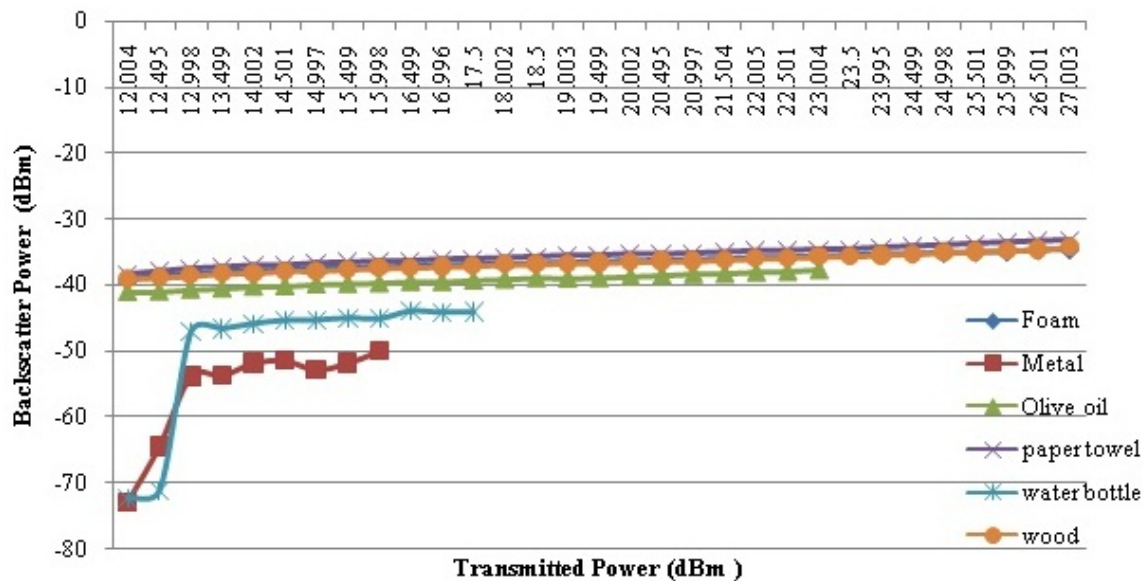


Figure 6.7. Bow-Tie Tag Power Sweep results for multiple products.

The power sweep on different products shows that the paper towel and the wood have the best performance and the metal has the worst, followed by water bottle. We can thus calculate the metric values for both the tags across the multiple products as given below (Table 6.2)

Table 6.2. The Tag Metric for Alien Squiggle Tag and Bow Tie Tag, multiple Products

Product	Metric	
	Bow-Tie Tag	Squiggle Tag
Wood	96	91
Paper Towel	96	93
Water Bottle	80	86
Olive Oil	90	86
Foam	95	90
Metal	80	79

From the above table (Table 6.2) it can be observed that the tag metric value for Bow Tie tags is in general higher than the Metric value for the Squiggle tag. The metric value of paper towel was found to be the best in both cases (Squiggle and Bow-Tie tags). Thus, the *Golden Tag-Product* combination that is used is **Bow-Tie Tag on Paper Towel**.

6.2.4 Experiment 3

This is the final experiment. This experiment is carried out using **Theia** to calculate the tag metric for a Bow-Tie Tag on a paper towel. The procedure followed was the same as on the Voyantic Tagformance Lite. A frequency sweep is run to get the optimum frequency of operation, using this frequency a power sweep was run and from that data the Reader Metric is calculated. The following graphs (Figure 6.8 and Figure 6.9) show the results of the frequency and power sweeps performed using Theia.

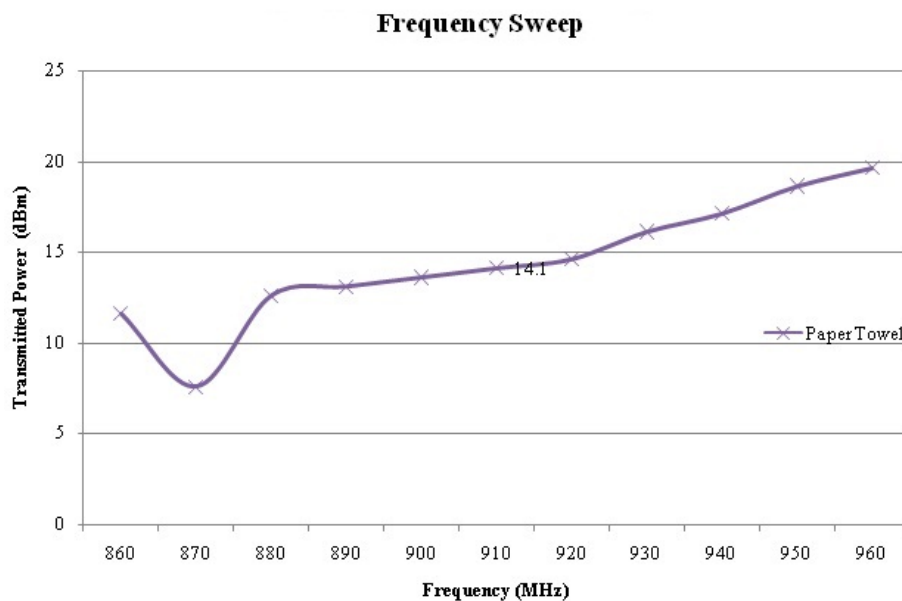


Figure 6.8. Bow-Tie Tag Frequency Sweep for Paper Towel.

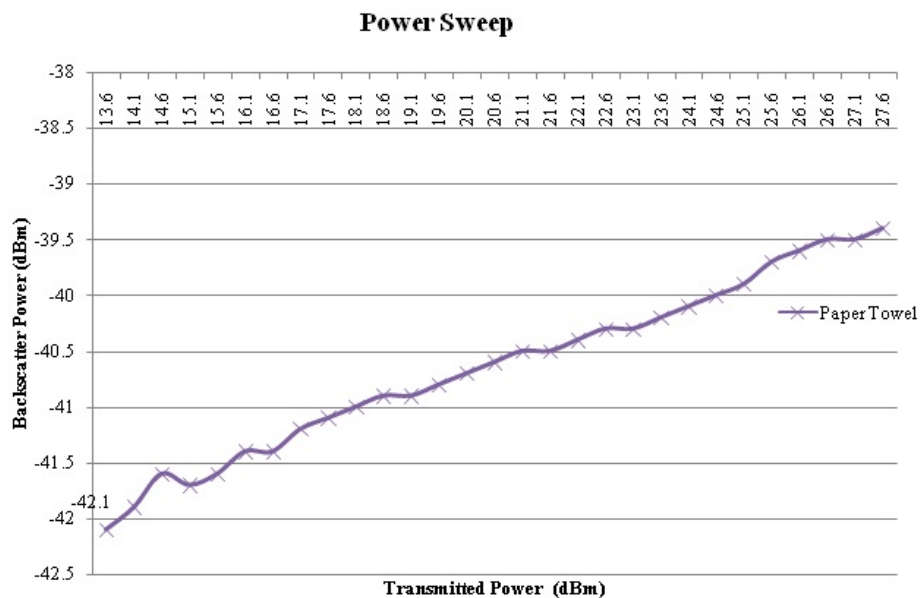


Figure 6.9. Bow-Tie Tag Power Sweep for Paper Towel.

From these data sets the tag metric using Theia was 92. Thus, the reader metric of the Sirit INfinity 510 was calculated as given below :-

Given,

Calculated Tag Metric value = 92

Expected Tag Metric value = 96

Using the formula $ReaderMetric = \frac{CalculatedTagMetricvalue}{ExpectedTagMetricvalue} \times 100$, we get

$$ReaderMetric = \frac{92}{96} \times 100$$

Reader Metric = 96

CHAPTER 7

CONCLUSION

7.1 Conclusion

In this research, a unique software was created to transform a common Ultra High Frequency RFID reader (Sirit INfinity 510) into an RFID performance analysis tool. This work presented a methodology to gauge the read capability of an UHF RFID reader using a single numerical value : A Reader Metric.

This metric offers to the user a simple comparison of the generic read-ability of the given UHF RFID reader, to the Voyantic Tagformance Lite, which is considered in this work as the Gold system.

The software code that was created for the Sirit INfinity 510, was successfully tested on multiple Sirit readers. The software transformed the Sirit from a basic RFID reader into an RFID environmental analysis tool. This new system that was created was named Theia. Theia offers the functionalities of the Voyantic Tagformance Lite on the Sirit *albeit* at lower sensitivity levels and ranges, but still well within the UHF Generation 2 18000-6C operational parameters. Theia also added some further functionalities than the Voyantic Tagformance Lite, it has the methods and the calculation of Athena Tag Metrics and Reader Metrics automated. Theia can also perform its analysis on multiple tags simultaneously, thus taking into account the interference of other tags in the analysis. Finally, since Theia runs on the Sirit INfinity 510 we can say that the cost of the system is approximately that of the Sirit INfinity 510, which when compared to the cost of the Voyantic Tagformance Lite

(Which is laboratory test equipment) results in tremendous cost savings for the user with a slight trade-off on sensitivity and range. Another point to note, is that since Theia is an RFID testing tool on a reader, its read results can be considered as more relevant to real world scenarios, since in the real world laboratory equipment is not used to read tags, hence when we test the environment using Theia, which is run on an actual industry reader, the data we get is far more accurate in a sense.

7.2 Future Work

During the course of this thesis work, it became evident that Theia could be modified still further; to include even more functionality that can be offered to a user. The additions that will be added in later revisions of the code, would include a graphical programming interface that would allow a user to drag and drop reader tasks onto a clipboard, which can be then connected together like a flowchart so as to make macro functions on the fly. This functionality will be very helpful from a laboratory point of view as well as for industry oriented applications.

Regarding the methodology behind the reader metric calculation, in future work the methodology can be modified to account for a fixed number of multiple products thus further focusing the Reader Metric value upon the read ability of the reader.

CHAPTER 8

GLOSSARY OF TERMS

ROM	:	Read Only Memory
WORM	:	Write Once Read only Memory
UHF	:	Ultra High Frequency
HF	:	High Frequency
LF	:	Low Frequency
SAW	:	Surface Acoustic Wave
VHF	:	Very High Frequency
RFID	:	Radio Frequency IDentification
ISO	:	International Standards Organization
OSI	:	Open System Interconnection
UID	:	Unique IDentification number
RCT	:	Reader Configuration Tool
Tx	:	Transmit
Rx	:	Receive
LBT	:	Listen Before Talk
RAPID	:	RFID Application Programming Interface for Developers
API	:	Application Program interface

ALE	:	Application Level Events
LED	:	Light Emitting Diode
LAN	:	Local Area Network
TXD	:	Transmit Data
RXD	:	Receive Data
NC	:	No Connection
VSWR	:	Voltage Standing Wave Ratio
EIRP	:	Effective (or equivalent) Isotropically Radiated Power
ERP	:	Effective Radiated Power

REFERENCES

- [1]
- [2] <http://en.wikipedia.org/wiki/polarization>.
- [3] <http://helios.gsfc.nasa.gov/glossmn.html>, in cosmicopia, nasa.
- [4] [http://www.elkadot.com/corpuscular/differences between light and electromagnetic wave polarization.htm](http://www.elkadot.com/corpuscular/differences%20between%20light%20and%20electromagnetic%20wave%20polarization.htm).
- [5] www.iop.org, in institute of physics.
- [6] Draft paper on the characteristics of rfid systems, 2000.
- [7] EPC Global Radio Frequency Identity Air Interface Protocol Class 1 Generation 2 UHF RFID version 1.0.5, 2004.
- [8] Epc global radio frequency identity air interface protocol class 1 generation 2 uhf rfid version 1.0.5, 2004.
- [9] The true cost of radio frequency identification, 2004.
- [10] US Patent 6104291. Method and apparatus for testing rfid tags.
- [11] US Patent 7295117. Rfid device test thresholds systems and methods.
- [12] US Patent 7359823. Rfid device variable test systems and methods.
- [13] Inc. AIM. Shrouds of Time: The History of RFID, 2001. http://www.aimglobal.org/technologies/rfid/resources/shrouds_of_time.pdf.
- [14] M. Ali, R. Dougal, G. Yang, and H. Hwang. Wideband Circular Polarized microstrip patch antenna for wireless LAN application.
- [15] Various authors. Business metric. <http://searchcrm.techtarget.com/definition/business-metric>.

- [16] Nikhil Ayer. Evaluation Of ISO 18000-6 Type-C Class 1 Generation 2 RFID Protocol Artifacts. Master's thesis, University Of Texas at Arlington, Arlington, TX, 2008.
- [17] C. Balanis. *Antenna Theory: Analysis and Design*. John Wiley and Sons Inc, 2003.
- [18] David K. Cheng. *Field and Wave Electromagnetics*. Addison-Wesley Publishing Co., 1992.
- [19] R. Clarke, D. Twede, J. Tazelaar, and K. Boyer. Radio frequency identification performance: The effects of the tag orientation and the content. *Package Technology Science*, pages 45–54, 2006.
- [20] J. Curty, N. Joehi, C. Dehollain, and M. Declercq. Remotely powered addressable uhf rfid integrated systems. *IEEE Journal of Solid-State Circuits*, 40(11):2193–2202, 2005.
- [21] John D. Day and H. Zimmerman. The OSI Reference Model. *IEEE Proceedings*, 71:1334–1340, 1983.
- [22] D. Dobkin and S. Weigand. Environmental effects on rfid tag antennas. *Microwave Symposium Digest*, 2005.
- [23] Jim Eagle. RFID: The Early Years 1980-1990, 2001. <http://members.surfbest.net/eaglesnest/rfidhist.htm>.
- [24] D. Engels and S. Sharma. Technical report: On the future of rfid tag protocols. Technical report, Auto-ID Labs, June 2003.
- [25] Daniel Engels. Review of RFID Technology. *Texas RF Innovation and Technology Center*, 2007.
- [26] European Telecommunication Standard Institute ETSI.
- [27] Federal Communications Commission FCC.
- [28] Klaus Finkerzeller. *RFID Handbook*. John Wiley and Sons, 1999.

- [29] R. Glidden. Design of ultra-low-cost uhf rfid tags for supply chain applications. *IEEE Communications Magazine*, 42:140–151, 2004.
- [30] Bill Glover and Himanshu Bhatt. *RFID Essentials*. O’Reilly, 2006.
- [31] Robert Blair Green. *The General Theory of Antenna Scattering*. PhD thesis, The Ohio State University, Columbus, OH, 1963.
- [32] R. C. Hansen. Relationships between antennas as scatterers and as radiators. *IEEE*, 77(5):659–652, 1989.
- [33] J. Ho, D. Engels, and S Sharma. Hiq: A hierarchical q-learning algorithm to solve the reader collision problem. *SAINTW*, 2006.
- [34] M. Hossain and V. Prybutok. Consumer acceptance of rfid technology: An exploratory study. *IEEE Transactions-Engineering Management*, 55(2):316–328, 2008.
- [35] Sirit Inc. Infinity 510 quick start guide, v2.0. <http://www.sirit.com>.
- [36] Sirit Inc. Infinity 510 user’s guide. <http://www.sirit.com>.
- [37] Sirit Inc. Protocol reference guide. <http://www.sirit.com>.
- [38] Sirit Inc. Rapid developers guide. <http://www.sirit.com>.
- [39] Amit Jain. Athena-RFID Tag Metrics. Master’s thesis, University Of Texas at Arlington, Arlington, TX, 2009. Unpublished.
- [40] Yogesh Joshi. Information Visiblity and Its Effect on Supply Chain Dynamics. Master’s thesis, Massachusetts Institute of Technology, Cambridge, MA, 2000. <http://auto-id.mit.edu/research/whitepapers.html>.
- [41] W. Kahn and H. Kurss. Minimum-scattering antennas. *IEEE Transactions on Antennas and Propagation*, pages 671–675, 1965.
- [42] Keskilamni and M. Kivikoski. Cylindrical patch antenna array for rfid appilcations. *ITG FACHBERICHT*, 2003.

- [43] Keskilamni and M. Kivikoski. Cylindrical Patch Antenna Array for RFID applications. *ITG FACHBERICHT*, 2003.
- [44] Eugene F. Knott, John F. Shaeffer, and Michael T. Tuley. *Radar Cross Section, 2nd ed.* Artech House, Boston, 1993.
- [45] A. Koelle, S. Depp, and R. Freyman. Short-range radio-telemetry for electronic identification, using modulated rf backscatter. *Proceedings of The IEEE*, 63:1260–1261, 1975.
- [46] J. Landt. The History of RFID, 2005.
- [47] Voyantic Ltd. Tagformance Lite Measurement System, 2009.
- [48] Microsoft. C# (programming language). [http://en.wikipedia.org/wiki/C_Sharp_\(programming_language\)](http://en.wikipedia.org/wiki/C_Sharp_(programming_language)).
- [49] P. Nikitin and K. V. Rao. Performance limitations of passive uhf rfid systems. *IEEE Conference*, 2006.
- [50] P. Nikitin and K.V Rao. Theory and measurement of backscattering from rfid tags. *IEEE-Antennas and Propagation Magazine*, 48(6):212–218, 2006.
- [51] M. Ohkubo, K. Suzuki, and S. Kinoshita. Rfid privacy issues and technical challenges. *ACM Commununication Journal*, 48(9):66–71, 2005.
- [52] S. Pete. Passive RFID Basics. <http://www.jimfranklin.info/microchipdatasheets/00680b.pdf>.
- [53] V. Pillai. Impedance matching in rfid tags: To which impedance to match? *IEEE Antennas and Propagation Society International Symposium*, pages 3505–3508, 2006.
- [54] D. Ranasinghe, D. Engels, and P. Cole. Low-cost RFID systems: Confronting Security and Privacy. *Presented at Auto-ID Labs Research Workshop*, 2005.
- [55] K. Rao. An overview of backscattered radio frequency identification system RFID. *Microwave Conference*, 3:746–749, 1999.

- [56] Theodore S. Rappaport. *Wireless Communications: Principles and Practice*. Prentice Hall, New Jersey, 1996.
- [57] Thierry Roz and Vincent Fuentes. Using Low Power Transponders and Tags for RFID Applications. <http://www.emmrin.ch/>.
- [58] Tom Ahlqvist Scharfeld. An Analysis of Fundamental Constraints on Low Cost Passive RFID System Design. Master's thesis, Massachusetts Institute of Technology, Cambridge, MA, 2001.
- [59] S. Shuji, H. Yuzo, A. Dobashi, M. Okumara, and T. Kusuzaki. Products Lifecycle Management System Using RFID Technology. *IEEE International Conference on Emerging Technologies and Factory Automation*, 2:1459–1467, 1999.
- [60] S. Shuji, H. Yuzo, A. Dobashi, M. Okumara, and T. Kusuzaki. Products lifecycle management system using RFID technology. *IEEE International Conference on Emerging Technologies and Factory Automation*, 2:1459–1467, 1999.
- [61] David H. Staelin, W. Morgenthaler, and Jin Au Kong. *Electromagnetic Waves*. Prentice Hall, New Jersey, 1994.
- [62] Warren Stutzman and Gary Thiele. *Antenna Theory and Design*. John Wiley and Sons Inc., 1998.
- [63] P. Sweeney. *RFID for Dummies*. John Wiley & Sons, 2005.
- [64] L. Sydanheimol, J. Nummetla, L. Ukkonen, J. McVay, A. Hoorfar, and M. Kivikoskil. Characterization of passive UHF RFID tag performance. *IEEE-Antennas and Propagation Magazine*, 50(3):207–212, 2008.
- [65] S. Tung and A. Jones. Physical layer design automation for rfid systems. *IEEE International Symposium-Parallel and Distributed Processing*, pages 1–8, 2008.
- [66] John R. Tuttle. Traditional and Emerging Technologies and Application in the Radio Frequency Identification (RFID) Industry. *IEEE Radio Frequency Integrated Circuits Symposium*, 1997.

- [67] ITU RR International Telecommunication Union, 1998.
- [68] H. Vogt. Efficient object identification with passive rfid tags. *International Conference on Pervasive Computing*, pages 98–113, 2002.
- [69] J. Waldrop, D. Engels, and S. Sharma. Colorwave: An anti-collision algorithm for the reader collision problem. *IEEE-Wireless Communications and Networking Conference*, pages 1206–1210, 2003.
- [70] J. Waldrop, D. Engels, and S.E. Sharma. Colorwave: A mac for rfid reader networks. *IEEE Wireless Communications and Networking Conference*, pages 1701–1704, 2003.
- [71] W. Wasylkiwskyj and W. Kahn. Theory of mutual coupling among minimum-scattering antennas. *IEEE Transactions on Antennas and Propagation*, pages 204–216, 1970.
- [72] E. Zeisel. *RFID+ CompTia Certification*. Que Certification, 2006.

BIOGRAPHICAL STATEMENT

Jason F. Pereira was born in Bangalore, India, in 1984. He received his B.E. degree from Visveswaraya Technical University, India, in 2002, his M.S. in Electrical Engineering degree from The University of Texas at Arlington in 2009. His current research interests include Radio Frequency Identification systems, Virtual Reality, Intelligent Systems and Robotics. He is a member of the IEEE society.