PRACTICAL EVALUATION AND ANALYSIS OF
PASSIVE UHF RFID TAGS

by

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ABSTRACT

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In this thesis, we have identified the important parameters that impact the performance of passive UHF RFID tags and developed a testing methodology to evaluate and characterize tags. We have also developed the theory to validate the empirical data and analysis. The high performance, low cost and increased storage capacity of the RFID tags has led to the economic adoption of this technology by many industries. Choosing the right tag for the right application might be quite a task with the number of commercially available tags today. It is very important to test the tags and analyze the results to gain an insight into the impact of the products being tagged and the environment, on the tags themselves. Hence, there is a potential need to understand the impact of some of the factors such as tag sensitivity, backscatter signal strength and tag communication range on the performance of tags. A systematic testing methodology to test and analyze passive UHF RFID tags are also provided. A general theory is developed to enumerate the factors affecting tag performance. Analytical evaluations are provided to validate the theory with practical results. It is shown that the sensitivity of the tag, backscatter signal strength, electric field strength

at the tag, communication range, reflection efficiency of the tag, reader sensitivty and tag antenna design are all inter-related and specific relationship between them is described and analzed in detail. Testing is also performed in an anechoic chamber to validate the test results under lab conditions. Performance of tags on water and detergent are also analyzed and validated with the test results in an anechoic chamber.

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CHAPTER 1

INTRODUCTION

Radio Frequency Identification Systems have begun to find tremendous use as Automated Identification and Data Capture (AIDC) Systems within several applications such as access control, livestock management and tracking and tracing of products through the supply chain [3], [4]. The most common AIDC system is the Bar Code system that was developed during the 1970's [5]. The low cost and contactless reading technology have made bar code systems the most popular and the most widely used AIDC systems in the world. However, bar code systems have certain limitations such as line of sight reading requirement and limited storage capacity that confines their use as identification systems in some applications. Though RFID technology has been around for decades, invention of the integrated circuit or the microchip led to the adoption passive RFID technology as an automated identification system due the reduced size, cost and power requirements of the RFID tags [6]. The combination of high performance and low cost of RFID tags provide an economical path for the adoption of this technology in increasing number of applications [7]. The following sections provide an overview of the basic components of an RFID system and the need for RFID tag analysis.

1.1 RFID and the Need for Tag Analysis

Low cost Radio Frequency IDentification (RFID) technologies began their adoption within the retail and pharmaceutical supply chains in 2003 when Wal-Mart, the world's largest retailer, began deploying passive UHF (Ultra High Frequency) RFID

systems within its warehouses and the back rooms of its retail stores. Since then, the U.S. Department of Defense (DoD) and a significant number of additional retailers, including Target, Tesco, and Metro, have adopted passive RFID technologies within their supply chains. Consequently, the demand for RFID tagged items that can be automatically identified without human intervention at all points within the supply chain has increased.

An RFID system consists of RF tags or transponders, RF tag readers or transceivers and an information system. An RFID tag consists of an integrated circuit connected to an antenna. The reader queries the tag over an RF interface for information stored on it. Though the concept of RFID systems originated during World War II and research on RFID was a government sponsored endeavor, recently RFID technology has been adopted by the private sector within a broad array of applications. The safety and security surrounding government programs and particularly nuclear materials was the main reason behind instigating research effort on RFID [8], [9]. With the advent of the microchip, the design of passive RFID tags has reduced the cost, size and power requirements of the tags. Consequently, the number of industries that can use RFID systems in a variety of applications has also increased.

The high performance, low cost and increased storage capacity of the RFID tags has led to the economic adoption of this technology by many industries. The location of the readers and the tags may vary and thus it is important to survey the site before the deployment of an RFID system. There are several tags that are commercially available that satisfy the afore mentioned criteria. However, it is imperative to have a complete understanding of RFID tag designs and innovations to choose and decide tags for the required application. There are several tags with leading edge antenna designs and different tags may be suitable for different applications. Thus it is essential and crucial to understand and analyze the performance of various tags in

different environments. This thesis acts as a guide to test passive UHF RFID tags and provides an understanding of some of the factors that affect the performance of tags.

1.2 RFID System Basics

A typical RFID system consists of three main components: Tags, Readers, and Information Systems, as shown in Figure 1.1. Tags and readers are the most prolific components in an RFID system. The Tags are affixed to objects that are to be automatically identified. Readers are placed in locations where the tags need to be identified for the intended applications. Readers may be either fixed location, like a cellular telephone tower, or they may be mobile, allowing them to be brought to the tags. Readers read the data that is stored on the tags, often, simply an identifier such as the Electronic Product Code (EPC) but possibly historical or other cached information. The readers communicate their captured information to the information system. The Information System utilizes the data obtained from the tags for for a defined set of applications. A comprehensive of RFID technology is provided in [10].

- Tag or Transponder - This is affixed to the object to be identified and is the data carrier of the system
- Reader or Interrogator - Reads the data from and writes the data to a tag
- Information System - Utilizes the data received by the reader from the tag in a useful manner

Tags may be either active, passive or semi-passive. Active tags have an on-tag power supply while passive tags obtain their power from the signal transmitted by the reader. Semi-passive tags have their own power supply such as a battery to power the tag IC however they use the reader signal to communicate the data back to the reader. An RFID reader interrogates the tags using radio frequency waves for the data stored
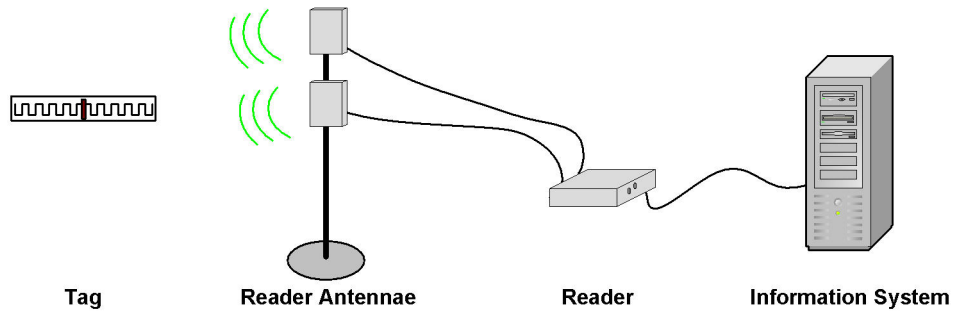
Figure 1.1. Basic RFID System.

in them. Readers communicate with tags using radio frequency waves which allow medium read ranges for passive tags and large read ranges for active tags depending upon the desired application. The radio interface allows readers to communicate with tags even in hostile and non-LOS environments. The data received by the reader is communicated to an information system for data processing purposes.

1.2.1 Tag Physics

To understand the fundamentals of tag design, it is important to delve into the physics behind RFID tags. Irrespective of the application, the accuracy of tag reads is an inevitable requirement. This can be achieved with optimal tag designs. Thus, knowledge on tag designs is priceless since it enables the right choice of tags for the right application. Most UHF tags use dipole antennas since UHF frequencies are electric in nature while most LF and HF tags use coiled antennas due to their frequencies being magnetic in nature.

RFID transponders consist of a microchip (the tag IC) and a coupling element (the tag antenna). Figure 1.2 shows a picture of an Alien Squiggle Tag [11]. The tag IC is strapped to the tag antenna which acts as a coupling element. Antenna design considerations are provided in [12]. A substrate which is commonly a plastic film

holds the tag IC and the tag antenna together [13]. The tag IC has a memory which stores the data that uniquely identifies the tag. This data is the serialized EPC code which is programmed in the tag during the tag manufacturing process. Most passive tags can store upto 96 bits of data. The minimum threshold power required to the read the EPC data is approximately -10 dBm. Depending upon the chip design the tag is a read-only or a read-write tag. The tag IC receives power from the tag antenna in the form of an alternating current at the reader frequency. This current must be down-converted and rectified by circuitry tuned to a specific frequency. The efficiency of the power circuitry of the tag IC is dependent on the matching of the individual components of the tag IC.
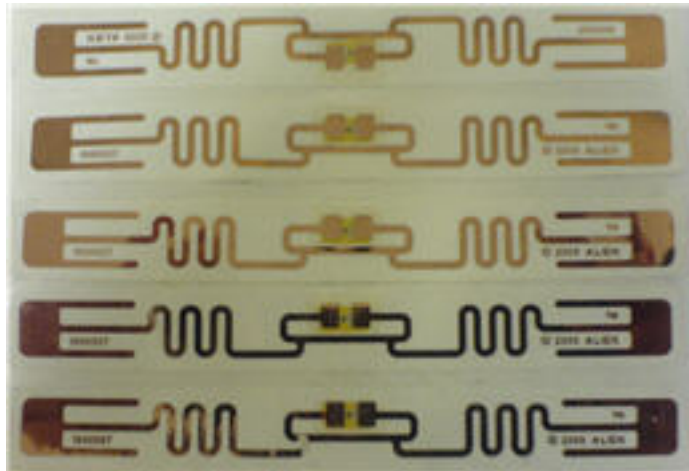
Figure 1.2. Picture of Alien Squiggle Tags.

The tag antenna acts as the coupling element of the tag as it couples with the electromagnetic field emitted by the reader. The tag antenna plays a very significant role in a passive RFID tag as it is instrumental in absorbing the energy from the RF field of the reader and powering the tag IC for it to communicate data back to the reader. The extent to which power is transferred from the reader's electromagnetic

field to the antenna and from the antenna to the microchip is provided by the coupling efficiency of the antenna. The impedance matching between the chip and the tag antenna is of significance since the power delivery to the chip is dependent on the matching circuitry.

The efficiency with which electromagnetic waves are reflected by the tag antenna is given by its reflection cross section. Antenna that is tuned (resonance) to a particular frequency has a larger reflection cross section at that frequency. The signal reflected by the tag antenna has a small proportion of the power harvested from the reader signal. The amoutn of power absorbed and scattered by antennas is explored in [14]. The reflected wave is modulated by varying the reflection cross section (the impedance) of the tag antenna. More details on the backscatter signal strength and Radar Cross Section (RCS) of a tag are covered in chapter 6. The reflection cross section of the tag antenna has a direct dependence on the size of the tag antenna. This is very critical to the performance of the tag as it determines the maximum read range of the RFID system.

1.2.2 Reader Fundamentals

An RFID reader is a radio transciever that interrogates the tags to retrieve the information that is stored in them. The reader emits energy using radio waves to activate and establish communication with a tag. The amount of power transmitted by the reader operating within the United States is restricted by regulations. The control unit within the reader modulates the amplitude and frequency of the wave that is generated by the reader. The antenna used by the reader sends out the modulated data-carrying RF signal to the interrogate the tag. The reader transmits continuous wave signals while listening to the tag response. Since an RFID reader also acts as a receiver, data coming from the tag is received and decoded as well. The information

that is received by the reader is sent to an information system for data processing purposes.

Since RFID is a resource that is used internationally, there are certain regulatory boards like the FCC and the ITU that govern security issues, standards and specifications for spectrum allocation and use [15] [16]. Safe power levels for secure communication are specified by these regulatory bodies. A radio device that operates in the unlicensed ISM band (902 - 928 MHz) is required to hop frequencies within the band every 0.4 seconds. These restrictions imposed on the reader have tremendous impact on the RFID system performance parameters such as backscatter signal strength and maximum operable read range. The European Regulations provide a specific set of power levels and frequency spectrum (865 - 868 MHz) for RFID reader operation. The ETSI (European Telecommunications Standards Institute) specifically requires RFID readers to listen for any communication in the desired frequency level before transmitting on it. This is popularly known as Listen Before Talk (LBT).

Figure 1.3. UHF RFID Reader by Alien Technology.

RFID readers are required to operate in full-duplex mode where they transmit and receive simultaneously at the same frequency. Operating as a transceiver in full-duplex mode comes with its own challenges. Leakage from the transmitter to the

receiver is a very important issue and can be minimized by using separate antennas for transmission and reception. This configuration is called Bistatic Configuration. However, this configuration increases the complexity, expense and the size of the system. A single antenna can be used for transmission and reception. This configuration is called a Monostatic Configuration. The receiver must be designed to detect the signal from the tag despite the leakage.

The reader antenna is the most significant part after the control unit in the reader system. The antenna plays a key role in the transmission and reception of electromagnetic waves. Reader antennas must have high gain and directivity. Commonly used antennas in UHF RFID readers are Patch Antennas [17], [18]. Directivity provides a measure of the ability of the antenna to focus energy in a particular direction. It is important to have a highly directional antenna for transmission as well as reception as the signal transmitted and received by the reader need to be confined to a specific area. This would prevent ghost reads and reader collision problems to a certain extent. The gain of the antenna is a measure of both the efficiency and the directivity of the antenna.

$$Gain = \frac{\text{Efficiency}}{\text{Directivity}} \tag{1.1}$$

The ratio of the power delivered to the antenna to the power that is actually radiated by the antenna gives the efficiency of the antenna. The reader antennas must be able to power the tag for it to respond in the case of transmission and must also be able to receive and detect the feeble backscatter of the tag in the case of reception. Polarization is another important concept in RFID readers. The polarization of the reader antenna must match that of the tags for efficient communication between the

reader and tag. Other antenna parameters such as radiation efficiency and impedance matching are also of significance in the design of reader antennas.

1.2.3   Behind the Scenes - The Information Systems

The Information Systems play a very crucial role at the back-end of RFID systems. All the data that is collected by the reader is processed by the information systems. After capturing the data with the help of readers and tags, it is important to process the data and integrate it into useful applications. This is where the functional benefits of a Middleware or a Data Processing Sub-System come into the picture. A network infrastructure that will support efficient collection of data obtained by the reader is developed [19]. Some of the important challenges faced by middlewares are filtering out all the unwanted data or ghost reads, data mining and sorting and making the middleware cutomizable for every available reader.
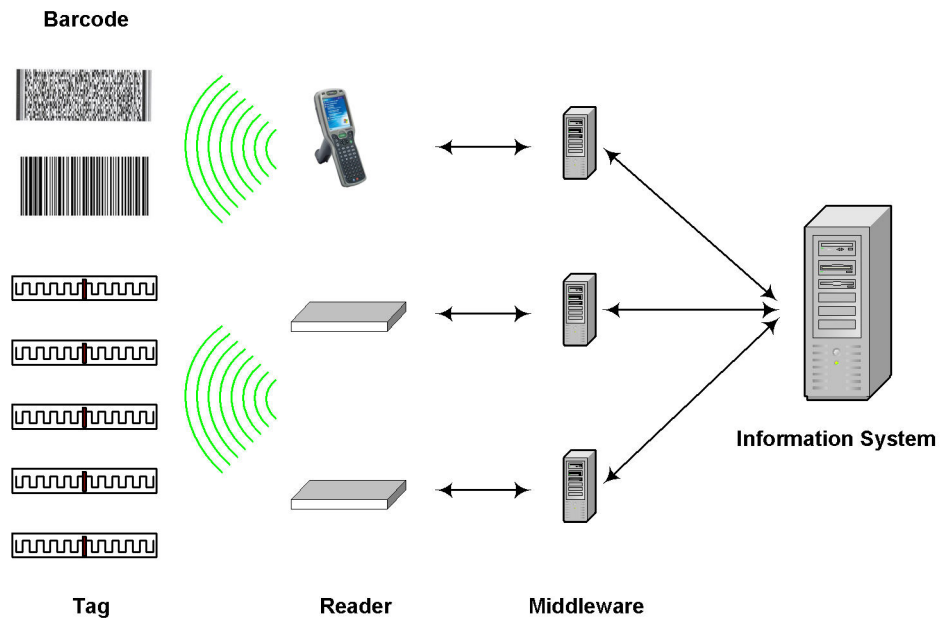
Figure 1.4. Middleware and Information Systems in an RFID Network.

Some of the functions of an RFID middleware are processing the raw data obtained by the readers, providing an interface to manage all the readers and to encapsulate all the applications as different data needs to be routed to different applications. Middlewares usually provide reader management for easy configuration and deployment of RFID readers. They can also be integrated with other data sources such as sensors. Data managements is a very critical requirement. Middlewares must filter out redundant and undesirable data and must also route the data to appropriate destinations.

Many implementations of RFID middleware are possible. Application Level Events (ALE) by EPCglobal specification provides a standard interface to obtain filtered, consolidated EPC data from RFID readers and other data sources [20]. The ALE specification provides flexible mechanisms to filter and group raw RFID data. This filtering and grouping capability provides a means to isolate and focus specific and desired applications.

1.2.4 Working of the whole RFID System

Any system comprises of individual components that work in consonance to meet the requirements of the system. With the increasing number of RFID applications there are different architectures of RFID that can be implemented however the basic underlying system is the same. RFID systems are multi-layered. The physical layer components include RFID tags, antennas and readers. The basic components of an RFID system combine in the same manner for all applications and variations of RFID systems. RFID middleware provides important features such as reader and data management as discussed in the previous section.

All objects to be detected are physically tagged with tags. The readers are strategically placed to interrogate the tags. The type of tags and readers used and

data that is stored in the tags varies with different applications. The reader continuously transmits the interrogation signal. The interrogation signal forms an interrogation zone within which the tags are read. The size of the interrogation zone depends on the reader and tag characteristics. The readers and tags provide the mechanism to obtain data. The data that is obtained by the reader is communicated to an information system for data processing.

There is a certain amount of intelligence involved in RFID systems that reduces the need for human intervention in the implementation of RFID in many applications. The level and scale of automation poses different challenges for these systems. However, RFID systems will continue to evolve to meet the spectrum of needs for any application.

1.3 Summary

RFID systems are poised to become the most popular and the most widely implemented AIDC systems in the world. As tags and readers become less expensive, economic adoption of this technology will be faster. An overview of the basic components and the working of an RFID system were provided in this chapter. Tags can be read at a very high rate and without line of sight requirement. The data stored in a tag can be used to uniquely identify the object to which it is affixed. Due to this automated identification, human intervention can be reduced tremendously and this leads to overall reduction in the operating cost of a system. Furthermore, technological advancements in the near future with the combination of computing systems, will overwhelmingly increase the performance of RFID systems.

CHAPTER 2

PHYSICS OF RFID

Many RFID systems have found applications in the UHF range of frequencies (> 30 MHz). Electromagnetic waves (specifically radio waves) operate in this range of frequencies. It is imperative that we understand the fundamental physics of RFID systems to gain an insight into the data transfer and power harvesting principles of a passive UHF RFID system. This chapter elucidates the physical electromagnetic principles behind the propagation of waves in the far-field.

2.1 Introduction

An RFID system consists of a reader and tags communicating over an air interface at a particular frequency. It is important to understand how the readers and tags communicate and the nuances behind the working of an RFID system. Electromagnetic radiation includes radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X - rays and gamma rays. Together they form the electromagnetic spectrum. The following sections provide an overview of the physical principles behind the propagation of electromagnetic waves to better understand the subsequent chapter on antenna theory.

2.2 Electromagnetic Theory - The Physical Principles

The laws of electromagnetic radiation play a vital role in understanding the fundamental working of an RFID system. The foundation for all wireless communication systems is based on the understanding of electromagnetic field theory [21].

Regardless of the form or nature of any wireless communication system, wireless communication is based on the fundamental laws of physics. An electromagnetic wave comprises of two orthogonal time-varying fields: electric and magnetic fields. They form the mathematical basis for electromagnetic wave propagation [22].

2.2.1 Electric Field

Electric Field is generated by an electric charge. It is defined as the vector force exerted on a unit charge. The units of electric field are newtons per coulomb (N/C) which volts per meter (V/m) equivalently. The direction of the field at a point is defined by the direction of the electric force exerted on a positive charge placed at that point. The strength of the field is given by the ratio of the electric force on a charge at a point to the magnitude of the charge placed at that point. Electric field can be defined in several different ways. A stationary charged particle in an electric field experiences a force proportional to its charge.
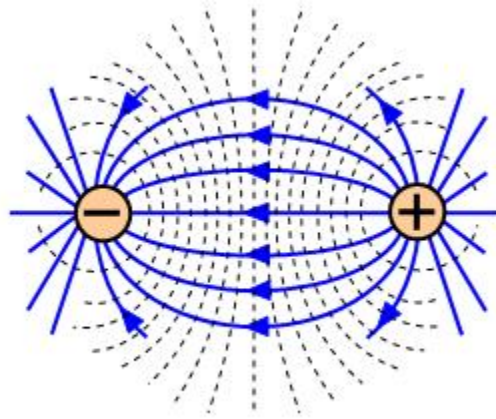
Figure 2.1. Electric Field Lines [1].

$$E = \frac{F}{q} \tag{2.1}$$

where F is the force exerted on the charge, q is the charge of the particle and E is the electric field strength. Equation 2.1 holds good only for stationary charges. Electric Field is dependent on the amount of flux or flux density and the permitivitty of the material (ε).

$$E = \varepsilon D \tag{2.2}$$

The flux density vector has the same direction as that of the Electric Field and has a strength proportional to the charge that generates the electric field. Permitivitty is the property of a dielectric. Permitivitty is expressed with respect to permitivitty in free space (ε_0) and relative perimitiviity (ε_r) or the dielectric constant of the material.

$$\varepsilon = \varepsilon_0 \varepsilon_r \tag{2.3}$$

with $\varepsilon_0 = 8.854 \times 10^{-12} F/m$. The energy stored by an electric field is given by the following equation.

$$u = \frac{1}{2}\varepsilon E^2 \tag{2.4}$$

where E is the electric field vector and ε is the permittivity of the medium in which the electric field exists.

2.2.2 Magnetic Field

Magnetic fields can be generated by steady current flow or by magnetic materials. Magnetic field can be expressed as magnetic field strength (B) and magnetic flux density (H). This is similar to the electric field. The unit for magnetic field strength is

amperes per meter (A/m) and the unit for magnetic flux density is weber per square meter (Wb/m^2). Magnetic field strength and magnetic flux density are related by permeability of the material (μ) as given by the following equation.
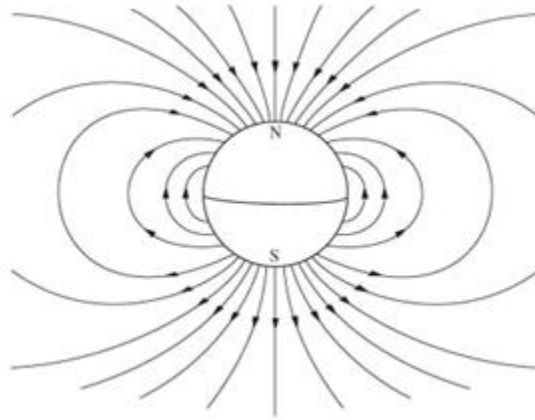
Figure 2.2. Magnetic Field Lines [2].

$$B = \mu H \tag{2.5}$$

The unit for permeability is henries per meter. Permeability is expressed as relative permeability (μ_r) and permeability of free space (μ_0) by the following equation.

$$\mu = \mu_0 \mu_r \tag{2.6}$$

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

The Biot-Savart Law (also known as Ampere's Law) quantifies the relationship between the electric current and magnetic flux. The magnetic flux is proportional to the current flow.

2.2.3 Electromagnetic Wave Generation

Electromagnetism is the physics behind the electromagnetic field which exerts a force on electric charges. Electric charges in motion (electric current) produce a magnetic field. Electromagnetic waves are created by the vibration of an electric charge. This vibration creates a wave which has both electric and magnetic components. Maxwells equations provide the unified electromagnetic theory which form the basis of electromagnetic wave propagation [23]. All classical electromagnetic phenomena is well explained by the Maxwells equations given by

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{2.7}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \tag{2.8}$$

$$\nabla \cdot D = \rho \tag{2.9}$$

$$\nabla \cdot B = 0 \tag{2.10}$$

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 volume current density vector (A/m^2) and ρ is the volume charge density (C/m^3). Equation 2.7 is Faraday's Law, equation 2.8 is Ampere's Law and equations 2.9 and 2.10 are Gauss's Laws.
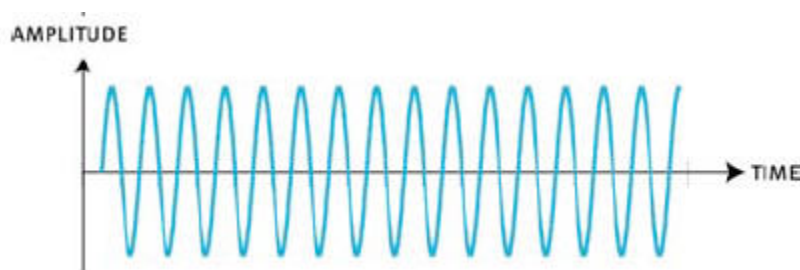
Figure 2.3. Wave Propagation.

Time-varying electric field produces a magnetic field and a time-varying magnetic field produces an electric field. Electric field, magnetic field and the direction of propagation are mutually orthogonal. The fundamental relationship that governs the propagation of electromagnetic waves is given by the wave equation.

$$\frac{\partial^2 E_x}{\partial t^2} = \mu\varepsilon\frac{\partial^2 E_x}{\partial z^2} \tag{2.11}$$

The velocity of propagation of an electromagnetic wave is derived from the wave equation and is a function on permitivitty and permeability of the medium of propagation is expressed as

$$v = \frac{1}{\sqrt{\mu\varepsilon}} \tag{2.12}$$

The velocity of propagation of an electromagnetic wave in terms of relative permeability and permitivitty is as follows

$$v = \frac{1}{\sqrt{\mu_r\varepsilon_r}\sqrt{\mu_0\varepsilon_0}} \tag{2.13}$$

Using the values of μ_0 and ε_0 we get

$$v = \frac{1}{\sqrt{\mu_r\varepsilon_r}}c \tag{2.14}$$

where $c = 2.998 \times 10^8 m/s$. Thus the velocity of propagation is equal to the velocity of light in free space divided by the square root of the product of the relative permittivity and permeability of the medium of propagation.

2.2.4 Data Transfer

RFID systems operate using either full-duplex or half-duplex data transfer protocols or sequential data transfer protocols. Full-duplex systems allow concurrent

data transfer between the reader and tags and requires the use of multiple frequencies or channels. The tag's response is broadcast when the reader's RF field is turned on. Half-duplex systems alternate between sending data to and receiving data from the tags. These systems usually serialize the data transfer and may communicate in a single channel or frequency.

Transmitter   **Receiver**
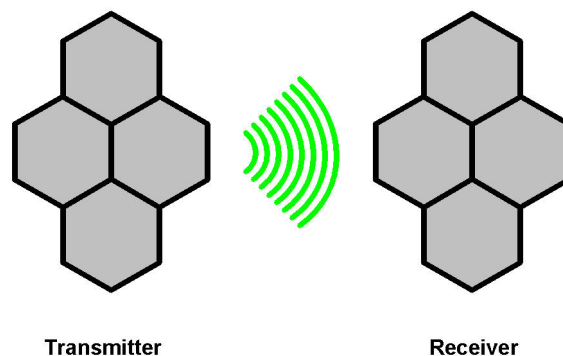
Figure 2.4. Energy and Data Transfer.

Sequential data transfer protocols employ a system whereby the field from the reader is turned off briefly at regular intervals. These intervals are recognized by the tag and are used to send data back to the reader. Though the sequential data transfer protocol and the half-duplex protocol are similar they also have their own differences. The significant difference between the two data transfer protocols is signal from the reader is continuously transmitted though they alternate between sending and receiving data in the case of half-duplex data transfer protocol while it is periodically turned off in the case of sequential data transfer protocol.

Irrespective of the data transfer protocol used by RFID systems, data may be transferred using many methods such as backscatter, load modulation or subharmonic generation. There are certain limitations on the practical frequencies that

can be used with backscatter communication. Passive UHF RFID systems have found backscatter as the best mode of communication from the tag to the reader. Electromagnetic waves are reflected by objects with dimensions greater than half the wavelength of the wave. The efficiency with which an object reflects electromagnetic waves is described by its reflection cross section. A tag with a high reflection cross section for a particular frequency reflects electromagnetic waves at that frequency. The reflected wave has a smal proportion of the power of the incoming wave. The power of the reflected wave is modulated by varying the power of the reflection cross section of the tag.

The communication frequency has a significant impact on the data transfer method used for an application [24]. Frequencies above 300 MHz have sufficiently small wavelengths for backscatter data transfer however this poses a limit on the inductive and capacitive coupling ranges. Thus the operating frequency is very critical for an RFID system.

2.2.5   Polarization

Polarization is defined as the orientation of the electric field of an electromagnetic wave and characterizes the electromagnetic wave. Longitudinal waves such as sound waves do not exhibit polarization. Polarization is generally elliptical in nature. The two types of elliptical polarization are Linear and Circular polarizations. The classification for polarization is shown in the figure below.

The electric field vector stays in the same field in the case of Linear Polarization. The electric field vector appears to be rotating about the direction of propagation in the case of Circular Polarization. The electric field vector has perpendicular components x and y and z in the direction of propagation.
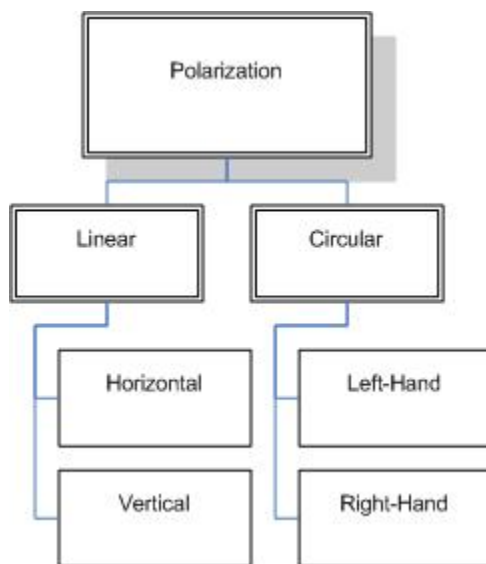
Figure 2.5. Polarization Classification.

2.2.6 Propagation Loss

Propagation loss or the path loss is the attenuation of an electromagnetic wave as it propagates through space. There are several reasons for propagation loss such as reflection, refraction, scattering, diffraction and absorption. Parameters affecting radio propagation for wireless systems is explained in [25] and [26]. In RFID, the distance between the reader and tag has a very significant effect on the power loss which decreases as the inverse square of the distance between the reader and tag. The power density received at a distance d is given by the free space transmission formula,

$$S = \frac{P}{4\pi d^2} \tag{2.15}$$

where S is the received power density, P is the power radiated by the reader antenna and d is the distance between the reader and tag. Propagation loss is also

affected by the terrain, environment, buildings and vegetation between the reader and tag.

2.2.7 Laws governing Electromagnetics

It is important to understand the laws governing electromagnetics to understand the physics behind RFID systems. Coulomb's Law, Faraday's Law, Gauss's Law and Ampere's Law will be discussed in this section [27].

2.2.7.1 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.

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2} \tag{2.16}$$

where F is the electostatic force, q_1, q_2 are the point charges, r is the distance between the point charges and ε_0 is the permitivitty of free space.

2.2.7.2 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. The differential form of Faraday's law is one of the four Maxwell's equations.

$$E = -N\frac{d\phi_B}{dt} \tag{2.17}$$

where E is the electromotive force, N is the number turns in the wire and ϕ_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.

2.2.7.3   Ampere's Law

Ampere's law relates the integrated 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, with again the right hand rule relating the senses of the contour and the surface.

$$\nabla \times B = \mu_0 J + \varepsilon_0 \mu_0 \frac{\partial E}{\partial t} \tag{2.18}$$

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

2.2.7.4   Gauss's Law - Electric Flux and Magnetic Flux

Gauss's law is the electrostatic application of the generalized Gauss's theorem giving the equivalence relation between any flux and electric charges enclosed within a closed surface. The differential form of Gauss's law forms 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.

$$\phi = \oint_S E.dA \tag{2.19}$$

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

2.3 Summary

In this chapter, a review of the fundamentals of electromagnetic theory was provided. It is important to delve into the principles of electromagnetics to understand the physics behind RFID systems. The physics behind every component of an RFID system was analyzed in detail. This will provide an insight into the working of the entire system. The propagation of electromagnetic waves in the far-field was introduced to better understand the communication between the reader and tag. Also, the fundamentals behind the data transfer between the reader and tags are illustrated.

CHAPTER 3

RELATED WORK

There are several commercial tags that are available with a gazellion inlay and antenna designs. Unfortunately, not all tags work well for all applications and each RFID application needs its own customization. The main reason behind testing and analyzing RFID tags is to choose the right tags for the correct application. The tag that was used for baggage tracking might not work at all on a bottle of coke ! Testing and performance analysis of tags gives an idea of the impact of the environment and the objects that are tagged on the tags themselves. Thus it is essential and crucial to understand and analyze the performance of various tags in different environments.

The key parameters in the successful implementation of an RFID system are the correct choice of readers, tags, tag location, antennas, reader configuration, analysis of objects to be tagged and characterization of the environment. There are several parameters such as tag sensitivity, backscatter signal strength, communication range, reflection efficiency of the tag, reader sensitivty, IC design and antenna design that affect the performance of tags in different environments and on different objects to be tagged.

In the paper by Namhoon Kim et al [28], the performance analysis of an RFID tag antenna at 911 MHz has been discussed. A brief overview of the limitations on the performance of passive UHF RFID systems such as communication range, tag characteristics and reader properties are discussed in [29]. Theoretical and practical aspects of low cost and long range RFID tag design and the different appraoches in the modulation of the reply from the tags is provided in [30]. The theory and practical

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analysis behind the backscattering and radar cross section of tags is provided in [31]. Simulation and practical results are provided for the backscattering and radar cross section of tags by optimizing the load impedance to achive maximum RCS is discussed in [32]. The effect of environmental factors on the performance of specific parameters such as impedance pattern and radiative efficiency of RFID tags is discussed in [33].

An ultra low power battery integrated IC for an RFID tag operating at UHF range of frequencies which makes it function as a passive tag as well when the battery is dead is designed and developed in [34]. The variations in the antenna impedance due to the surrounding objects and the shadow region problems have been discussed. The impact of the distortion of tags is discussed in the paper by J.Siden et al in [35]. A generic design process with elucidating the requirements in the design of passive UHF RFID tag antennas are provided in [36]. RFID tag characteristics such as maximum communication range and orientation sensitivity can be improved using multiple RF ports have been explained in [37]. Performance of a passive UHF RFID tag on the power reflection coefficients for complex impedances are described and analyzed in detail in [38]. Impact of the quality factors of the tag antenna and tag IC on the communication range of the tag is provided in [39]. The impact of curving of antennas on the read range and thus the consideration of certain antennas that are not affected by this curving is provided in [40]. Design criteria for passive UHF RFID tags for the RF section is described in [41].

In this chapter, we discussed the work that has been accomplished in the past on the analysis of various parameters that individually impact the performance tags. All the research work that has been done so far only discuss the effect of indivdual parameters on the performance of tags. Thus, this thesis aims to fill this void and achieve a cumulative and comprehensive analysis of all the factors together, that affect performance of tags.

In the following chapters the analysis of some critical parameters that affect tag performance have been dicsussed in detail. A comprehensive test methodology to analyze passive UHF RFID tags is provided with a systematic approach. A general theory is developed to enumerate the the factors affecting tag performance. Analytical evaluations are provided to validate the theory with practical results. Testing is also performed in an anechoic chamber to validate the test results under lab conditions. Performance of tags on water and detergent are also analyzed and validated with the test results in an anechoic chamber.

CHAPTER 4

TESTING METHODOLOGY

There are several tag designs in the market today with many inlay manufacturers and chip manufacturers with a gazellion antenna designs and each of them work differently for various passive UHF RFID applications [42]. Choosing the right tag for the right application might be quite a task with the number of commercially available tags today. However, it is very important to test the tags and analyze the results to gain an insight into the impact of the products being tagged and the environment on the tags themselves. In this chapter, we provide a step-by-step procedure for testing passive UHF RFID tags and analyzing the resulting data.

4.1 Introduction

As seen in the Introduction Chapter an RFID system consists of a Reader, Tag and an Information System. The working of the entire RFID system not only depends on the individual components comprising the system but also on all the components working together as a whole unit. The readers and the information system for an RFID implementation is mostly a one time cost, however the tags to be used on the products are a recurring expense. Thus, to generate an acceptable ROI the right tags for the correct environment is an inevitable requirement. Unfortunately, this is not a solution that can be universally adopted for all applications. RFID solutions must be customized based on the requirements of each application [4].

The key parameters in the successful implementation of an RFID system are the correct choice of readers, tags, tag location, antennas, reader configuration and

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characterization of the environment. It is very important to analyze the performance of tags on the products that need to be tagged and to characterize the surrounding environment. This is mainly to ensure higher read rates, high accuracy and better efficiency for the whole system. In this chapter, we introduce a systematic approach to test passive UHF RFID tags and analyze the test results to provide a better understanding of certain important parameters that impact the performance of tags.

4.2 Test Setup

There are several different ways to test and compare the performances of different tags. Measurements can be made to test antennas and cables. Traditional RF testing has been accomplished with a network analyzer to measure the properties of RF IC's. In this section, we explain how to set up the test equipment for the testing of passive UHF RFID tags. Testing of RFID tags can be achived with the help of the tradtional network analyzer or the more recent tag analyzer. Another very simple approach to test tags is use a commercial UHF RFID Reader.

All experiments were performed using the TagFormance Tag Analyzer measurement system by Voyantic Ltd. TagFormance is a complete measurement tool to analyze the performance of passive UHF tags. A signal source attached to a transmitting antenna sends a command to the tag. A vector signal analyzer attached to a receiving antenna detects and decodes the response from the tag. The reader uses DSB-ASK forward link modulation and FM0 return link modulation. Transmit and receive antennae are linearly polarized. The gain of the antennas used and the the cable losses for the antenna cables must be noted from the datasheet provided by the manufacturers of the antenna and cables. Most of the steps covered in the following paragraphs to set up the test equipment is generic with any signal source and signal
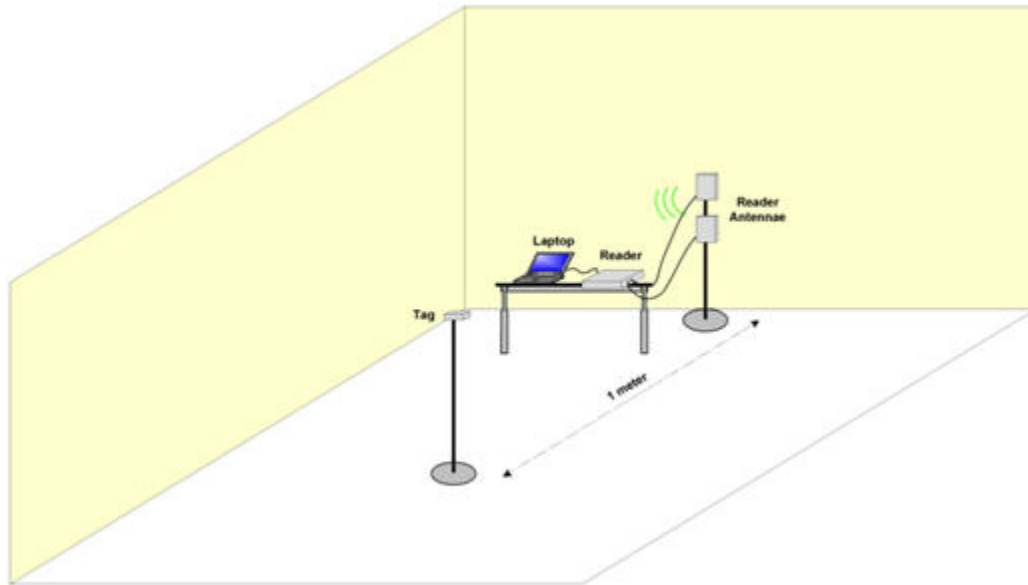
Figure 4.1. Test Setup.

analyzer connected to an antenna assuming that the EPC Gen2 protocol for Passive UHF RFID reader is implemented.

Following are some of the steps to setup the equipment for testing purposes.

1. The hardware connections to set up the test unit (reader or a tag analyzer) must be made according to the instructions provided by the unit manufacturer. The unit must be configured with the hardware and software as per the manufacturer's instructions.

2. Also, care must be taken to separate the transmitter and receiver antenna by about atleast 25 cms. The antenna stands must be made of non-conductive material such as wood or plastic. Circulators can also be used but a lot of care must be taken when using circulators.

3. After setting up and configuring the reader, the tag must be affixed to any RF transparent material such as foam for freespace tag testing or on the product

to be tagged. Again, the tag must be placed on a stand which must also be made of non-conducting material. It is advisable to use a tag stand which is approximately the same height of the antenna stand.

4. Place the tag at a desired distance from the test equipment. Usually, for range testing the tag is initially kept at 1 m from the test unit and then testing is done and then again the tag is placed at 2 m and testing is done and this is repeated until the tag can be read at a maximum distance from the test unit.

5. Make sure that the there are no other tags other than the tag under test in the room and follow the steps discussed in the testing section to start the test procedure.

The flowchart that indicates the step-by-step procedure or a cookbook recipe is shown in figure 4.2. Setting up the equipment used for testing which can be a reader or a tag analyzer depends on the manufacturer of the unit and this section covers the test setup procedure for testing of only RFID tags and not the individual reader or tag analyzer configuration.

4.3 Tag Testing - A Systematic Approach

A simple transmitter can be used to generate a carrier to power the tag. The carrier is modulated to create a command. The tag responds by changing the reflection coefficient and thus modulating the backscattered signal which is received and detected by the reader. For more details on the implementation of EPC Gen2 Protocol on the transmitter and receiver please check the following [43].

In this section we provide a systematic cookbook approach for the testing of passive UHF RFID tags. There are several factors that impact the performance of RFID tags. Testing tags under various conditions gives an idea of how the tags work

in different environments. Flowchart showing the testing methodology is shown in figure 4.3.

The following steps explain the systematic procedure for the testing of passive UHF RFID tags. Both frequency sweep and power sweep can be performed to test the tags at a broad range of frequencies and at various power levels.

1. Freqeuncy Sweep - Set the start frequency, stop frequency and frequency step size for the freqeuncy sweep. Power Sweep - Set the start power level, stop power level and the power step size of the transmitter for the power sweep.

2. Frequency Sweep - Set the power level at a constant value for the frequency sweep. Power Sweep - Set the frequency to a constant for the power sweep.

3. Start the testing. For example, the frequency sweep can be performed from 800 MHz to 1000 MHz for the UHF range of frequencies with a constant power level of 1 W. This power level can be changed to test the frequency response of tags at different frequencies with different power levels however kept constant for a full sweep. The power sweep can be performed from say 0 dBm to the maximum power level provided by the regulations at a constant frequency. Again the frequency can be changed to test the response of tags at various power levels however the frequency must be constant for a full sweep.

4. The above tests can be repeated at different distances of the tag from the test unit starting from 1 m to 10 m or the maximum range provided by the tags.

5. The above tests can also be repeated for different tag orientations. For example, keep the tag at 15 degree angle facing the test unit and perform the testing. This can be repeated for the full 360 degeree rotation.

6. The tag under test can be affixed to the product to be tagged to test the performance of the tag on that particular product or material. The above mentioned steps can be repeated.

7. The data obtained from both the frequency and the power sweep test will be the range of frequencies tested, range of transmitted power levels, received power levels at the test unit, electric field strength and the Radar Cross Section (RCS).

8. Perform the data analysis on the data obtained to evaluate the performance of the tags under test.

This is the crux of tag testing as it covers the frequencies at which the tags perform well and the amount of power required for the tags to respond and operate successfully. The following section provides some tips and hints to evaluate the tags that were tested.

4.4   Evaluation and Data Analysis

The evaluation and analysis of the data obtained from the testing of tags is also very important. There will be a huge volume of data collected after the complete testing of all the tags under test. Some might even be stupefied by the data generated. There are several ways to perform data analysis and in this section we explain the way data analysis has been performed in the forthcoming chapters to get useful results.

It is very important to first be clear as to what do you want to derive from the data that is obtained. In this section, we provide a systematic approach to perform data analysis on passive UHF RFID tags based on the testing procedure. Flowchart showing the testing methodology is shown in figure 4.4.

The following steps explain the systematic procedure for the data analysis of passive UHF RFID tags.

1. The data that is obtained from any test tag test equipment (depends on the test unit that is used) is frequency, power transmitted by the reader and power received by the reader. Based on these parameters several relationships can be drawn and many results can be established.

2. From the frequency sweep data that is obtained based on the tag tests conducted as explained in the previous section, the freqeuncy vs power received at the reader or the electric field strength at the tag if the data is available can be plotted in a graph for the tag under test. The graphs can be plotted using Microsoft Excel or any other charting software. This graph basically shows the performance of the tag at various frequencies. This also gives an idea of how well the tag works under different regulatory frequencies. A sample graph is shown in 4.5.

3. Using the Friis path loss equation, it is possible to obtain the power received at the tag and the power backscattered by the tag from the data obtained on the power transmitted and received by the reader. Refer to chapter 5 for more details. Using this calculated data, the frequency vs power received by the tag and the power backscattered by the tag can be plotted.

4. Using the power sweep test data obtained based on the tag tests conducted as explained in the previous section, the power transmitted by the reader vs the power received by the reader at a constant frequency can be plotted. A sample graph is shown in 4.6.

5. Using the Friis path loss equation, it is possible to obtain the power received at the tag and the power backscattered by the tag from the data obtained on the power transmitted and received by the reader. Refer chapter 5 for more details. Using this calculated data, the transmitted power vs power backscattered by the tag and the power backscattered by the tag can be plotted.

6. Similarities and differences between performances of various tag IC's and the tag antennas used by the tags can be compared based on the data collected. Refer chapter 5, 6 and 7 for more details.

7. Using the range test results obtained based on the tag tests conducted as explained in the previous section, the realtionship between the tags and the maximum range provided by them can be illustrated. This can also be related to the tags using the same IC's and the same tag antennas for comparisons. Relationship between the tag IC's and the electric field strength of the tags can also be obtained.

8. Performance analysis of tags on water, detergent, metal or the product to be tagged can be obtained for the all the above mentioned relationships and comparisons.

9. All the test results with the tests performed in an anechoic chamber can be compared to the tests conducted in the lab using the same data analysis procedure explained in the previous steps.

The testing of tags is a very important part in the successful depolyment of RFID systems. A systematic cookbook approach to setup the test equipment, to conduct the testing and to perform the data analysis is provided in this chapter. Again, there are several ways to perform testing and evaluation of RFID tags and this text covers one such generic approach to test, analyze and evaluate passive UHF RFID tags.
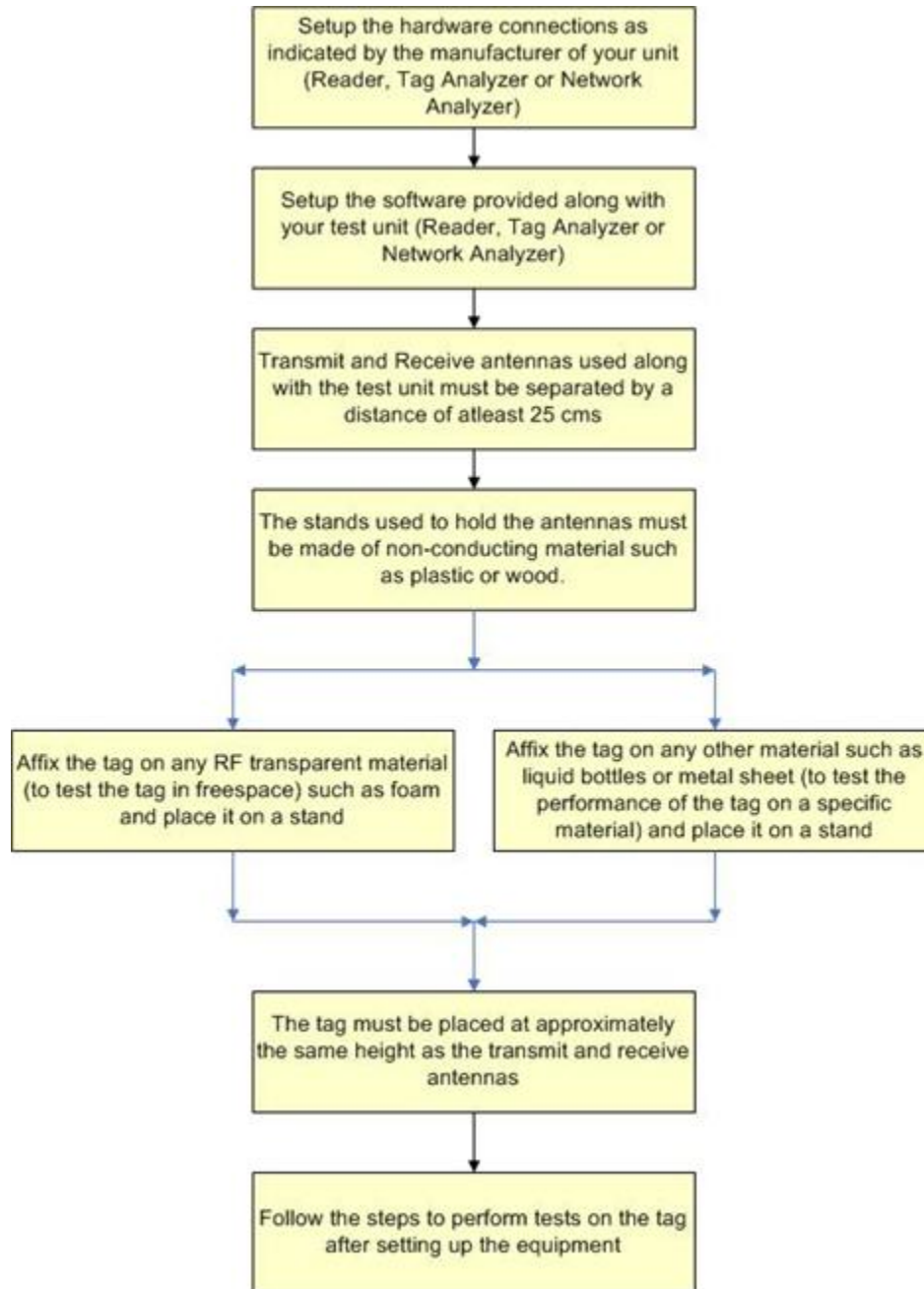
Figure 4.2. Test Setup Flowchart.

Figure 4.3. Testing Flowchart.

The data that is obtained from most tag test equipment are frequency, power transmitted by the reader and power received by the reader.

From the frequency sweep data the frequency vs power received at the reader can be plotted in a graph for the tag under test.

Using the Friis path loss equation, calculate the power received at the tag and the power backscattered by the tag from the data.

Using this calculated data, the frequency vs power received by the tag and the power backscattered by the tag can be plotted.

Using the power sweep test data the power transmitted by the reader vs the power received by the reader at a constant frequency can be plotted.

Using the Friis path loss equation, calculate the power received at the tag and the power backscattered by the tag from the data.

Using this calculated data, the transmitted power vs power backscattered by the tag and the power backscattered by the tag can be plotted.

Decipher the similarities and differences between performances of various tag IC's and the tag antennas and compare the results.

Draw the various relationships between the tags and the maximum range based on range test data.

Performance analysis of tags on water, detergent, metal or the product to be tagged can be obtained for the all the above mentioned relationships and comparisons.

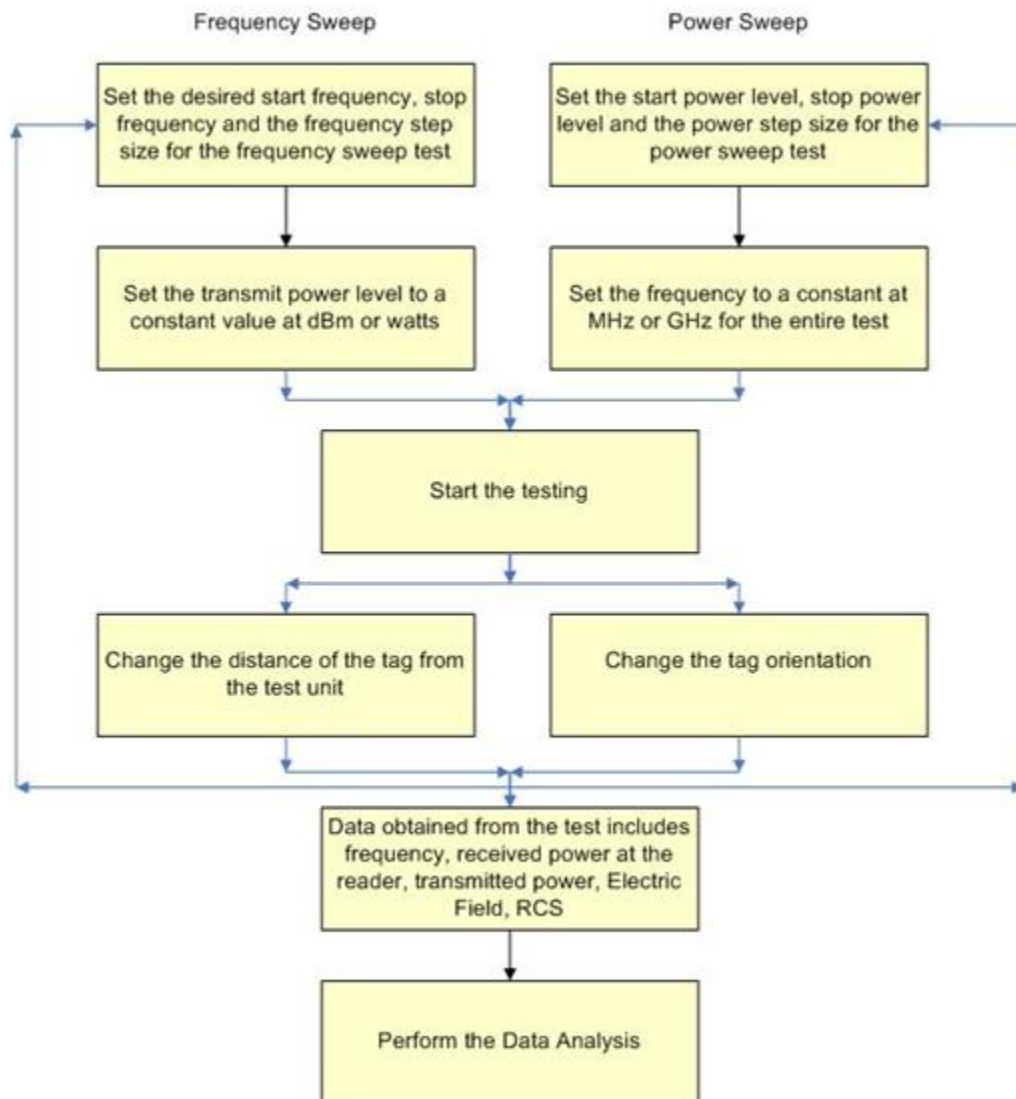Compare the testing in an anechoic chamber to the tests in the lab to get an idea on the characterization of the testing environment.
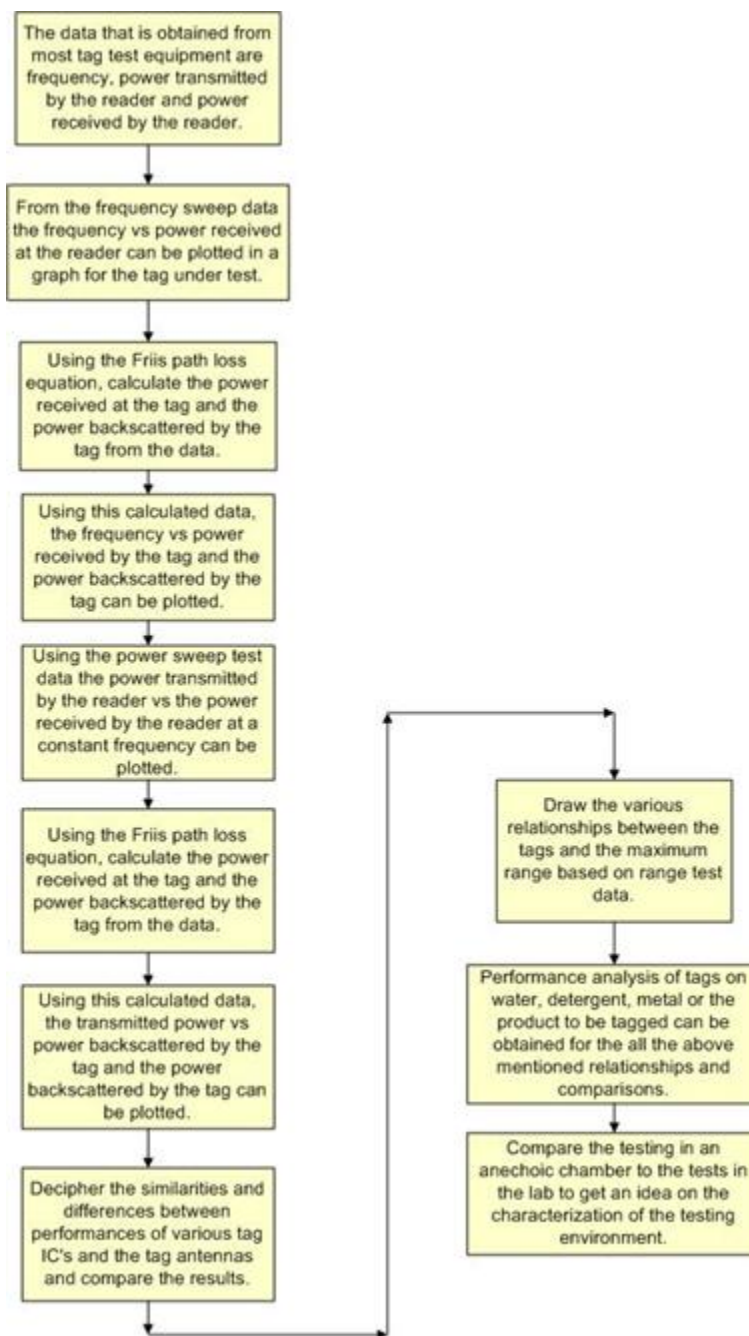
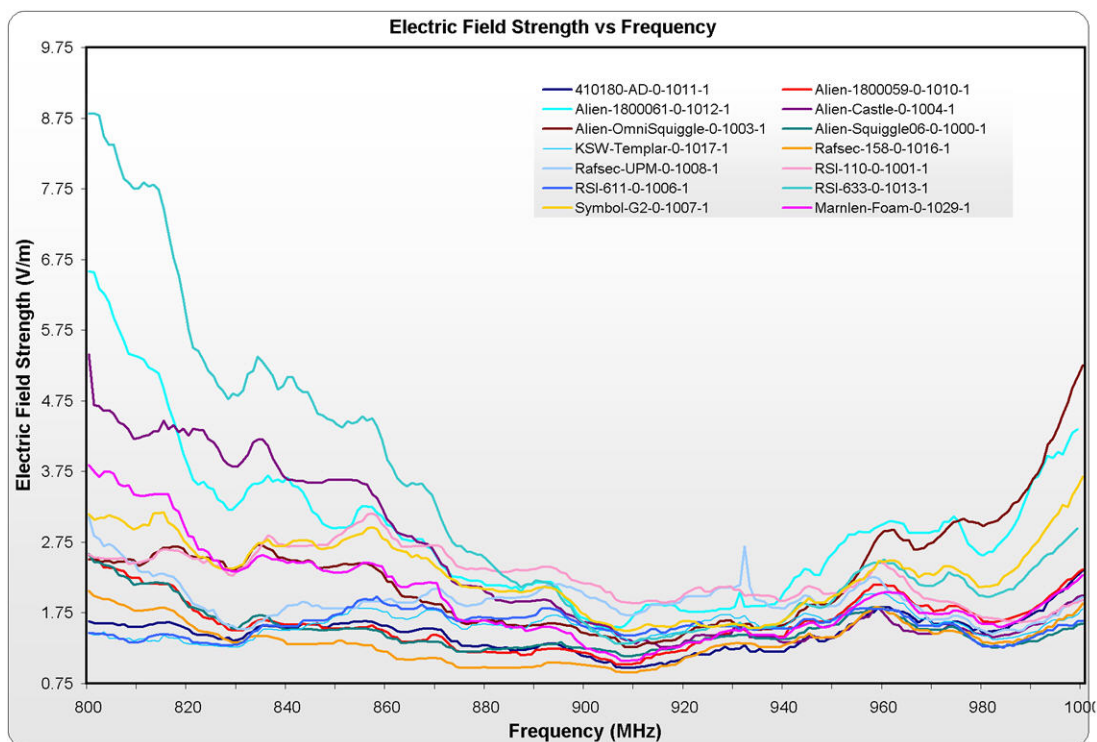Figure 4.4. Data Analysis Flowchart.

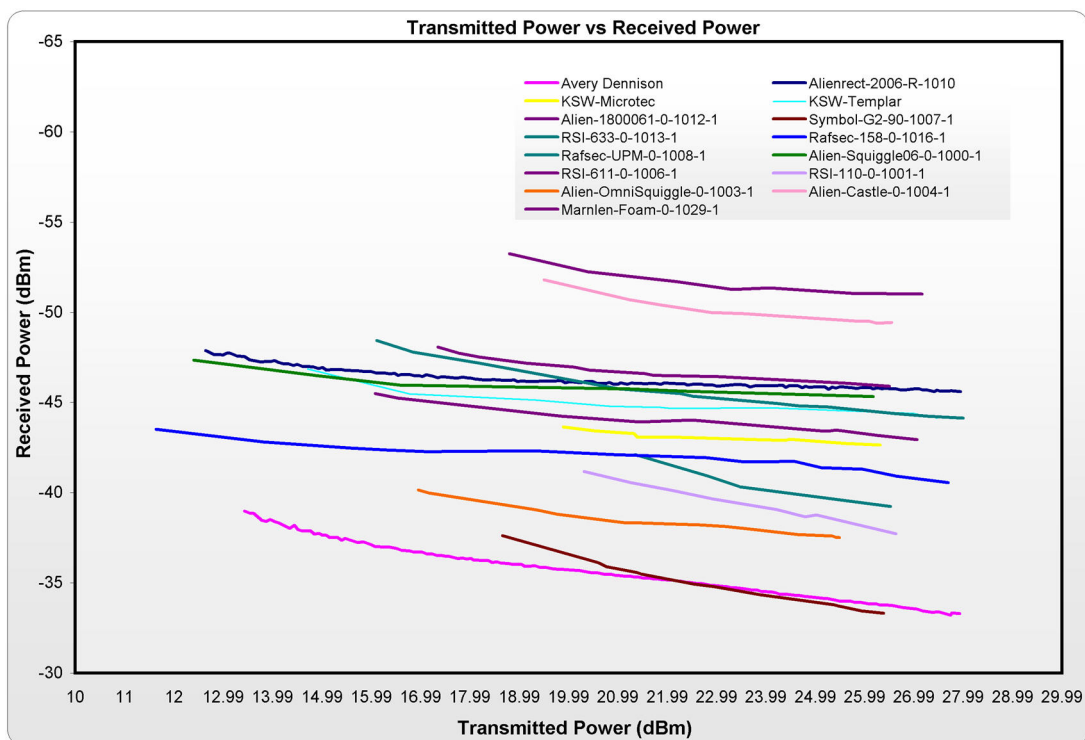Figure 4.5. Sample Frequency vs Electric Field Strength Graph.

Figure 4.6. Sample Transmitted Power vs Received Power Graph.

CHAPTER 5

TAG SENSITIVITY

Tag Sensitivity is one of the important parameters that can affect the performance of passive UHF RFID tags. The sensitivity of a tag is directly dependent on factors such as maximum communication range provided by the RFID system and the amount of power that can be backscattered by the tag. Backscattering of tags and the tag communication range are crucial parameters in a passive RFID system due to the lack of on-tag power supply. In this chapter, we discuss the test setup required to measure and analyze the sensitivity of a tag. We also provide a detailed analysis of the results obtained and delve into the mutual relationship between the sensitivity of tags, electric field strength, communication range, backscatter signal strength and the tag IC's used.

5.1   Introduction

Tag sensitivity can be defined as the minimum required threshold power for the tag to respond. One of the limiting factors impacting the read range of tags is the sensitivity of the tag IC. A passive tag typically uses far-field energy harvesting from the reader signal to power the tag. The signal incident upon the tag antenna induces a voltage at the input terminals of the tag. Power delivery to a tag is dependent on factors such as tag antenna design, matching circuitry and distance from the reader antenna. As the power transmitted by the reader decreases as a function of the inverse square of the distance from the reader, this imposes a fundamental limitation on the power detected at a distance away from the reader. Thus, tag sensitivity which

is directly dependent on the distance between the reader and tag must have a low threshold to achieve longer read ranges. Another factor impacted by tag sensitivity is power backscattered by the tag. Power reflected by the tag is directly dependent on the power received at the tag. In this chapter, we discuss the significance of tag sensitivity and also provide a mathematical analysis method to compute the reflection efficiency of a tag.

5.2 Experimental Setup

All experiments were performed using the Tagformance Tag Analyzer measurement system by Voyantic Ltd. Tagformance is a complete measurement tool to analyze the performance of passive UHF tags. A signal source attached to a transmitting antenna sends a command to the tag. A vector signal analyzer attached to a receiving antenna detects and decodes the response from the tag. The reader uses DSB-ASK forward link modulation and FM0 return link modulation. Transmit and receive antennae are linearly polarized with 8 dBi gain.

The tag is placed at a distance R from the reader. The transmit power is varied with a step size of 0.1 dBm for a frequency sweep of 800 MHz to 1 GHz. The minimum power, at which the tag responds is noted along with the frequency, received power at the reader, electric field strength, distances between the reader and tag, delta RCS and received signal phase.

5.3 Propagation and Antenna Fundamentals

A typical RFID tag consists of an antenna and a tag IC. The chip harvests power from the RF signal transmitted by the Reader in the case of a passive RFID tag. The tag backscatters the information to the reader by varying its input impedance thus

modulating the backscattered signal. Passive RFID systems do not have an on-tag power supply and hence they use either backscatter or load modulation to transmit data back to the reader.

The amount of power transmitted by the Reader is limited by regulations. The tag IC requires a certain threshold power to turn on and respond. This is called Tag Sensitivity. The amount of power transferred to the chip depends on the tag antenna design. Thus the power delivery to the tag over a particular distance depends solely on two parameters: the tag IC and the tag antenna design. However, there is a fundamental limitation on the power detected at a particular distance from the Reader. Let us assume that the power transmitted by the reader has a uniform power density in all directions over a spherical surface at any given distance R. Some of this power is received by the tag antenna and is proportional to the effective aperture of the tag antenna and the power impinging on the tag [44]. The power density of the power transmitted by the reader is given by,

$$P_D = \frac{P_t}{(4\pi R)^2} \tag{5.1}$$

P_t is the power transmitted by the reader and R is the radius of the sphere. From the above equation we see that the power transmitted by the reader decreases as a function of the inverse square of the distance from the reader. If we double the distance to the tag, the power received by the tag falls by a factor of 4. The power received by the reader falls by an additional factor of 4.

The Gain (G) of an antenna is the ratio of power radiated in the desired direction to the power radiated by an isotropic antenna as given by equation 5.2. The Gain gives a measure of the efficiency of the coupling devices in the reader and the tag.

$$G = \frac{\text{maximum radiation intensity}}{\text{radiation intensity of isotropic antenna}} \tag{5.2}$$

The gain of an antenna is measured with respect to an ideal isotropic antenna expressed in dBi. It is also common to measure the gain of antenna with respect to a standard dipole antenna expressed in dBd. Gain referenced to a dipole is 2.2 dB less than gain referenced to an isotropic antenna.

$$dBd = dBi - 2.2 \tag{5.3}$$

The power received by the tag in free-space propagation condition is given by the Friis free-space transmission formula,

$$P_{RX,tag} = P_{TX,reader} G_{reader} G_{tag} \left(\frac{\lambda}{4\pi R}\right)^2 \tag{5.4}$$

where $P_{TX,reader}$ is the power transmitted by the reader, G_{reader} and G_{tag} are the gains of the reader and tag antennae and λ is the wavelength of the transmission frequency. Also, there is a power loss between the power received by the tag and the power backscattered by the tag due to a certain amount of power used by the tag chip to turn on and respond. This is the backscatter transmission loss and is given by B_L [45]. The power transmitted or backscattered by the tag is given by,

$$
\begin{aligned}
P_{TX,Tag} &= P_{RX,tag} B_L \\
P_{TX,Tag} &= P_{TX,reader} G_{reader} G_{tag} \left(\frac{\lambda}{4\pi R}\right)^2 B_L
\end{aligned}
\tag{5.5}
$$

The power received by the reader decreases as the inverse fourth power of distance. The power backscattered by the tag is significantly small and hence there is a potential necessity that the reader sensitivity be as low as possible as this impacts the read range. The power received by the reader is given by,

$$P_{RX,reader} = P_{TX,Tag}G_{reader}G_{tag}\left(\frac{\lambda}{4\pi R}\right)^2$$

$$P_{RX,reader} = P_{TX,reader}G^2_{reader}G^2_{tag}\left(\frac{\lambda}{4\pi R}\right)^4 B_L \tag{5.6}$$

From the above equation we can calculate the Backscatter transmission loss, B_L as

$$B_L = \frac{P_{RX,reader}}{P_{TX,reader}G^2_{reader}G^2_{tag}\left(\frac{\lambda}{4\pi R}\right)^4} \tag{5.7}$$

From the above equations, it is possible to estimate the path loss between the reader and tag both in forward as well as in the reverse links. The path loss is given by the difference between the power transmitted by the reader and the power received by the tag and this is the loss due to the signal traveling from the reader to the tag.

$$PL_{\text{Forward Link}} = P_{TX,reader} - P_{RX,tag} \tag{5.8}$$

$$PL_{\text{Reverse Link}} = P_{TX,tag} - P_{RX,reader} \tag{5.9}$$

Tag antenna polarization is another parameter that is of vital significance. The energy radiated by an antenna is contained in a transverse electromagnetic wave that has an electric and magnetic field. These field are orthogonal to one another and to the direction of propagation. The electric field of the electromagnetic wave is used to describe the polarization. When the direction of the field is constant in time then the wave is linearly polarized. When the electric field rotates around the axis of propagation without varying magnitude then the wave is circularly polarized. Polarization has a direct impact on the voltage induced to power the tag IC to allow the tag to communicate with the reader. If the electric field is along the direction of the tag antenna, it induces a voltage to power the tag IC and allows it communicate

with the reader. However if the electric field is perpendicular to the direction of the tag antenna, it induces negligible voltage that is not sufficient to power the tag IC and respond.

In the following sections we compute the various values for the power received by the tag, $P_{RX,tag}$, power backscattered by the tag, $P_{TX,tag}$ and the backscatter transmission loss, B_L at different frequencies.

5.4 Backscatter Loss

The power transmitted and received by the reader $P_{TX,reader}$, $P_{RX,reader}$ respectively are recorded using the experimental setup described in section 5.2. Several commercial tags were used for experimental purposes. Some of the tags used were the Alien family of tags (Squiggle, 2006, Castle, Omnicastle), Symbol (G2), RSI (Spyder), Rafsec (Dogbone, Frog-UPM) and KSW Microtec(Templar). The power received by the tag and the power reflected or backscattered by the tag are calculated using equations 5.4 and 5.5 respectively. B_L is the ratio of the power reflected or backscattered by the tag to the power received by the tag and is calculated using equation 5.7. Figure 5.1 shows the Backscatter loss ratio vs Frequency for an Alien Squiggle tag at a distance of 1 m from the reader.

$$B_L = \frac{\text{Power received by the tag}}{\text{Power reflected by the tag}} \tag{5.10}$$

The amount of power received and also backscattered by a tag is dependent on the frequency, power transmitted by the reader and the distance between the reader and the tag. From figure 5.1, it can be observed that for an Alien Squiggle tag, the backscatter ratio is low for the range of frequencies between 800 - 875 MHz. This implies that the reflection efficiency of the tag is low for the lower range of frequencies.
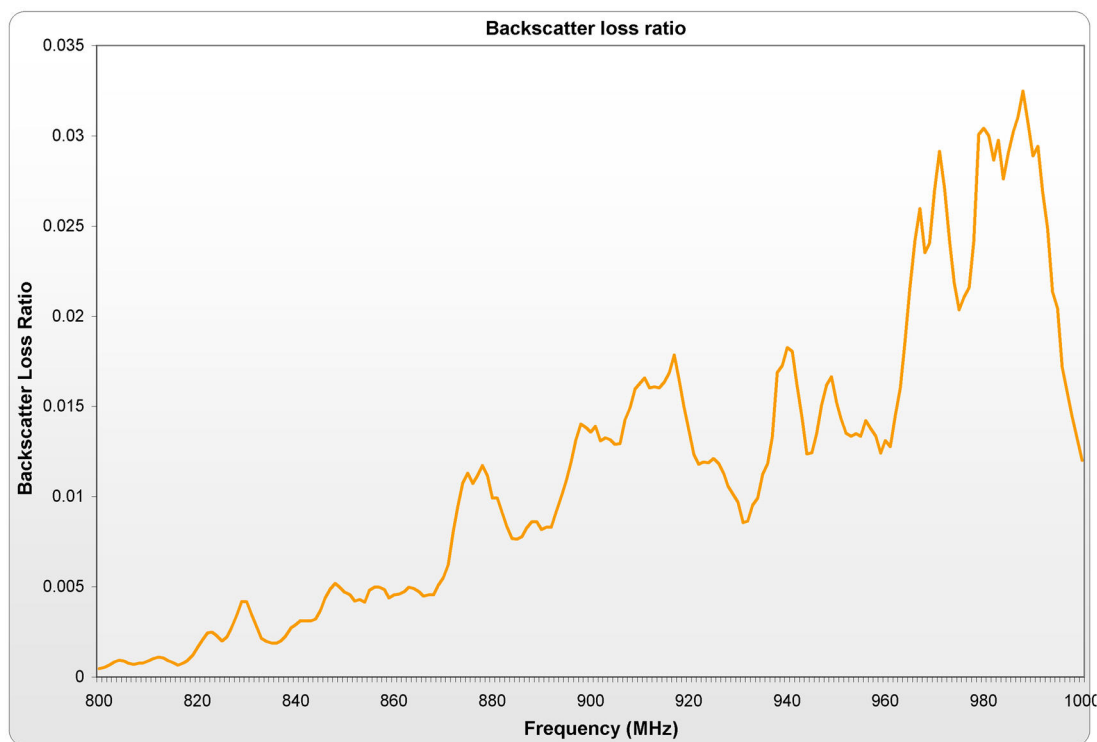
Figure 5.1. Backscatter Loss Ratio vs Frequency for an Alien Squiggle Tag.

The reflection efficiency of the tag is however moderate in the 897 - 926 MHz range of frequencies which falls in the U.S FCC bandwidth. Though the Alien Squiggle tag operates in the global UHF range of frequencies between 860 - 960 MHz, it is however optimized to operate at 915 MHz. The backscatter ratio graph obtained with the help of practical experimental results proves that the reflection efficiency for the Alien Squiggle is optimized in the given frequency range.

5.4.1 Backscatter Signal Strength

Electromagnetic waves are reflected by objects with dimensions greater than half the wavelength of the wave. The efficiency with which an object reflects electromagnetic waves is described by its reflection cross section. Antennae that are tuned to the frequency of the waves have a large reflection cross section. The reflected wave

has a small proportion of the power received by the tag from the reader signal. The reflected wave is modulated by changing the reflection cross section of the tag. This is achieved by switching the load impedance of the tag.
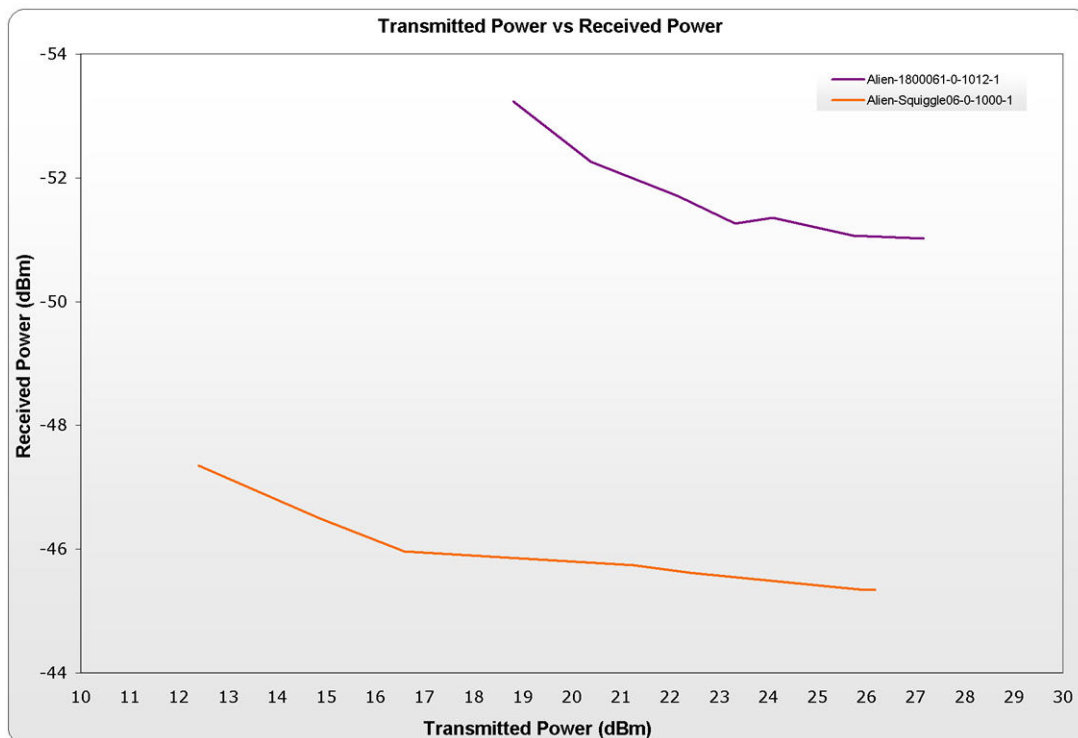

Figure 5.2. Transmitted vs Received Power for Alien H2 IC Tags.

The power reflected or backscattered by a tag is based on the tag IC and on the tag antenna design. Due to the varying antenna designs of tags, it can be inferred that even for tags using the same tag IC's, the tag responses can be very different.

From figure 5.3, we see that though Rafsec Dogbone and Rafsec UPM Frog use the same Impinj Monza tag IC, their backscatter plots are very different. This is due to the different antenna designs used by these tags. The same applies to the Alien Squiggle and the Alien 2006 tags that use the same H2 tag IC (figure 5.2) while
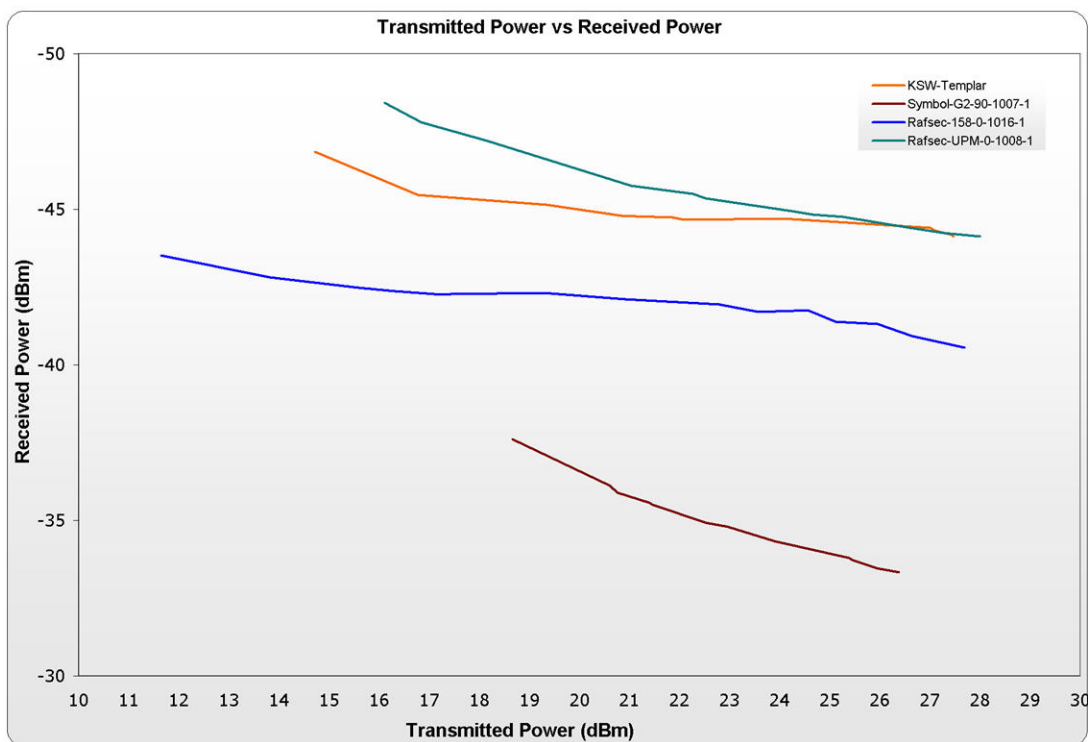
Figure 5.3. Transmitted vs Received Power for Impinj Monza IC Tags.

their antenna designs are very different and hence their backscatter responses are very different.

5.4.2 Path Loss

Path Loss is the attenuation of an electromagnetic wave as it propagates through space. Path loss may be caused by several factors such as propagation loss, penetration or absorption loss, diffraction loss, refraction loss, fading loss due to multipath and other miscellaneous effects based on frequency and the surrounding environment. Path loss is also influenced by the distance between the reader and tag, reader and tag antennae, terrain contours and the propagation medium.

The fundamental path loss equation can be expressed as

$$PL(dB) = -20log\left(\frac{\lambda}{4\pi R}\right) \tag{5.11}$$

PL is the path loss in dB, R is the distance between the reader and tag and λ is the frequency wavelength. Path loss between the reader and tag can be calculated using the equations 5.9 and 5.9 for both the forward and reverse links. The experimental setup to record all the measurements is explained in the section 5.2. Figure 5.4 shows the path loss vs frequency graph for an Alien Squiggle tag.
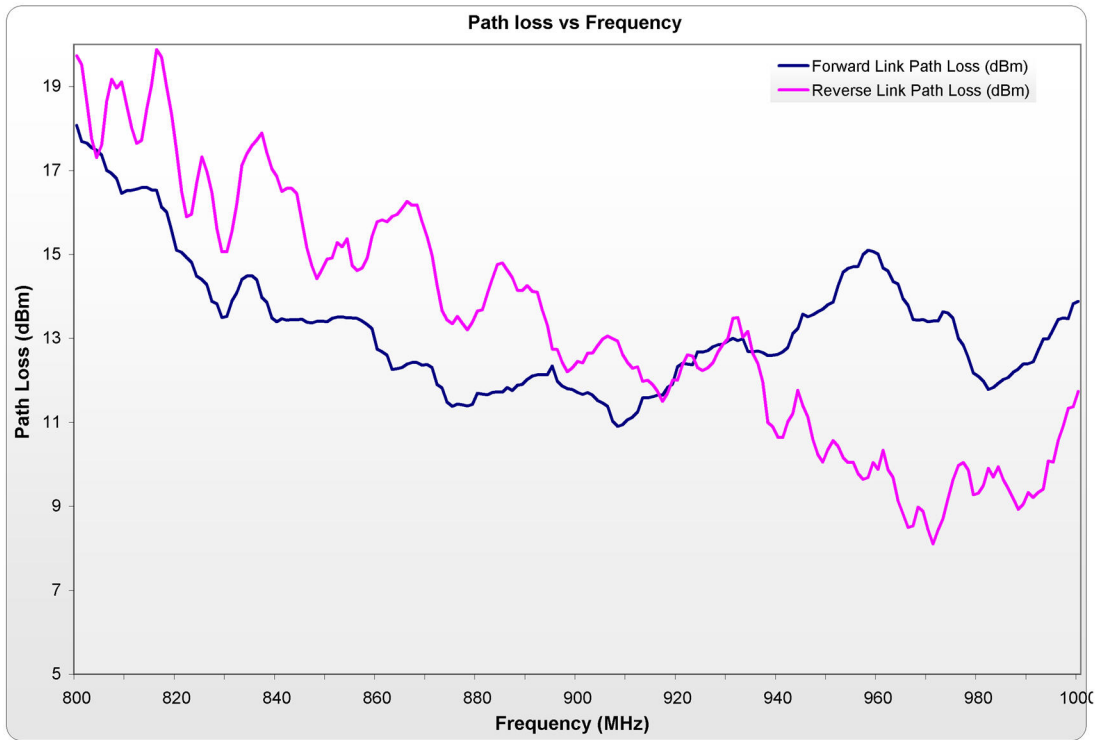

Figure 5.4. Frequency vs Path Loss for an Alien Squiggle Tag.

The forward link and reverse link path loss between the reader and tag have a 2 dB difference in the lower and higher range of frequencies. For the frequencies between 910 and 940 MHz the forward and reverse link path loss remain approximately the same. This also asserts the fact that though the Alien Squiggle tag operates at the

global range of frequencies (860 - 960 MHz), it is highly tuned to operate in the U.S FCC bandwidth.

5.5 Tag Sensitivity

Tag sensitivity or Chip sensitivity is the minimum required threshold power for the tag IC to turn on and respond. Lower the threshold value of tag sensitivity, longer the read range of the tag. The experimental setup used to measure the threshold powers of the tags is described in section 5.2. Tag sensitivity can be expressed as a power density or as an electric field strength at the location of the tag.
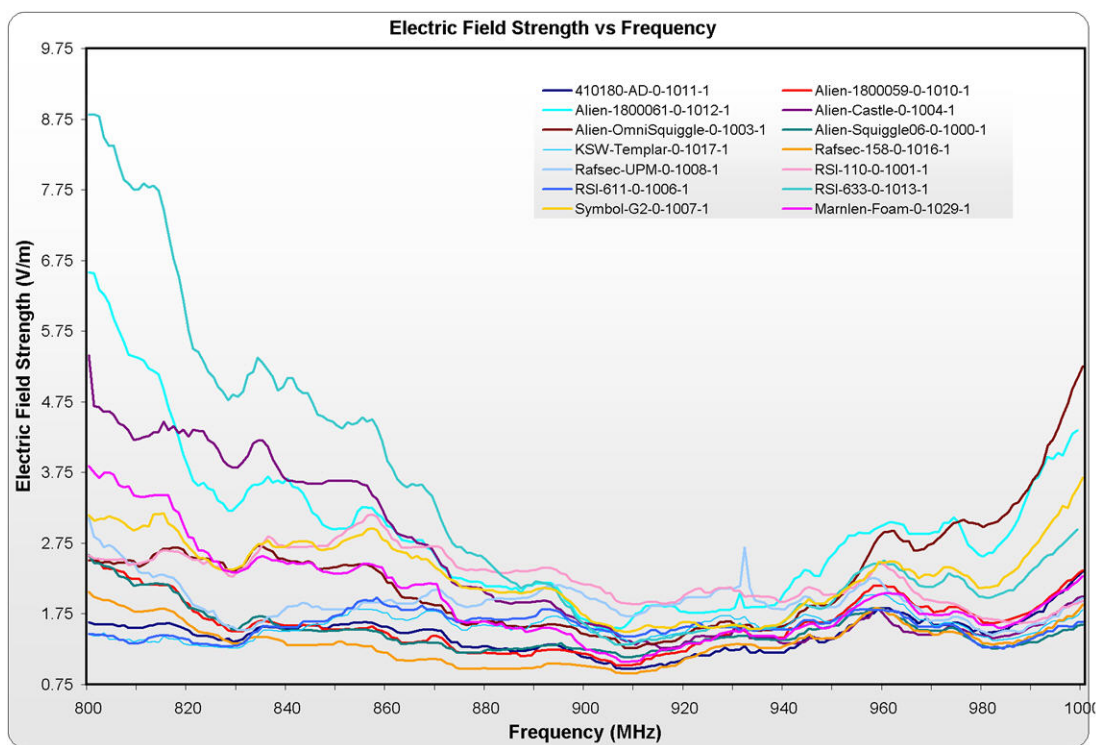

Figure 5.5. Electric Field Strength vs Frequency.

Figure 5.5 shows the electric field strength at the tag for frequencies between 800 MHz - 1 GHz. We can see that the AD-612, Rafsec Dogbone and the Alien Squiggle
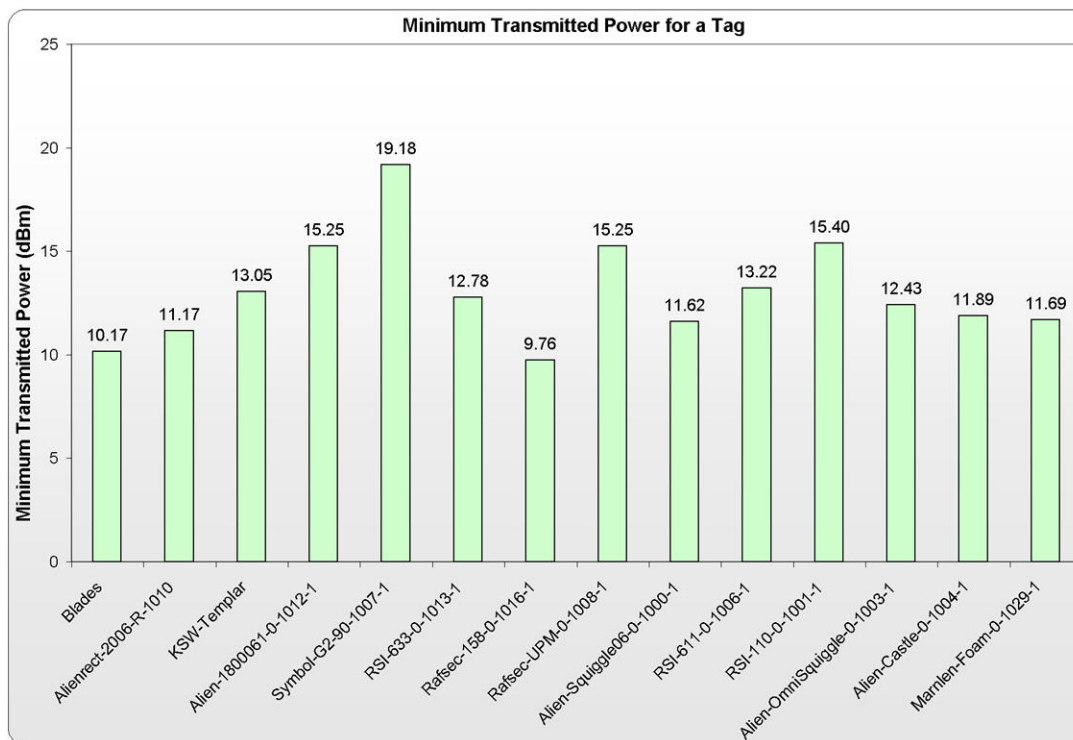
Figure 5.6. Minimum Transmitted Power vs Tags.

tags have the lowest electric field strength for the U.S FCC range of frequencies between 902 - 928 MHz. The AD-612, Rafsec Dogbone and the Alien Squiggle tags also exhibit minimum required threshold power in terms of power density from figure 5.6.

Figure 5.7 shows the maximum range achieved by some of the tags based on range experiment results. It can be shown that most tags with the lowest electric field strength and minimum threshold power density exhibited maximum range with the exception of a few.

5.6 Electric Field Strength,Range,Tag IC Relationship

An electromagnetic wave consists of electric and magnetic field components that are time-varying and mutually orthogonal. Maxwell's equations form the mathemat-
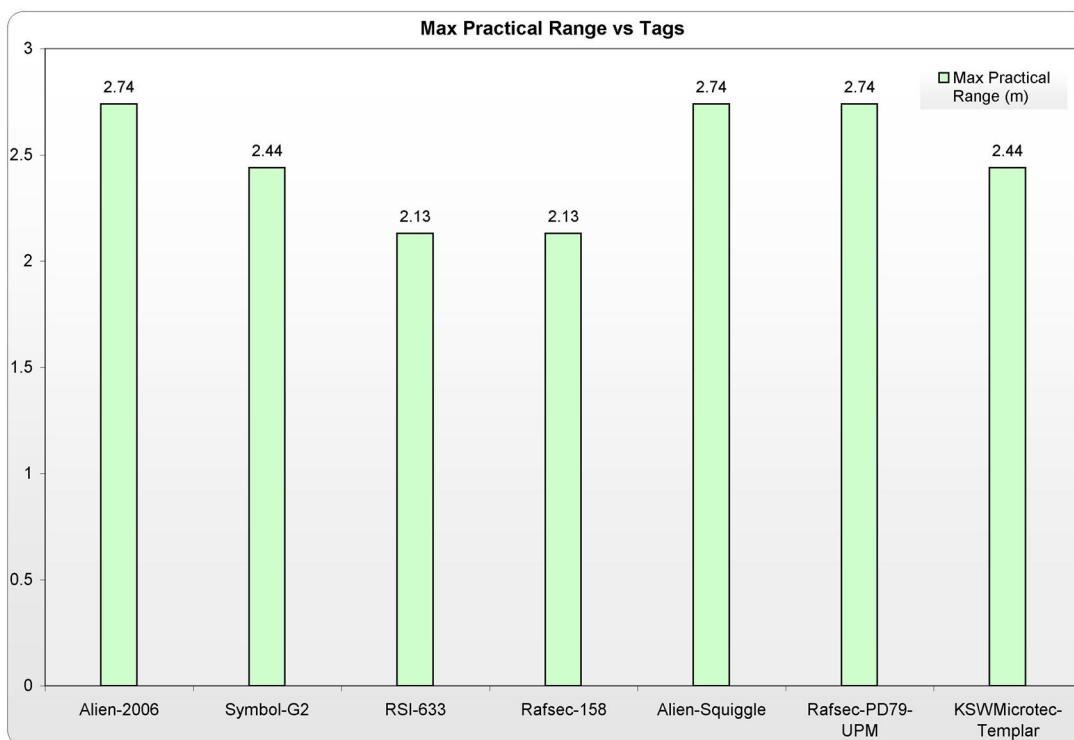
Figure 5.7. Maximum Practical Range vs Tags.

ical basis for electromagnetic wave propagation. The crux of Maxwell's equations are based on the fact that time varying electric fields produces a magnetic field and a time varying magnetic field produces an electric field.

An electric charge creates an electric field. Electric field strength surrounding a point charge is given by Coulomb's Law. The inverse-square law dependence of electric field in Coulomb's law follows from Gauss's law.

$$E = \frac{1}{4\pi\epsilon_0}\frac{Q}{r^2} \qquad (5.12)$$

where Q is the enclosed charge, r is the electric field radius and ϵ_0 is the permittivity of free space. Equation 5.12 represents the fundamental relationship between electric field strength and distance which follows the inverse-square law. A series of range tests were conducted with the experimental setup described in section 5.2 with

the tag analyzer and several tags. Range measurement tests of upto 10 feet between the reader and tags were performed and recorded.
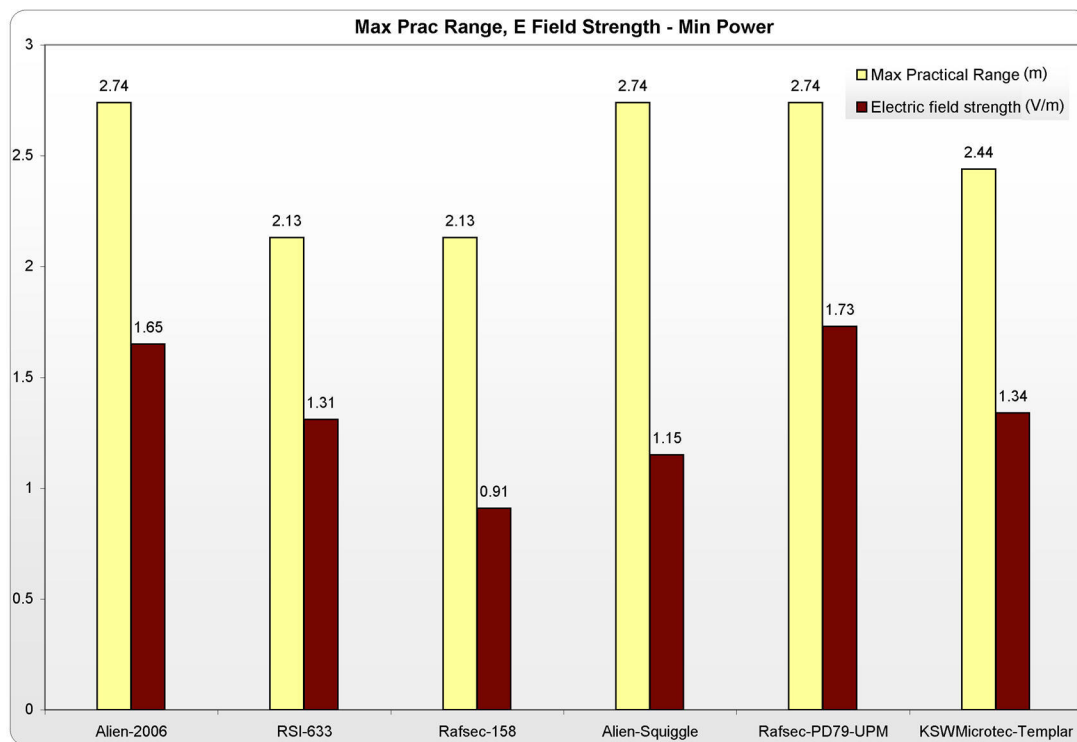

Figure 5.8. Range, Electric Field Strength at minimum transmitted power.

Figure 5.8 shows the relationship between electric field strength and the maximum practical range observed for some of the tags listed in the graph. This graph shows the Electric Field strength - Range relationship when minimum power is transmitted by the reader at maximum range. Figure 5.9 shows the Electric Field strength - Range relationship when maximum power is transmitted by the reader at maximum range. It can be inferred from figures 5.5, 5.6 and 5.7 that as the electric field strength is increased by increasing the transmitted power of the reader, the maximum practical range observed for the tags under test decreased. This implies that the tag sensitiv-
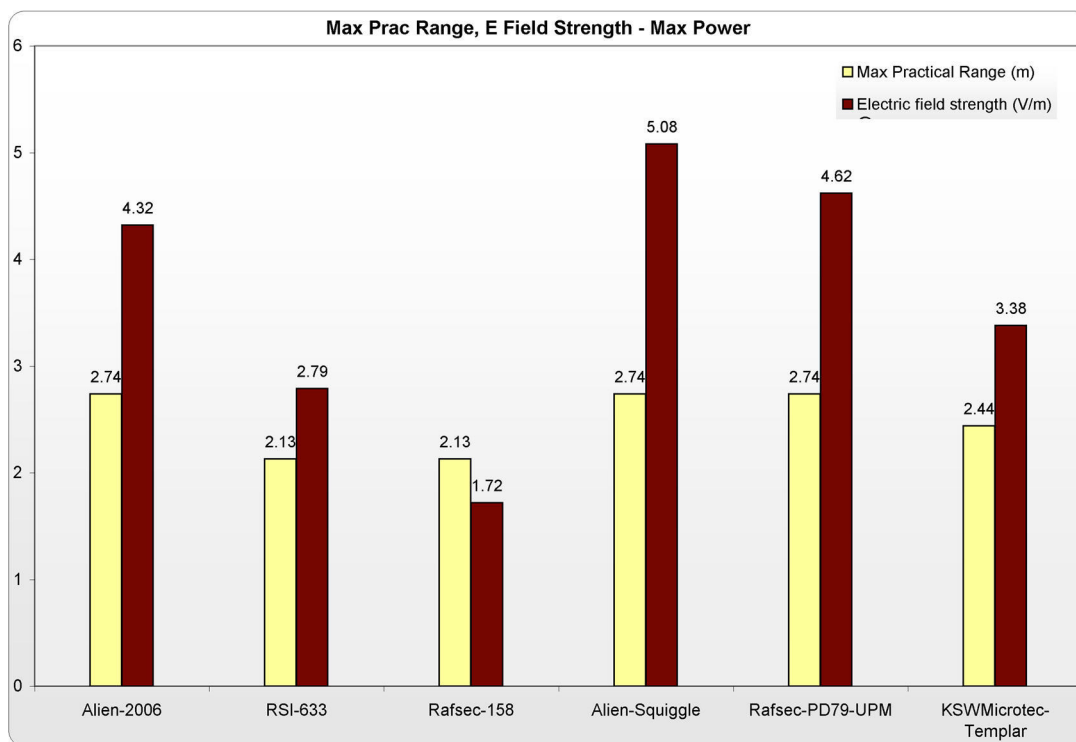
Figure 5.9. Range, Electric Field Strength at maximum transmitted power.

ity and the maximum possible read range for a tag follow an inverse relationship as explained in section 5.5. Figures 5.8 and 5.9 roughly assert this relationship.

Figures 5.10 and 5.11 show the electric field strength - range relationship at minimum and maximum transmitted powers for tags with Alien H2 tag IC's. The inverse relationship between electric field strength and range can again be roughly justfied for the Alien tags with the same H2 tag IC's. This same inference is also applicable to the tags with the Impinj Monza tag IC's as seen in figures 5.12 and 5.13.

5.7 Summary

The amount of power required to turn on and power the tag IC imposes a significant limitation on the read range of RFID tags. This minimum threshold power required by the tag IC to respond is the Sensitivity of the tag. Power transmitted
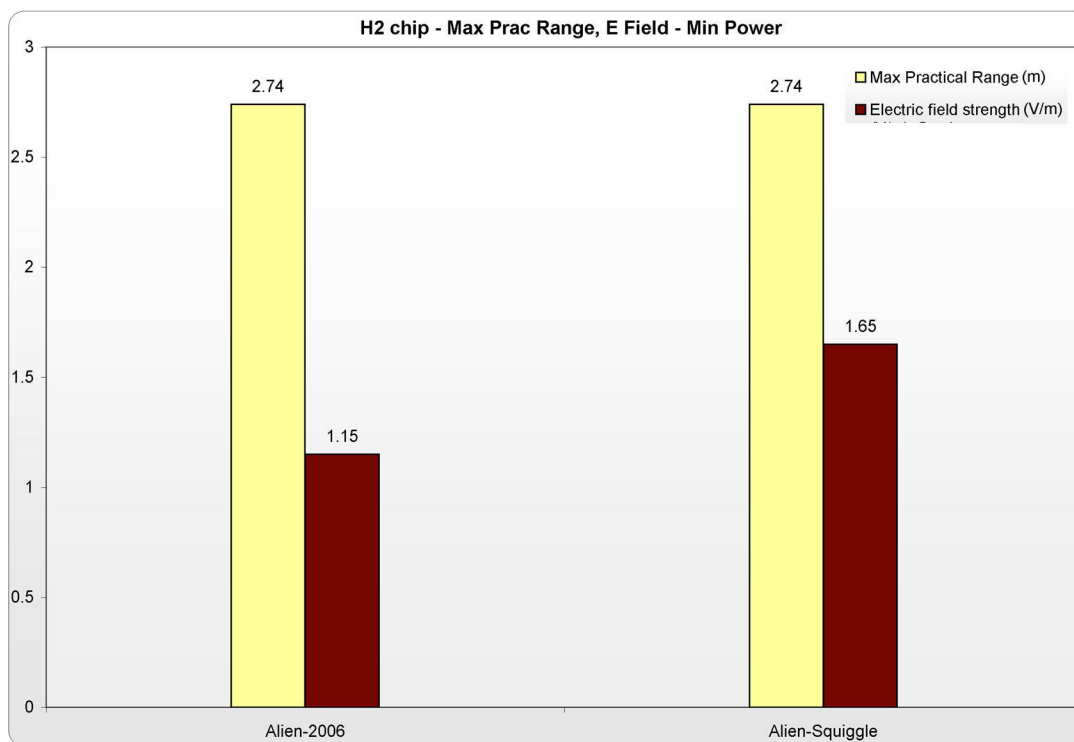
Figure 5.10. Range, Electric Field Strength at min power: Alien H2 Tag IC.

by the reader decreases as a function of inverse-square of the distance and is also restricted by regulations. Also, the amount of power backscattered or reflected by a tag has a direct dependence on the power received by the tag. Thus tag sensitivity has a very consequential role on the maximum possible read range of a tag and also on the amount of power backscattered by a tag. Reader sensitivity is another critical parameter in determining the maximum read range. The power reflected by a tag has a very small magnitude and hence the sensitivity threshold of the reader must be very low to receive and decode the signal from the tag.

The amount of power received and reflected by a tag is depedent on the frequency, power transmitted by the reader and the distance between the reader and tag. There is a certain amount of power loss between the power received by the tag and the power reflected by the tag which the backscatter transmission loss ratio given
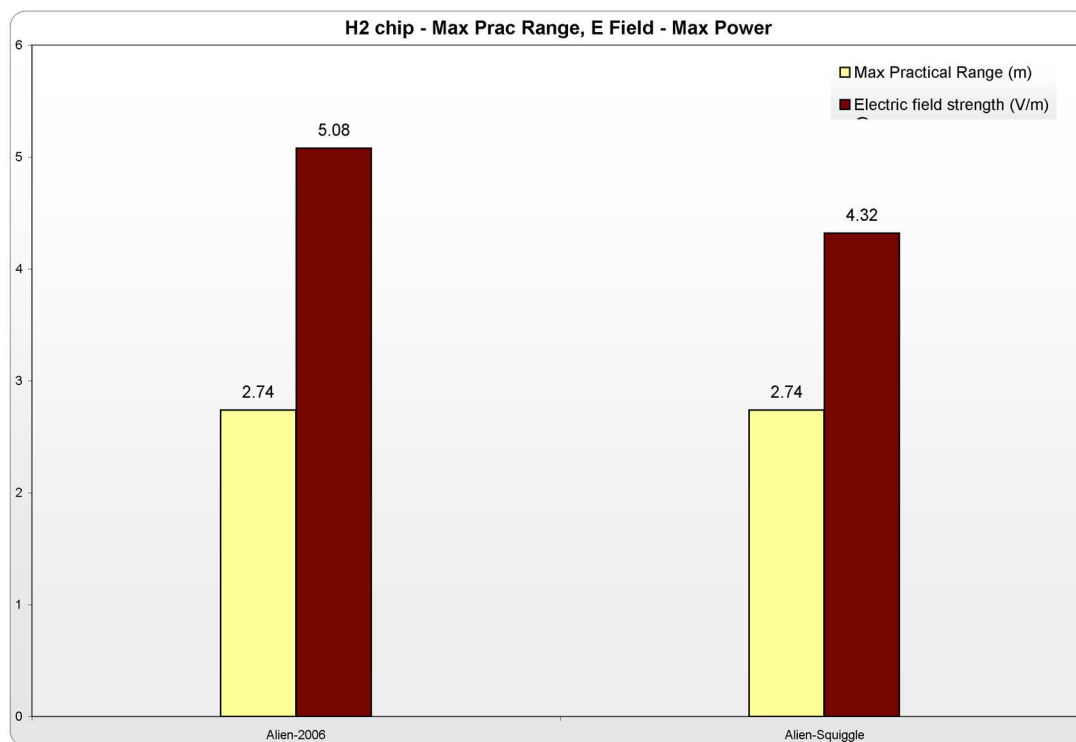
Figure 5.11. Range, Electric Field Strength at max power: Alien H2 Tag IC.

by B_L. We provide a mathematical analysis in section 5.3 to compute the backscatter transmission loss ratio and graphically represent (5.4) the reflection efficiency of a tag at a series of frequencies.

Tag antenna design and the tag IC tremendously impact the power reflected by a tag. Tag responses can be very different for varying tag antenna designs even for tags using the same tag IC's. This is highlighted with experiment results on tags with the Impinj Monza tag IC and the Alien H2 tag IC in section 5.4.1.

Path loss is the most important element in the computation and design of the link budget of a system. The path loss between the reader and tag for both the forward and reverse links can be calculated using the equations described in section 5.4.2. Analysis of the foward and reverse link path loss for the Alien Squiggle tag at a series of frequencies based on experimental data is also provided.
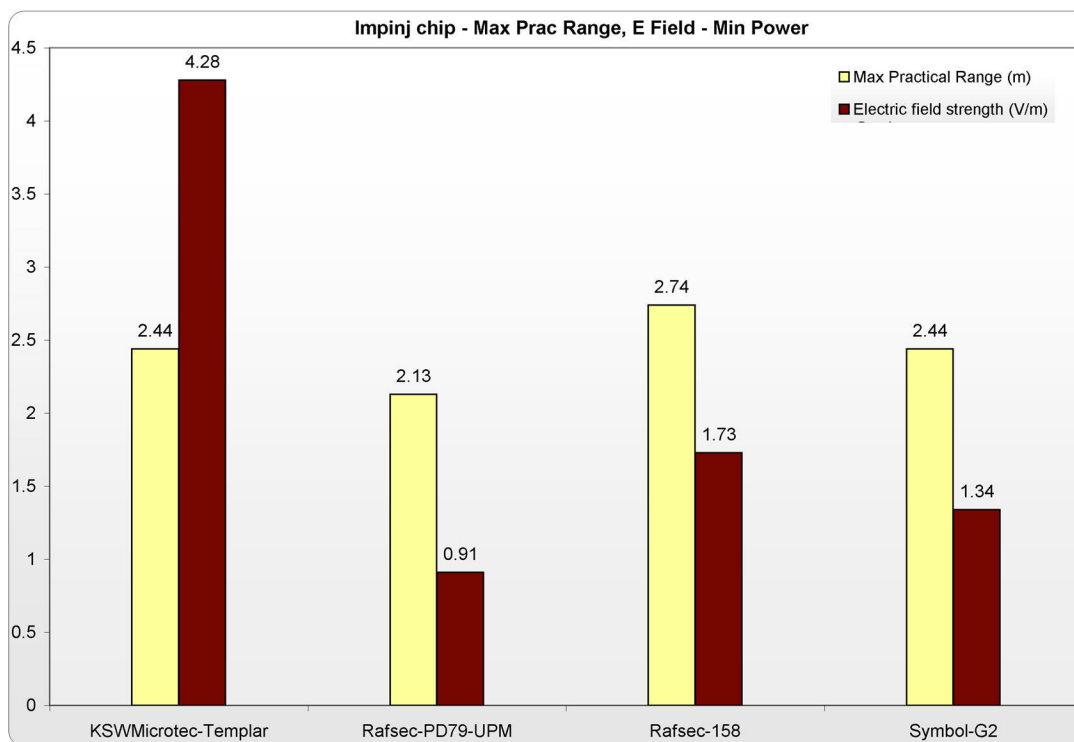
Figure 5.12. Range, Electric Field Strength at min power: Impinj Monza IC.

Tag sensitivity can be expressed as the electric field strength at the tag and as the minimum power at which the tag responds. Electric Field strength has an inverse-square relationship with range based on the fundamental Coulomb's law. The tag sensitivity (represented as electric field strength and minimum threshold power) and maximum practical read range relationship is explained in section 5.5. Since tag IC's impact the power backscattered by a tag, electric field strength and range relationship is analyzed for the individual tags with the same tag IC's. In this chapter we analyze and describe the cumulative relationship between tag sensitivity (as electric field strength and minimum threshold power) and maximum practical read range for various tags under test using different tag IC's.
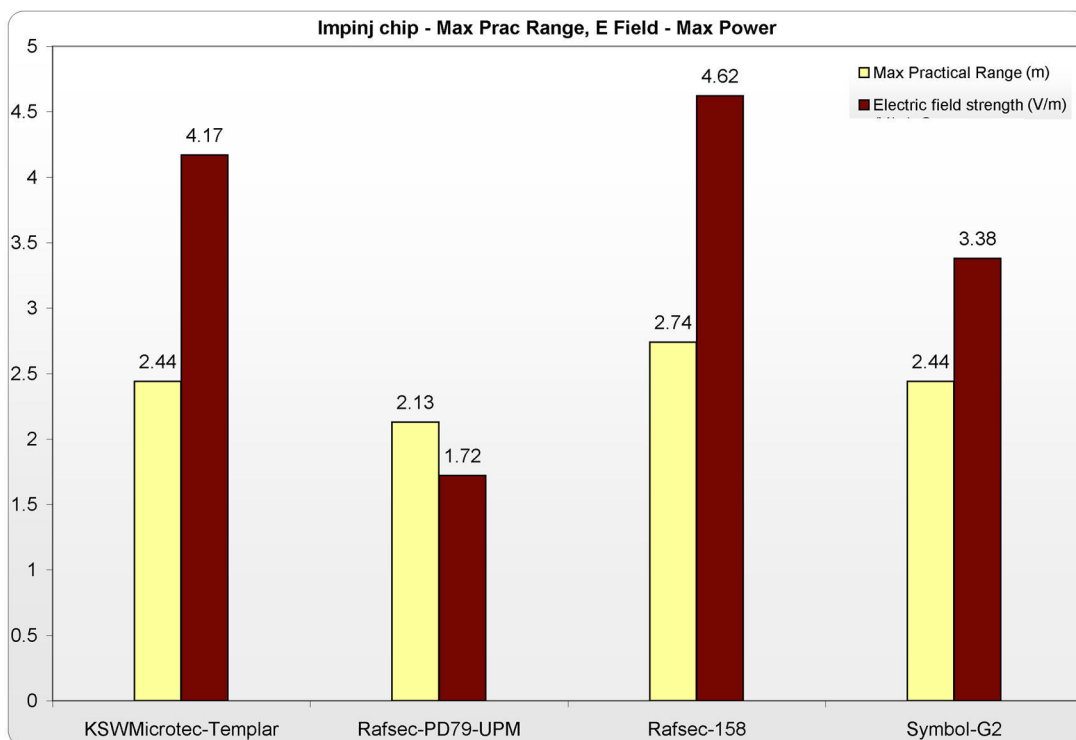
Figure 5.13. Range, Electric Field Strength at max power: Impinj Monza IC.

CHAPTER 6

BACKSCATTER SIGNAL STRENGTH AND RANGE

A passive RFID tag communicates with an RFID reader based on the principle of backscattering. Backscattering of electromagnetic waves by the tag is a very important part in its functionality. The operating range and reliability of the system is not only dependent on the amount of power transferred to the tag but also on the power backscattered by the tag. In this chapter, we discuss the testing methodology used to determine the backscatter signal strength of some commercial tags. Detailed analysis on the results obtained and the relationship between backscatter signal strength, tag communication range and tag sensitivity are performed.

6.1 Introduction

Backscattering is the reflection of electromagnetic waves and is commonly used in RADAR systems. A backscattering RFID system can be passive or semipassive. A passive backscattering RFID system does not have an on-tag power supply while a semipassive RFID system has a internal battery to assist in the digital circuitry of the tag IC. The backscattering of tags is a very important factor in determining the overall operating range provided by the system [46]. The reverse-link range is dependent on the amount of power backscattered by the tag and also the sensitivity of the reader [47]. In the following sections, we discuss the test procedure to determine the backscatter signal strength of a tag at various distances from the reader. We also analyze the results obtained and the impact of backscattering of tags and tag

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sensitivity on communication range. The fundamentals behind the backscattering of tags is explained in the forthcoming sections to better understand the data analysis.

6.2 Experimental Setup

The best method to measure the backscatter signal strength from the tag is to use a signal source attached to an antenna and send a command to the tag and measure the strength of the reponse with a signal analyzer. This test can repeated with different frequencies (frequency sweep) or with different power levels. The tag is placed at a desired distance (say 1 m) from the reader. The power transmitted by the reader is kept constant while the frequency is varied from 800 MHz to 1 GHz with step size of 1 MHz and the power received by the reader from the tag is recorded. Next, the transmit power is varied with a step size of 0.1 dBm while keeping the desired frequency constant. The power received by the reader is recorded. This entire procedure can be repeated at various distances and with different tag orientations to measure the backscatter signal strength of the tag. Other the backscatter signal strength, parameters such as electric field strength, delta RCS and the received signal phase are also measured.

All experiments were performed using the Tagformance Tag Analyzer measurement system by Voyantic Ltd. Tagformance is a complete measurement tool to analyze the performance of passive UHF tags. A signal source attached to a transmitting antenna sends a command to the tag. A vector signal analyzer attached to a receiving antenna detects and decodes the response from the tag. The reader uses DSB-ASK forward link modulation and FM0 return link modulation. Transmit and receive antennas used by the reader are linearly polarized with 8 dBi gain.

6.3 Theory behind the Backscattering of Tags

Backscattering of the tag is the process of reflecting the electromagnetic waves that are incident on it. Usually, electromagnetic waves are reflected by objects with dimensions greater than half the wavelength of the wave. The reflected wave has a proportion of the power of the wave incident on it. The reader antenna then detects the reflected wave since it is traveling in the 'backward direction' compared to the wave transmitted by the reader. The efficiency with which the tag reflects the incoming wave is dependent on its radar cross section or reflection cross section (RCS). A tag with a high reflection cross section for a particular frequency reflects the wave at that frequency [48]. Antennae that are tuned to a particular frequency present a large RCS at that frequency.

An RFID tag consists of an antenna and a tag IC. Both the antenna and the chip have complex impedances. The tag antenna is loaded with the chip which presents an impedance at two states: modulated and unmodulated. The tag usually communicates with the reader by switching the load (chip) impedance which modulates the RCS of the tag. This determines the amount of power is that is backscattered by the tag. The signal backscattered by the tag is thus modulated in this manner. In the following section, we discuss the fundamentals behind the RCS of a tag to provide an insight into how a tag backscatters the electromagnetic wave that is incident on it.

6.3.1 Tag Radar Cross Section Fundamentals

The amount of power that is backscattered by a tag is usually described by its Radar Cross Section (RCS). Change in Radar Cross Section or Δ RCS is the difference in the signal backscattered by the tag between modulated and non-modulated states. RCS is defined as the ratio of the power reflected by a tag to the power incident on it [49]. RCS is a composition of several fundamental topics discussed in chapter 2.

$$RCS = \frac{\text{Power reflected by the tag}}{\text{Power incident on the tag}} \tag{6.1}$$

$$P_R = \frac{P_T G_T A_e}{4\pi d^2} \tag{6.2}$$

where P_R is the power received by the reader from the tag, P_T is the power transmitted by the reader, G_T is the reader antenna gain, A_e is the effective aperture of the tag antenna and d is the distance between the reader and tag.

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi)^2 d^2} \tag{6.3}$$

where Gain is given by the following equation

$$G = \frac{4\pi A_e}{\lambda^2} \tag{6.4}$$

RCS is usually measured in m^2 or in dBsm. RCS varies with frequency and polarization of the electromagnetic wave. For a dipole antenna, the gain is around 2.2 dBi. For a tag with a small antenna, the Q value is high due to small radiation resistance and high reactive impedance and hence bandwidth over a large RCS is reduced. The power reflected by the tag is given by

$$P_{Refl} = \frac{P_T G_T RCS}{4\pi d^2} \tag{6.5}$$

The power density at the reader is given by the following equation

$$P_{Rcvd} = \frac{P_T G_T RCS}{4\pi d^2} \frac{1}{4\pi d^2} \tag{6.6}$$

The received power at the reader is the product of equation 6.6 and the effective aperture of the tag antenna which is given by

$$P_{Rcvd} = \frac{P_T G_T RCS A_e}{(4\pi)^2 d^4} \qquad (6.7)$$

Effective aperture can be derived from the equation 6.4 and substitued in equation 6.7. The effective aperture of an antenna is the product of the antenna gain and the effective aperture of an isotropic antenna. The power received by an antenna is the product of the power incident on it and affective aperture of the antenna. The power reflected by the tag is the power dissipated by the radiation resistance of the antenna. The RCS of a tag is thus determined by the antenna gain, load impedance and radiation resisitance.

$$P_R = \frac{P_T G_T G_R RCS \lambda^2}{(4\pi)^3 d^4} \qquad (6.8)$$

The above equation provides the power received at the reader in terms of the Radar Cross Section (RCS). For a small tag antenna, the RCS is usually not dependent on its physical dimensions.

$$RCS = \frac{P_R (4\pi)^3 d^4}{P_T G_T G_R \lambda^2} \qquad (6.9)$$

The above equation gives the final expression for RCS as a function of received power at the reader, power transmitted by the reader, wavelength of the wave, distance between the reader and tag and the gains of the tag and the reader. Change in radar cross section is expressed as δ RCS and is the difference between the modulated and unmodulated states of the backscattered signal. If the change in radar cross section is higher, this implies that the backscatter modulation of the signal from the tag is deeper. The more deeply the tag modulates its RCS the longer the range from the tag to the reader will be.

6.4 Frequency - RCS Relationship

The mathematics and physics behind backscattering of tags and radar cross section (RCS) are explained in the previous section. Some of the frequencies at which the principle of backscattering is used are 868 MHZ in Europe, 915 MHz in the U.S and 2.45 GHz. Based on the data collected using tests conducted under lab conditions with the test setup explained in section 6.2, the impact of frequency on Δ RCS is investigated here.
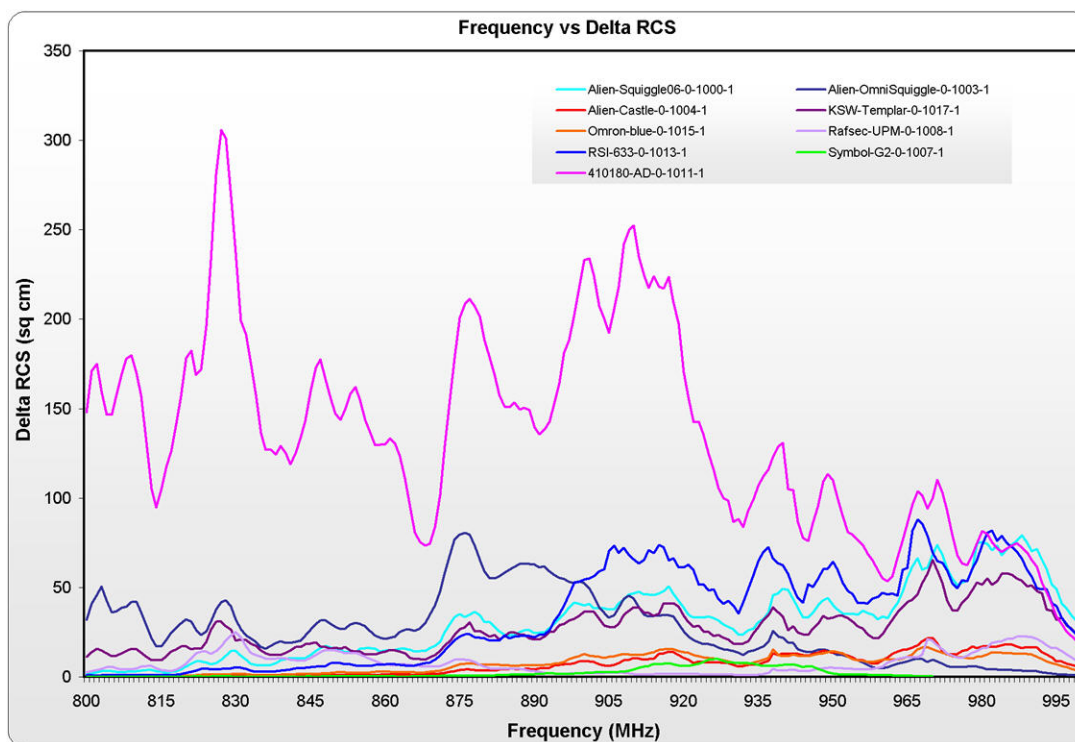

Figure 6.1. Frequency vs RCS.

The figure 6.1 shows the frequency and Δ RCS relationship. The first figure shows the frequency range between 800 and 1000 MHz and the second figure shows the particular relationship for the U.S range of frequencies from 900 - 930 MHz.
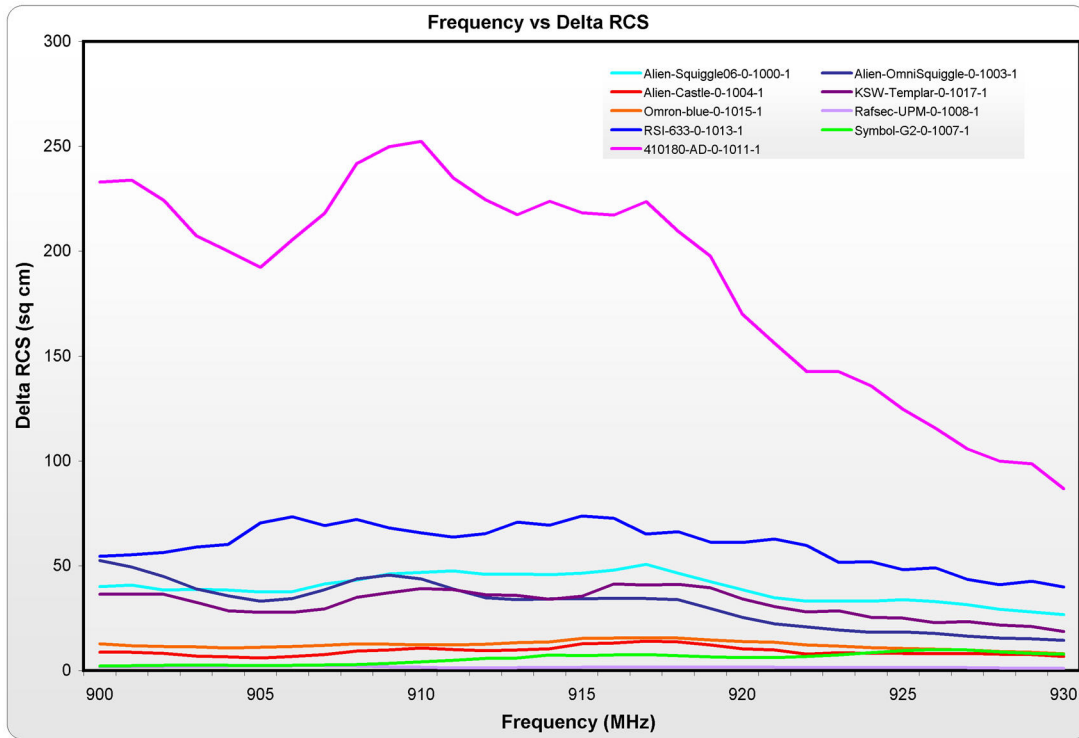
Figure 6.2. Frequency vs RCS 900 - 930 MHz.

From the equation 6.9, we see that RCS has an inverse square relationship between λ^2.

$$RCS \propto \lambda^2$$
$$RCS \propto \frac{f^2}{c^2} \tag{6.10}$$

where f is the frequency and c is the speed of light. In the above equation, we see that RCS is directly proportional to square of the frequency of the electromagnetic wave that is incident on it. The figure 6.2 shows a similar relationship between RCS and frequency for the U.S range of frequencies between 900 - 930 MHZ and is supported by the theory derived in the previous section. However, the figure 6.1 is

very nebulous due to the fact that all tags that were tested are tuned to the FCC range of frequncies and not the entire UHF band from 800 - 1000 MHz.

6.5   Backscatter Signal Strength Dependence on RCS

In passive backscattering RFID systems, the electromagnetic wave that is incident on the tag is reflected by the tag back to the reader after absorbing a portion of this energy for its own operation. This principle is borrowed from the Radar Technology. The dependence of backscatter signal strength on Δ RCS is analyzed in this section.
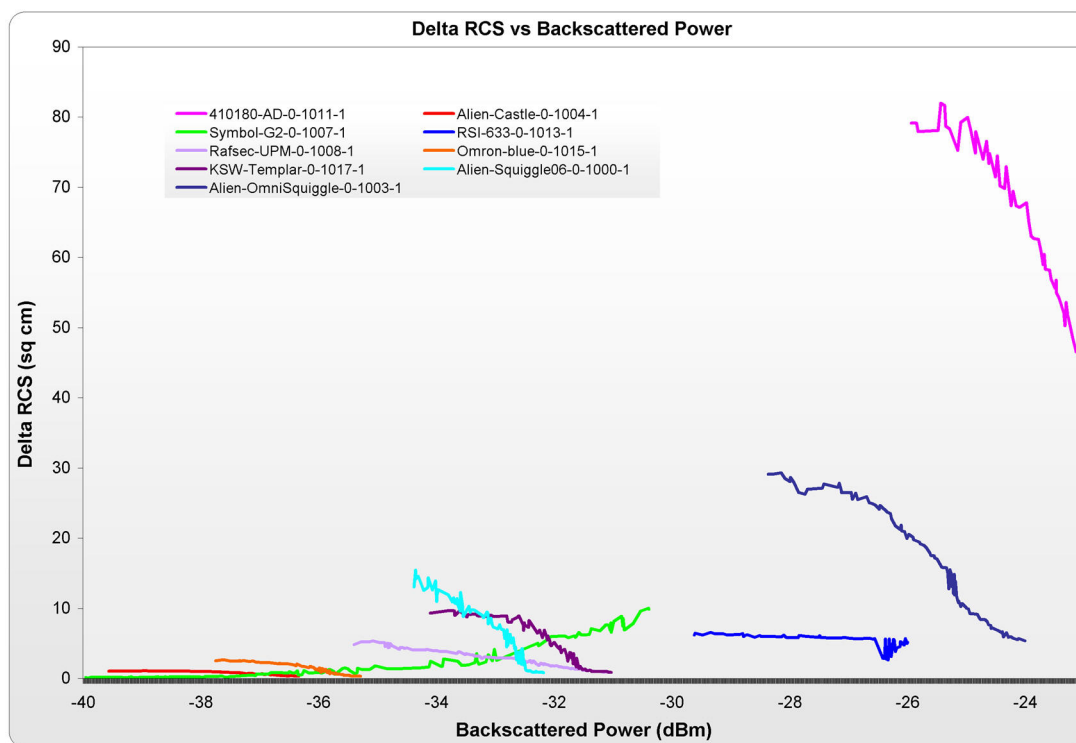

Figure 6.3. Power Backscattered by the tag vs Delta RCS.

The figure 6.3 shows the relationship between RCS and the power backscattered by some commercial tags. The Alien Castle, Omron, KSW-Templar, Alien

Omnisquiggle and Rafsec UPM show a similar relationship with repect to RCS and backscatter signal strength. The tags that show a striking difference in the RCS and backscatter relationship are the Symbol G2 and the Rafsec UPM tags though they use the same Impinj Monza chip as shown in figure 6.4. The Avery Dennison tag (AD) shows a very high backscatter signal strength due to physical size of the tag being much bigger than the other tags in comparison. This tag also provides the longest range among the group according to our test results. Thus the theoretical information is well supported by our practical tests and data.
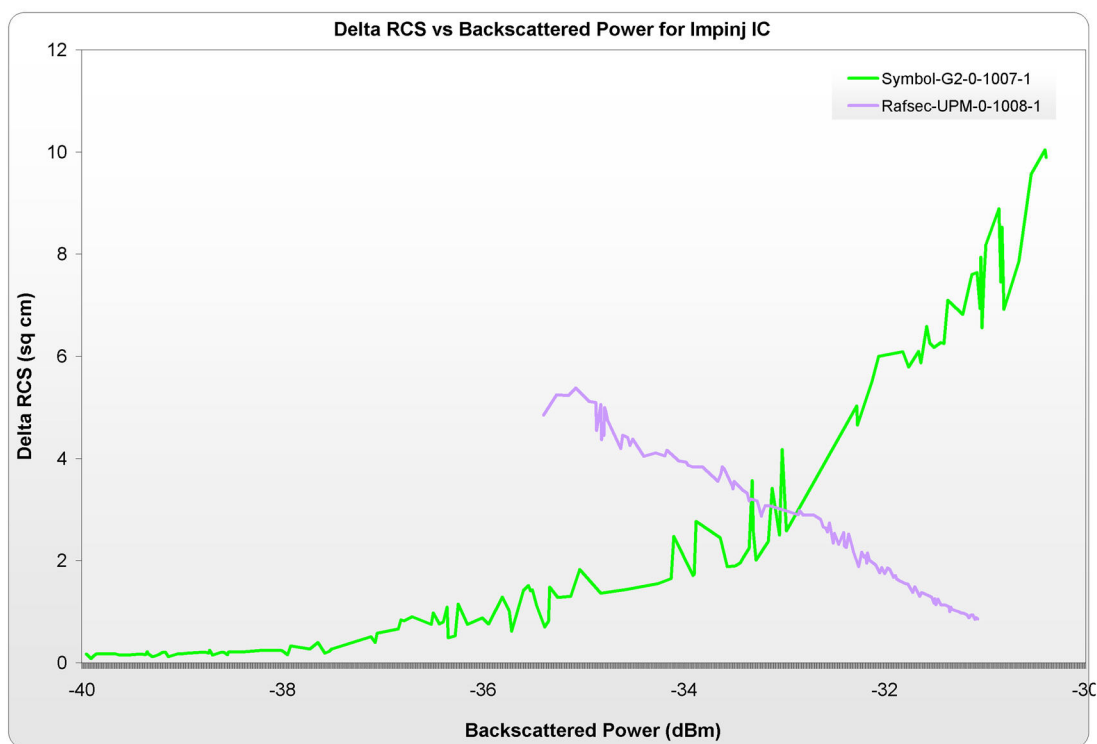

Figure 6.4. Power Backscattered by the tag vs RCS: Symbol and Rafsec Tags.

The likely reason for the difference in the response for the two tags though they use the same tag IC could be due to the varying antenna designs of the two tags. In the following graphs, we compare the response of tags having the same tag IC's. It

is important to note here that the tags having the same tag IC's need not have the same tag antennas.
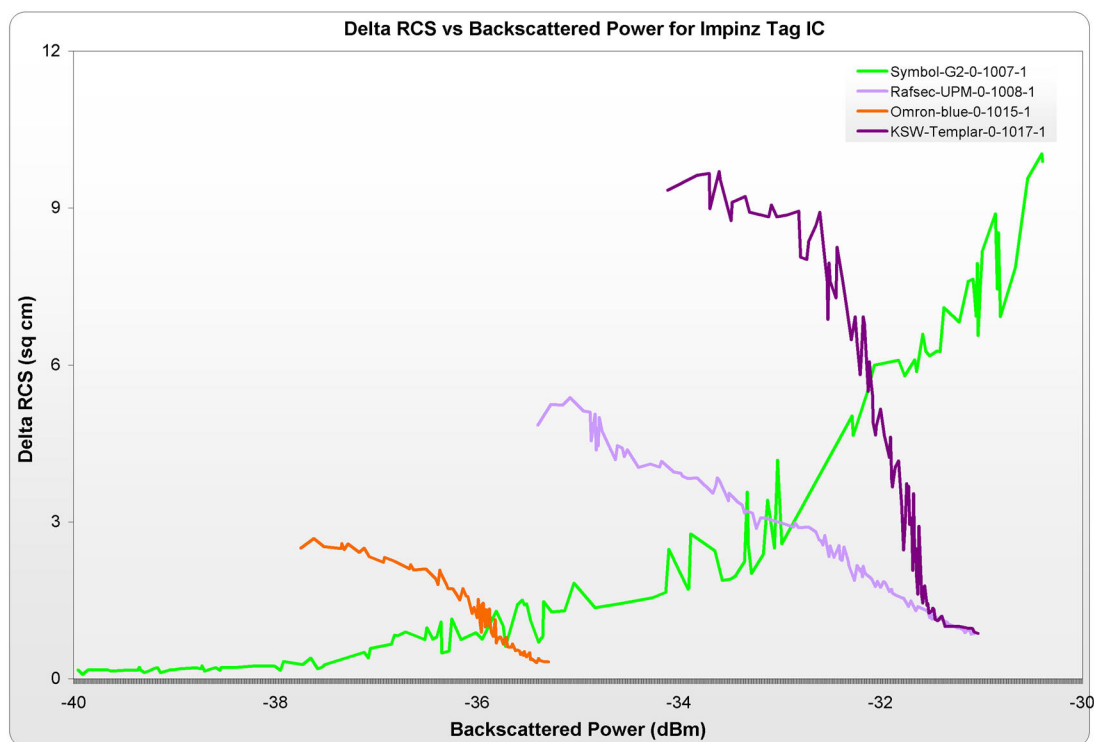

Figure 6.5. Power Backscattered vs RCS for Impinj Monza IC.

In the graphs shown, the relationship between RCS and backscatter for tags having the same chip (Impinj Monza tag IC and Alien H2 tag IC) have been plotted. Tags using the same Alien H2 tag IC exhibit a similar pattern however with varying backscatter signal strengths. The scaled backscatter signal strengths might be due to the difference in the antenna designs. All the tags using the same Impinj Monza chip have a similar patter except the Symbol G2 tag. This again could be due to the antenna design of the tag and some other factors that is beyond the scope of this book.
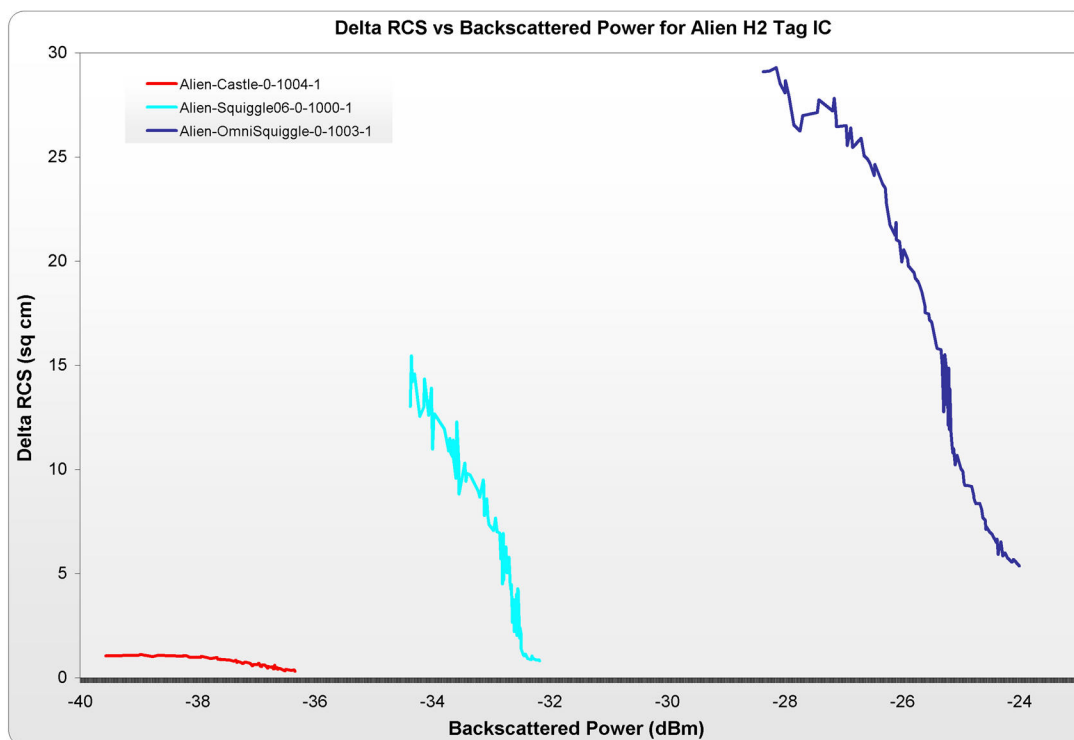
Figure 6.6. Power Backscattered vs RCS for Alien H2 IC.

6.6 Tag Sensitivity and RCS Relationship

Tag sensitivity or Chip sensitivity is the minimum required threshold power for the tag IC to turn on and respond. Lower the threshold value of tag sensitivity, longer the read range of the tag. The experimental setup used to measure the threshold powers of the tags is described in chapter 5.

The figure 6.7 shows the electric field strength and RCS relationship. Tag sensitivity can be expressed as a power density or as an electric field strength at the location of the tag. From the graph we can see that, for lower electric field strength values the Δ RCS values are much higher. This implies that for tags with high tag sensitivity, the RCS is high and thus the backscatter signal strength is high resulting in higher tag to reader communication range. According to our practical tests and analysis, the Avery Dennison bowtie tag has a high RCS and low tag sensitivity
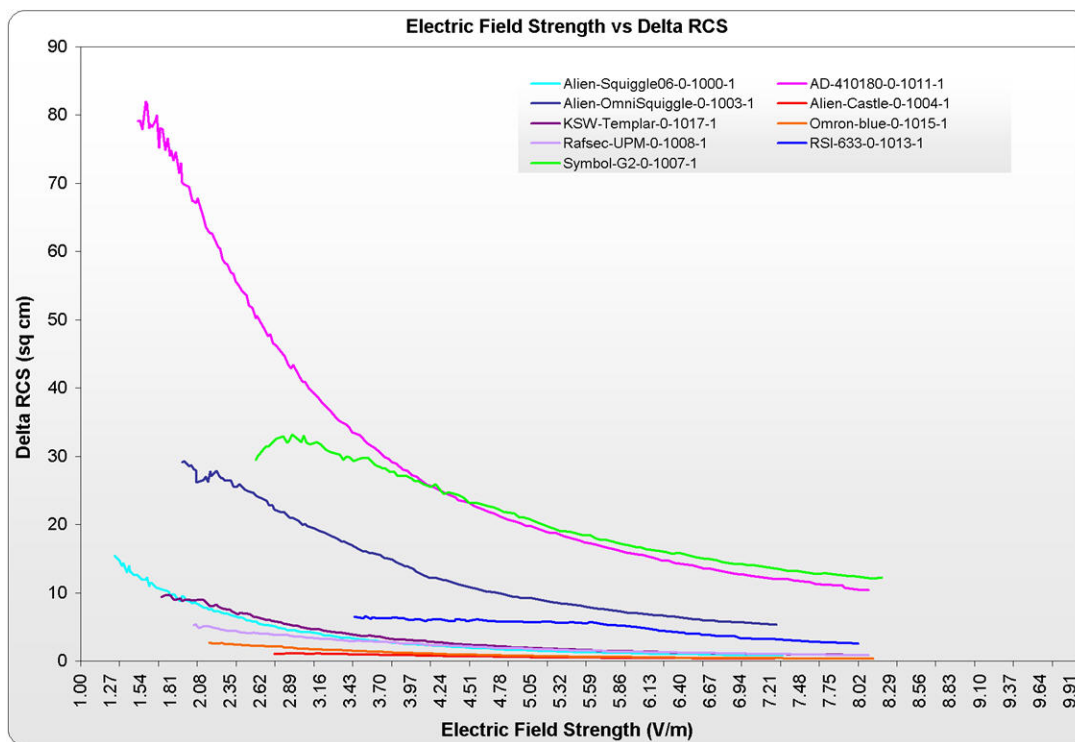
Figure 6.7. Electric Field Strength vs Delta RCS.

threshold and practically has the longest tag to reader range. Thus the theoretical study explored in this section and in section 6.3 in detail is very well supported by our practical data analysis.

6.7 Power Received by the reader and RCS dependence

The minimum amount of power required by the reader to decipher and decode the response from the tag is called Reader Sensitivity. The backscatter signal strength from the tag should be well above the reader threshold for accurate identification of the tag and working of the entire RFID system.

The power received by the reader and RCS relationship shown in figure 6.8 is quite similar to the RCS - Backscatter signal strength by the tag shown in figure 6.3. The RSI tag shows an entirely different pattern in its response is due to the fact that
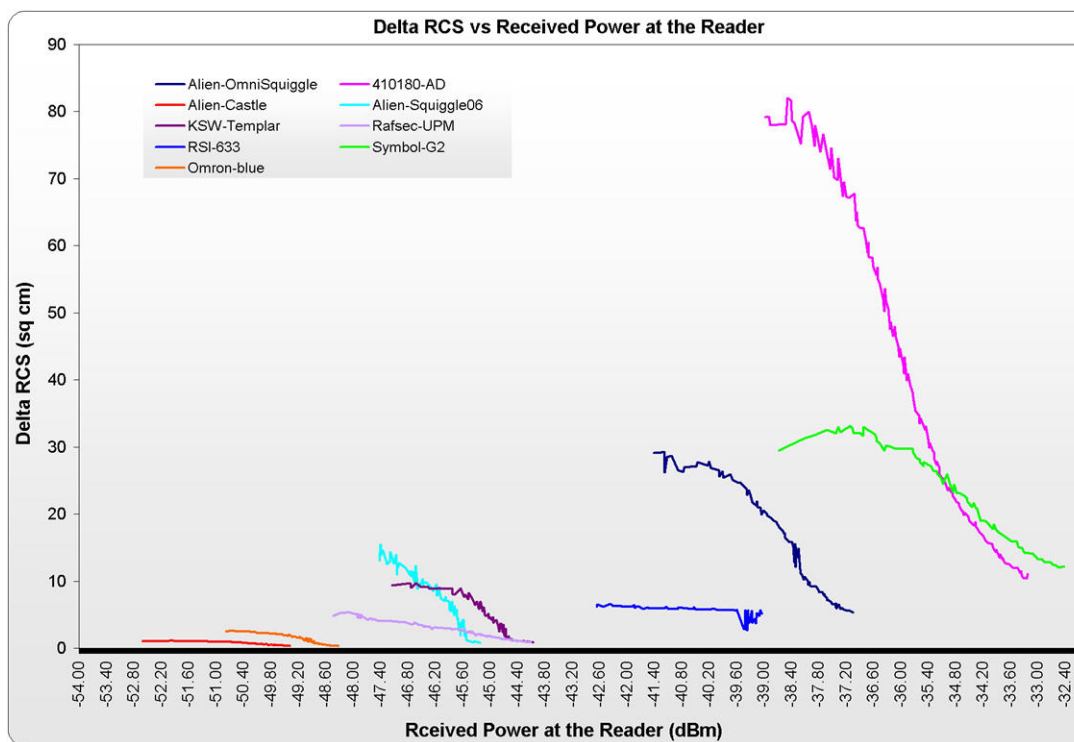
Figure 6.8. Power received by the Reader vs RCS.

it uses a different chip (NXP - UCode). Reader sensitivity plays a very important role in determining the reverse link range which is the tag to reader range. The higher the signal strength from the tag to the reader, it will be higher above the reader sensitivity threshold and longer is the tag to reader range. The reverse link range is very significant as it determines if a tag will be identified or not. Powering the tag and not being able to identify it are two different things with the latter being the most important than the former. In the graph, we see that the Avery Dennison tag had the highest backscatter signal strength as shown in figure 6.3 and correspondingly it also has the highest power at the reader as shown in figure 6.8 and thus this tag must have the longest range among the tags under comparison according to theory. According to our practical tests conducted under lab conditions, the Avery Dennison tag has a range of more than 10 feet at which most of the other tags did not respond.

Thus, from these graphs we see that tags having a higher backscatter signal strength and higher power at the reader have a really long range and this majorly depends on the tag antenna design than on the tag IC.

6.8   Relationship Trio: RCS, Tag Sensitivity, Communication Range

Individual relationship between the pairs of parameters were derived in the previous sections. In this section, we analyze the impact of RCS, Tag sensitivity and communication range on each other.
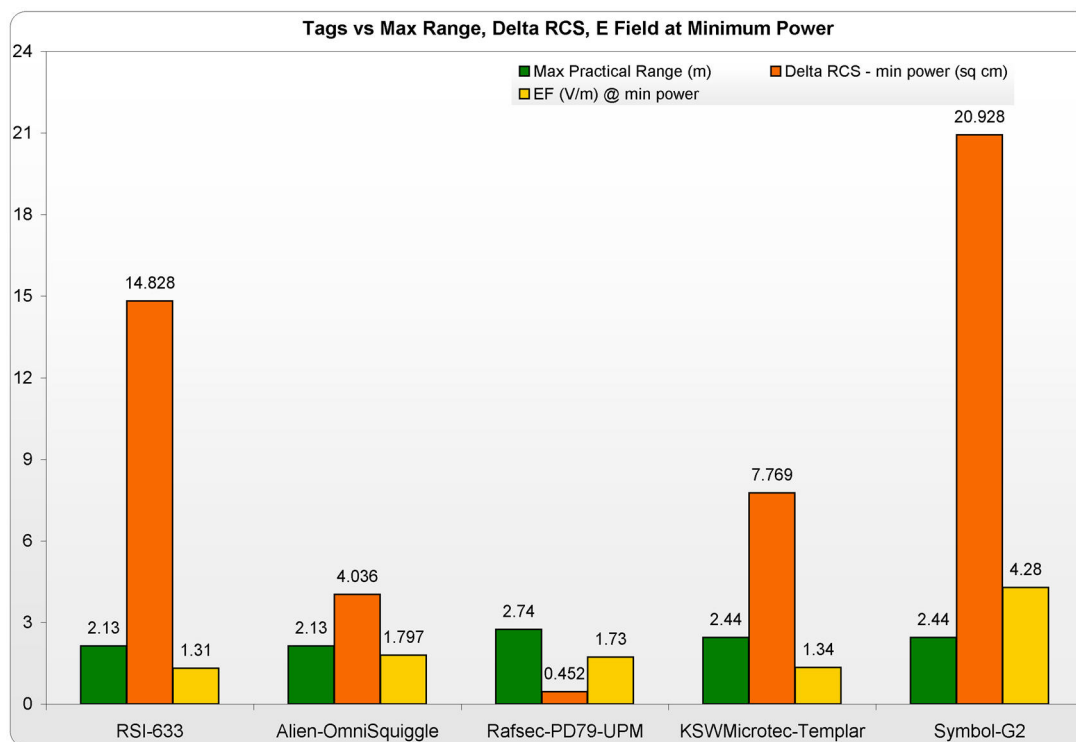

Figure 6.9. RCS, Range, Electric Field Strength at min power.

In figure 6.9, the realtionship between the 3 parameters mentioned above are shown. There seems to be an overall general relationship between RCS and tag

sensitivity. However, there is a better relationship between tag sensitivity and communication range in figure 6.10.
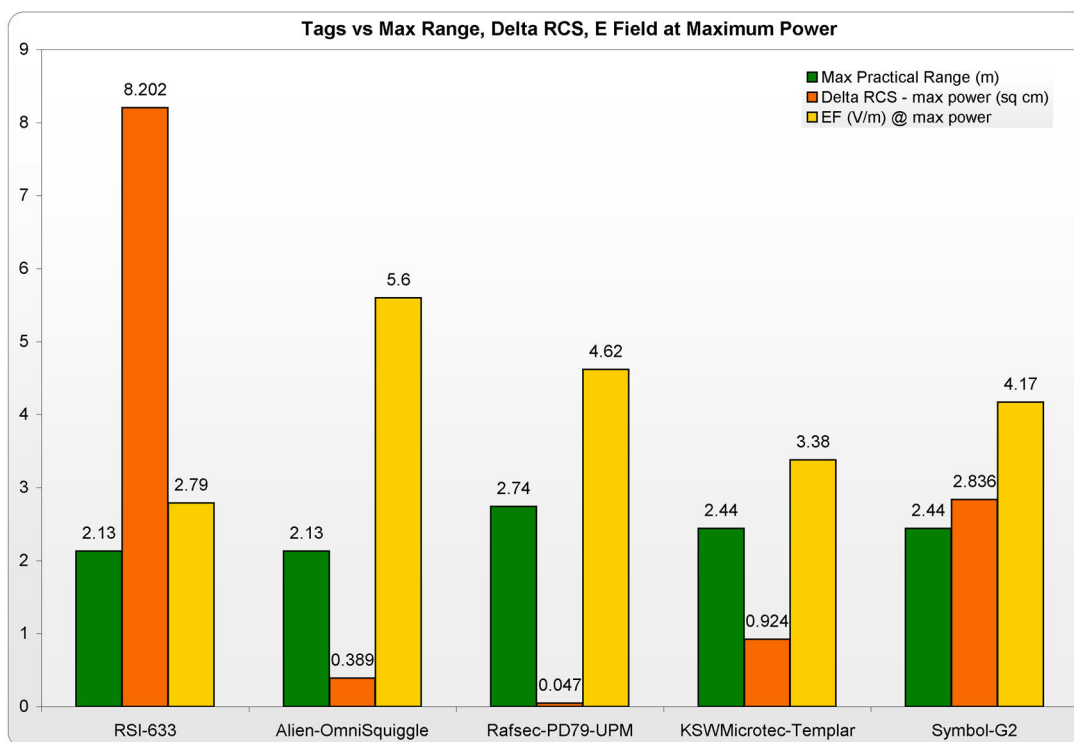

Figure 6.10. RCS, Range, Electric Field Strength at max power.

From figure 6.7, we can see the relationship between electric field strength and RCS. Lower the electric field strength, lower the tag sensitivity threshold, higher the RCS and hence longer the range. This has been proven very well in this graph with RSI-633 tag being an exception. Detailed analysis about the electric field strength and range relationship is provided in chapter 5.

6.9   Summary

In this chapter, we discussed the test procedure for obtaining and analyzing the backscatter signal strength of a tag. The backscattering of tags is a very important

factor in determining the overall operating range provided by the system. The reverse-link range is dependent on the amount of power backscattered by the tag and also the sensitivity of the reader. Backscattering of a tag can be related and to and be an impact on several parameters such as RCS, tag sensitivity and communication range. The fundamentals behind the backscattering of tags and RCS are elucidated to better understand the data analysis. Detailed analysis of the relationship between the afore mentioned parametes were performed and results were outlined.

CHAPTER 7

PERFORMANCE ANALYSIS

One of the main advantages of RFID systems is that RF tags can be read through obstacles and does not requires line of sight for their operation. Passive UHF RFID systems that are considered in this book, do not have an on-tag power supply and hence the overall communication range of the system is limited by the amount of power that is available for the tag IC and the amount of power it backscatters to the reader. Long read ranges are possible in the UHF and microwave range of frequencies due to the electric field coupling and thus the surrounding environment has a huge impact on the working of the system. In this chapter, we analyze the performance of some commercial tags on liquids such as water and detergent. We also analyze the performance of some of the tags in an anechoic chamber to validate our tests under lab conditions.

7.1   Introduction

There are several frequency ranges for the operation and use of RFID systems [4]. RFID systems operating in the 125 KHz and 13.56 MHz frequency bands use inductive coupling for communication with the tags. They exhibit low read ranges typically equal to the diameter of the tag antenna due to the inductive coupling and are not affected by metals or liquids. HF and LF RFID systems are mainly used in applications that do not require a long read range and are affected by metals and liquids.

UHF and Microwave RFID systems have longer communication range due to the capacitive coupling. The range from the reader to the tag is limited by the power transmitted by the reader which is in turn constrained by the regulations. This determines the power available to the tag IC. The range from the tag to the reader is determined by the amount of power backscattered by the tag and the reader sensitivity. In this chapter, we analyze the effect of materials such as water and detergent on tags and their effect on the readability of tags under such conditions. We also analyze some of the tests performed in an anechoic chamber to highlight the variations in the response under lab conditions as opposed to an ideal chamber test environment.

7.2 Experimental Setup

A signal source is used to send commands to the tag and response from the tag is measured with a vector signal analyzer. The tag is affixed to a gallon water bottle and is placed at a desired distance (say 1 m) from the reader. This test can repeated with different frequencies (frequency sweep) or with different power levels. The power transmitted by the reader is kept constant while the frequency is varied from 800 MHz to 1 GHz with step size of 1 MHz and the power received by the reader from the tag is recorded. Next, the transmit power is varied with a step size of 0.1 dBm while keeping the desired frequency constant. The power received by the reader is recorded. This entire procedure can be repeated at various distances. This test can also be performed in an anechoic chamber and the results noted. Next, the tag can be affixed to a gallon detergent bottle and the tests can be repeated.

All experiments were performed using the Tagformance Tag Analyzer measurement system by Voyantic Ltd. Tagformance is a complete measurement tool to analyze the performance of passive UHF tags. A signal source attached to a trans-

mitting antenna sends a command to the tag. A vector signal analyzer attached to a receiving antenna detects and decodes the response from the tag. The reader uses DSB-ASK forward link modulation and FM0 return link modulation. Transmit and receive antennas used by the reader are linearly polarized with 8 dBi gain.

7.3   Characterization of Tags: Anechoic Chamber and Lab

It is important to characterize the environment in which the tests have been conducted. Characterizing the environment is to check how repeatable the tests are in that same environment. This is done by performing the same tests on the same tag ten times without changing any of the test setup to see how variable the environment is. The same tests performed in the lab are also performed in an anechoic chamber to analyze the how different the lab environment is compared to an ideal chamber environment. This variability or repeatability test gives us an idea of how different the results are in a real lab environment as opposed to ideal conditions.

The figures show the characterization of the lab environment (using the Michelin rubber tag) in which all the tests were conducted. The same michelin rubber tag was tested under the same conditions without any change in the test setup for 10 different times and results were plotted.

In the figure 7.1, the transmitted power is plotted against the received power at the reader at a constant frequency fo 866 MHz. Though there is a slight variation in the environment, there is no drastic difference in the response. However, the response is very smooth and non-variant in the figure 7.2. This shows that though the received power is varying with the transmitted power each time the tag response is measured, the received power at the reader is almost the same at every frequency for every tag response.
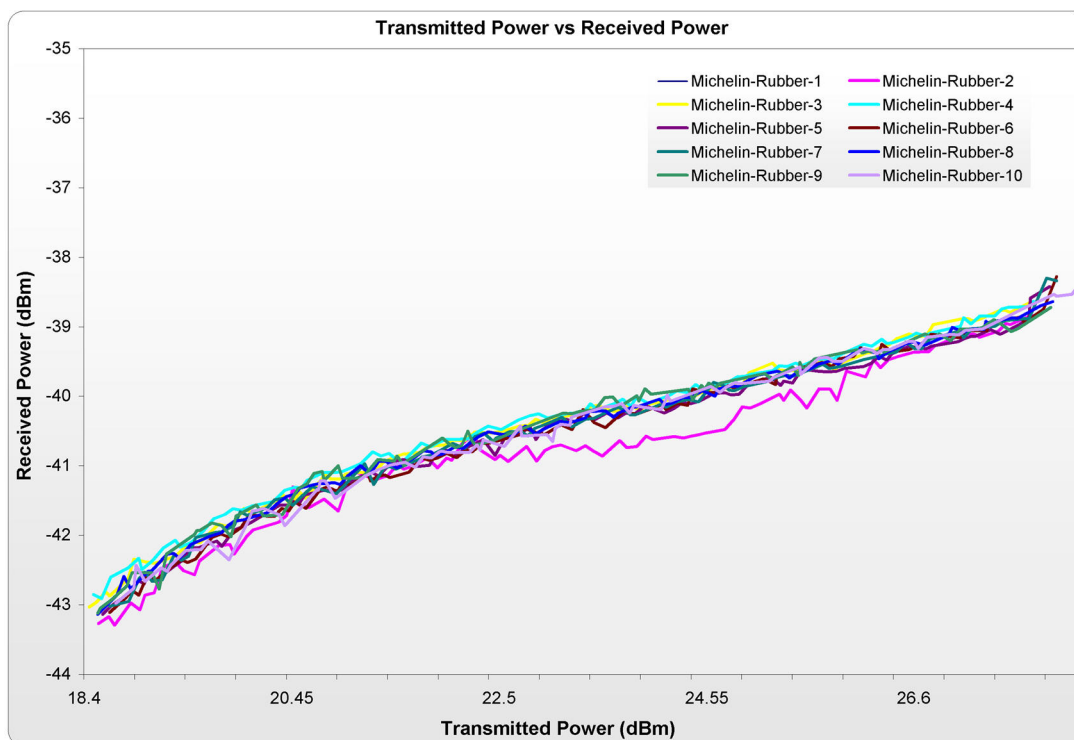
Figure 7.1. Transmitted Power vs Received Power.

The figures show the characterization of the anechoic chamber in which all the tests were also conducted to verify the validity of the tests in the lab. The Alien squiggle tag was tested 10 times under the same chamber conditions with the same test setup.

The backscatter plot in figure 7.3 shows the transmitted power plotted against the received power at the reader at a constant frequency of 866 MHz. It also shows a slight variation in the response while the frequency sweep plot in figure 7.4 shows a more subtle difference. This indicates that the frequency response of the tag is very smooth and does not change as much as the backscatter plot.

The two figures basically show that the performance of tags in an anechoic chamber is better than in the lab. However, it is not possible to achieve the chamber-like performance in real world due to the presence of several RF inhibitors. The
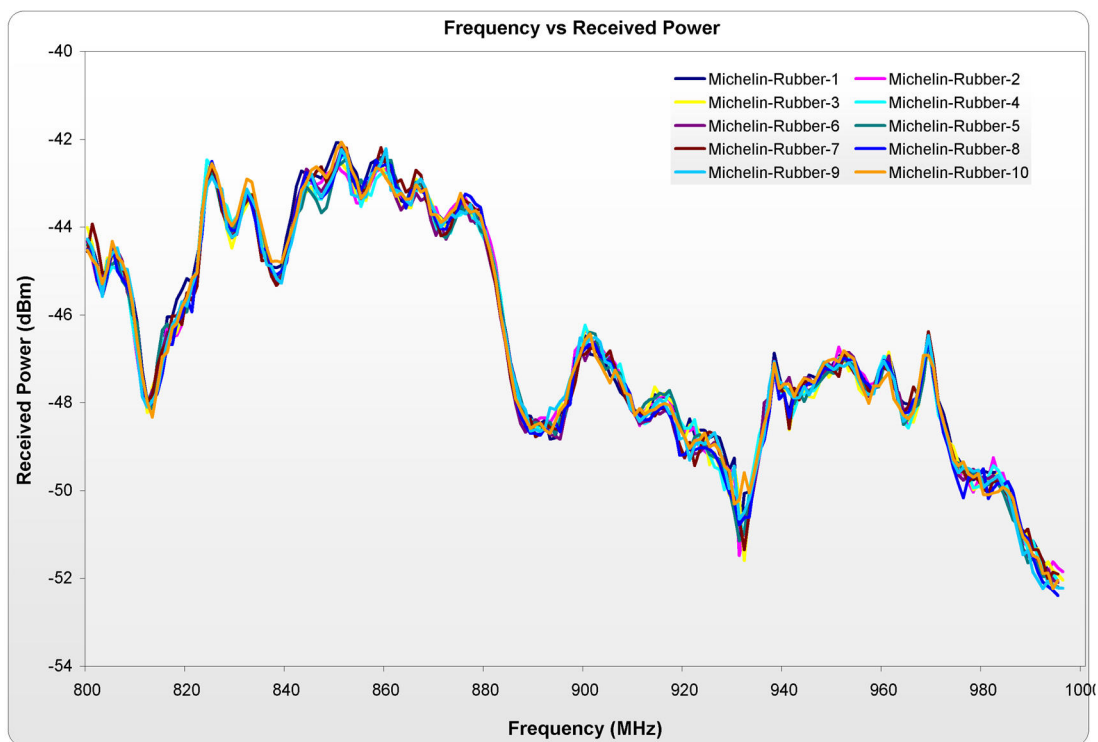
Figure 7.2. Frequency vs Received Power.

reason for performing tests in the chamber is to compare the results with real world environments and to provide a usable differential from an 'ideal' condition.

The figures show the freespace tag response comparison between an anechoic chamber and lab conditions. Figure 7.5 shows the backscatter plot at 866 MHz for the Michelin Rubber tag. From the same figure we can see that the tag in an anechoic chamber has a response starting from a threshold power level of 14 dBm to 28 dBm. The tag reponse in the lab starts from a power level of 19 dBm to 27 dBm.

The backscatter signal strength of the tag in an anechoic chamber is better than in the lab as expected however not a with a very large differential. There is roughly a 10 percent differential between tag response in an anechoic chamber and under lab conditions which is definitely acceptable due to the presence of several RF absorbent, reflecting and transparent materials. Thus a 10 percent deviation from
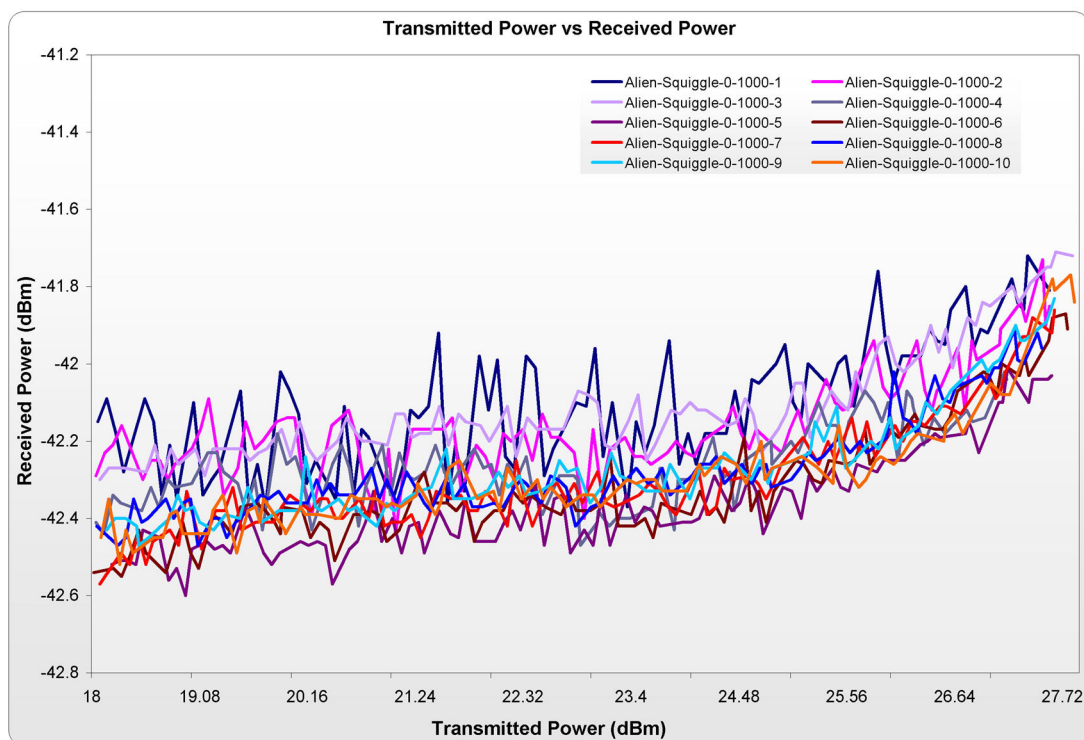
Figure 7.3. Chamber Characterization: Transmitted vs Received Power.

an 'ideal' environment based on practical tests and data obtained shows the validity of our tests in the lab. There is a very subtle deviation between lab and chamber conditions in figure 7.6. The change is mainly in the range of frequencies between 800 - 900 MHz. Frequencies from 910 - 970 MHz show almot no deviation in the received power at the reader.

7.4 Performance of Tags on Water

At the UHF range of frequencies, RFID tags operating at this range do not work well around water due to the detuning effect on the tag antenna. Electric field is attenuated by the presence of dielectrics and does not provide good performance in the presence of the same. Liquids such as water absorb the RF radiation from the
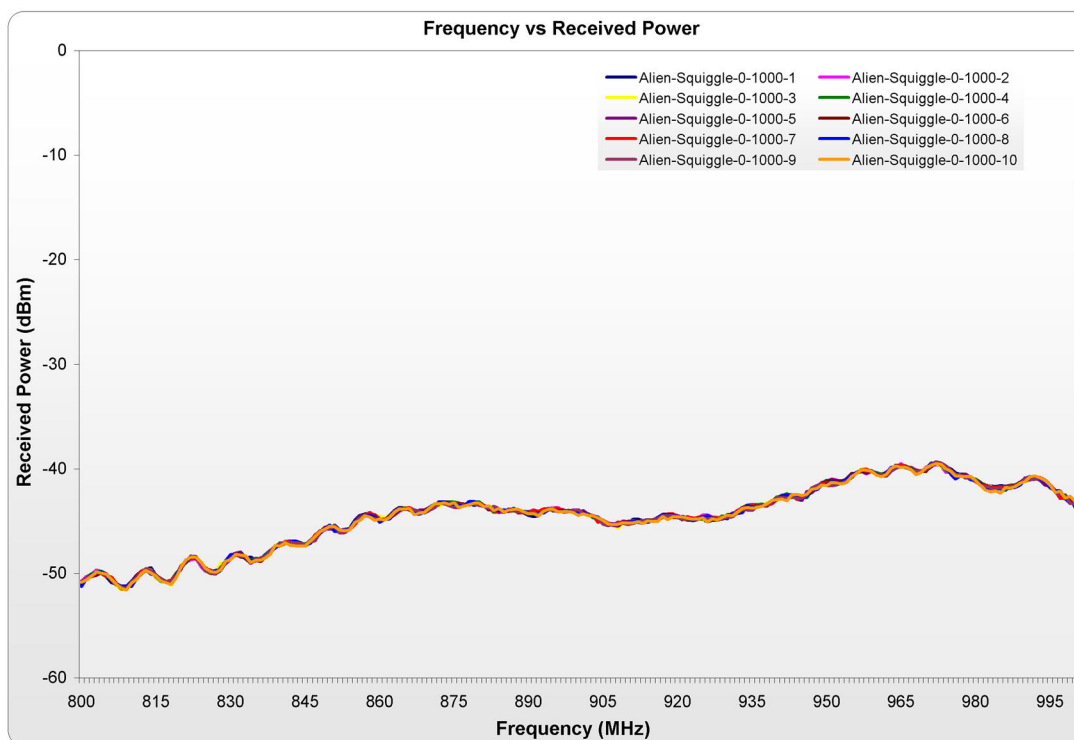
Figure 7.4. Chamber Characterization: Frequency vs Received Power.

reader and thus very less power is available to the tag IC to turn on and respond back to the reader.

We characterize the response of the Michelin Rubber tag on a gallon water bottle in an anechoic chamber as well as in the lab. The reason behind performing this test is to analyze the performance of tags in an 'ideal' chamber environment and their deviation in the practical lab tests. This gives an insight into how tags perform in the real world and helps validate our tests in the lab.

In the figure 7.7 the tag on water bottle response in the lab and the chamber are very similar except that the backscatter signal of the tag is better in the chamber than the lab at 866 MHz. Again, as discussed before the differential is the important factor here and is found to be 10 - 12 percent. Though the frequency sweep graph as
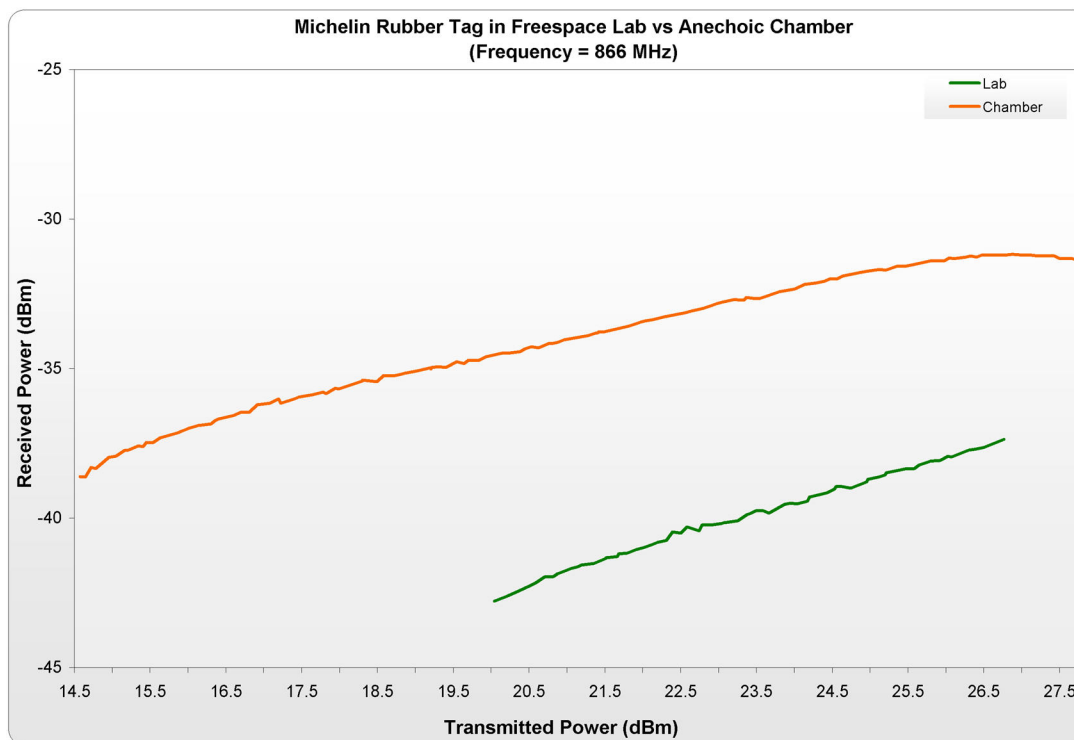
Figure 7.5. Freespace - Lab vs Chamber: Transmitted vs Received Power.

shown in figure 7.8 shows variations between the chamber response and lab response, the overall differential is even smaller is this graph.

In the figures, we compare the response of a tag on a water bottle with a tag in freespace under normal lab conditions. The reason behind this analysis is to show the performance of tags on water compared to freespace.

Based on the practical tests it is important to mention that some tags do not respond at all on a galloon water bottle or metal. We see that the performance of the Avery Dennison bowtie tag is much better in freespace as opposed to on a water bottle at 866 MHz as shown in figure 7.9.

The AD tag in freespace responds from 20 - 28 dBm transmitted power from the reader while the AD tag on a water bottle responds only from 26 - 28 dBm. Also, the backscatter signal strength for the tag in freespace is much higher to the order of
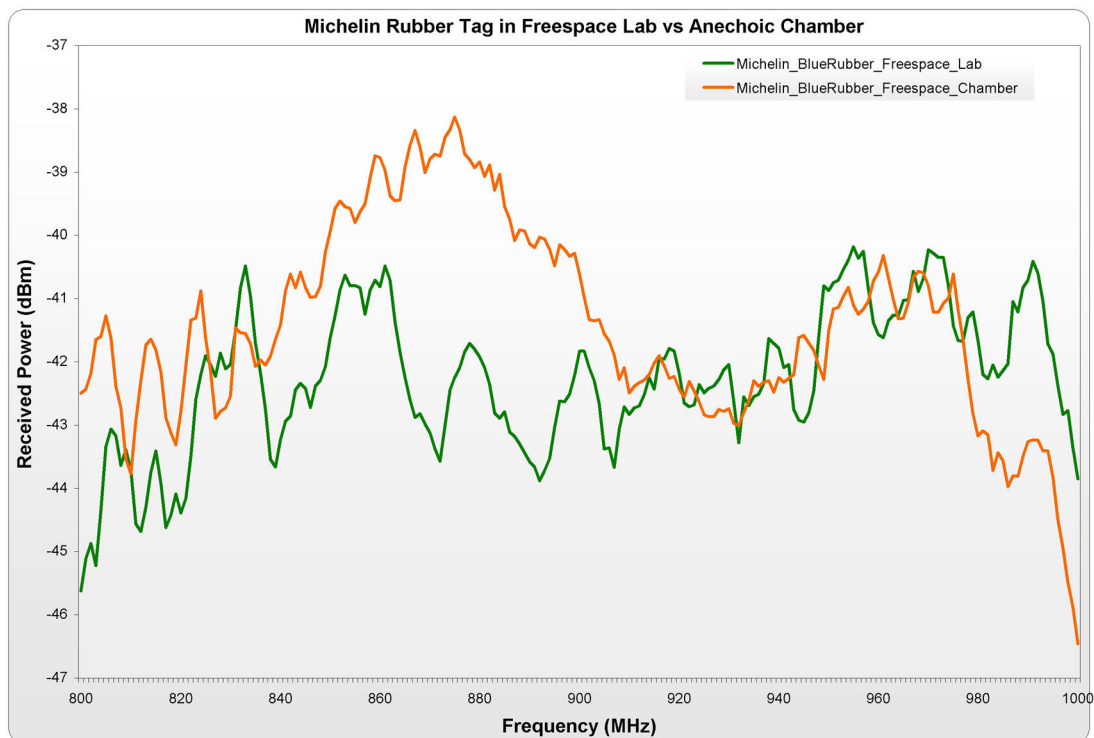
Figure 7.6. Freespace - Lab vs Chamber: Frequency vs Received Power.

-35 dBm while it is -48 dBm on a water bottle. This highlights the absorption effect of water on RF radiation and thus the low backscatter signal strength and low tag sensitivity. A similar response can be noted in the case of the frequency sweep shown in figure 7.10.

The same test is performed in an anechoic chamber to see the performance of a tag in freespace and on a gallon water bottle under ideal conditions and results are plotted as shown in figures 7.12 and 7.11. The graph patterns for the chamber are very similar to the ones for the lab except that the backscatter signal strength is higher which is expected. Again, the differential between lab and chamber is not very high. However, there is a difference in the frequency sweep plot between the chamber and lab. The tag responds at almost all frequencies in the chamber for freespace and on the water bottle. But, it responds only from 800 - 870 MHz on the water bottle
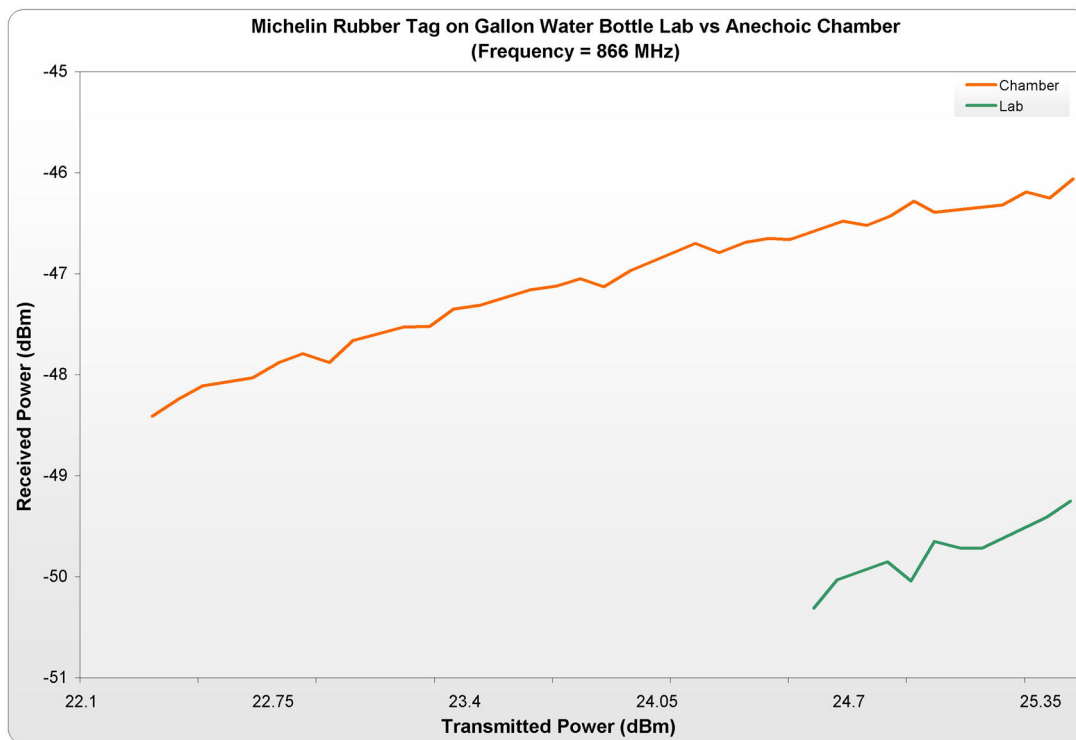
Figure 7.7. Lab vs Chamber (Water bottle): Transmitted vs Received Power.

while it covers all the frequencies in freespace in the lab. This highlights the detuning effect on the tag antenna by water.

7.5   Performance of Tags on Detergent

It is important to understand the performance of passive UHF RFID tags on liquids. Liquids with varying density have different effects on tag readability. Most of the RF waves transmitted by the reader are absorbed by the detergent or any other liquid and thus the amount of power available to turn on the tag IC is reduced. Liquids also produce a detuning effect on the tag antenna due to the shift in the center frequency.

The effect of density of liquids on the performance of tags is illustrated here. From the figure 7.13 we see that the amount of power required to turn on the Michelin
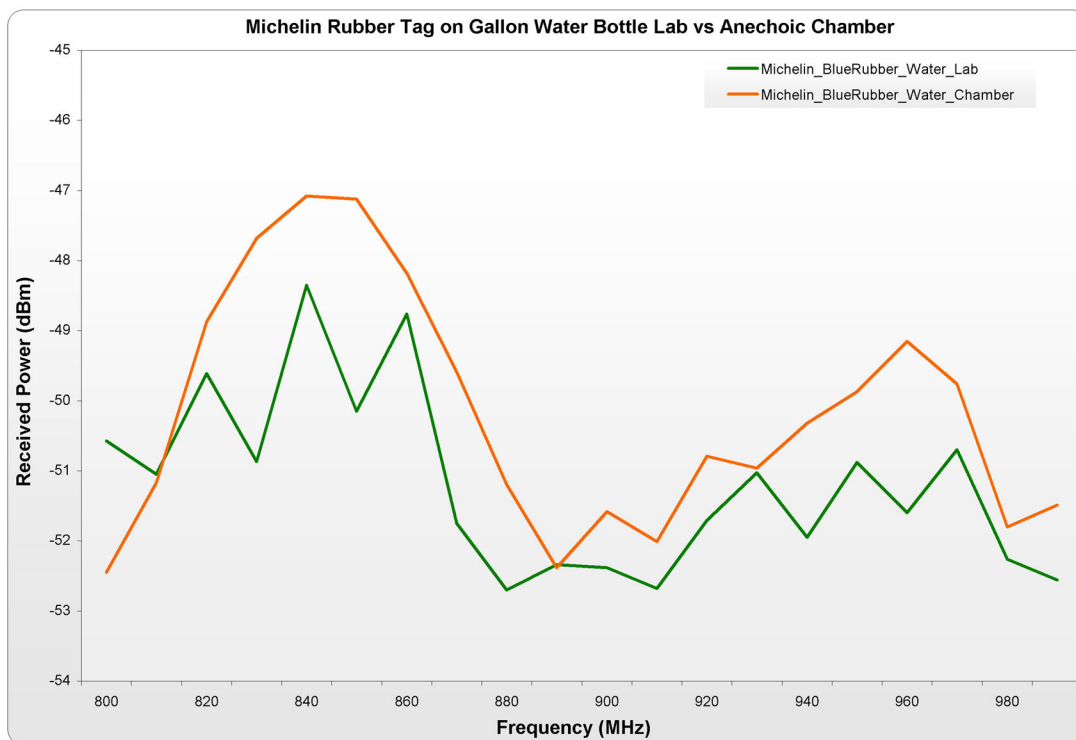
Figure 7.8. Lab vs Chamber (Water bottle): Frequency vs Received Power.

rubber tag and respond is much higher than for the same tag on water. Also, there is a 12 percent differential in the received power level at the reader between the michelin rubber tag on detergent and on water at a frequency of 866 MHz. In the figure 7.14 the frequency sweep for the michelin rubber tag on detergent and water are shown. There is a peak at the same 866 MHz frequency for the tag on water and again the received power level at the reader of the tag on the water is higher than on the detergent. Thus, this shows the effect of liquid density on the performance of tags.

Next, we characterize and compare the performance of tags on detergent in the lab and in an anechoic chamber. In the figure 7.15, we see a consistent differential of about 10 percent between the lab and anechoic chamber at 866 MHz between the transmitted and received at the reader.
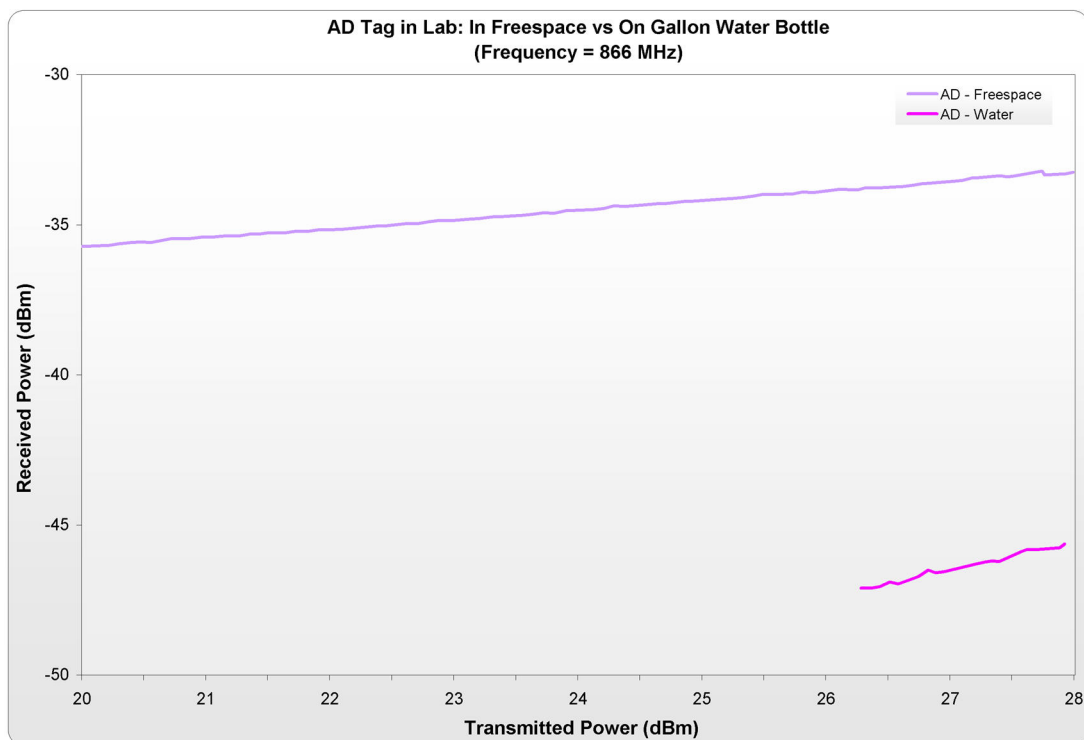
Figure 7.9. Lab: Water bottle vs Freespace: Transmitted vs Received Power.

Also, the amount of power required to turn on the Michelin rubber tag and respond is very high in the lab (roughly 27.5 dBm) as compared to the chamber which is around 18 dBm. This will have a strong impact on the readability of the tag at the reader and also on the overall communication range of the entire system. Consequently, the amount of power backscattered by the tag is also very low in the lab (around - 53 dBm) than in the chamber (around - 46 dBm).

The figure 7.16 shows the frequency sweep for the Michelin rubber tag on detergent in the lab and in an anechoic chamber. The frequency response is found to be very limited in the lab as opposed to the chamber response.

The peak is noted at around 863 MHz for the tag on detergent in the chamber and is around 880 MHz in the lab. This highlights the detuning effect on the tag
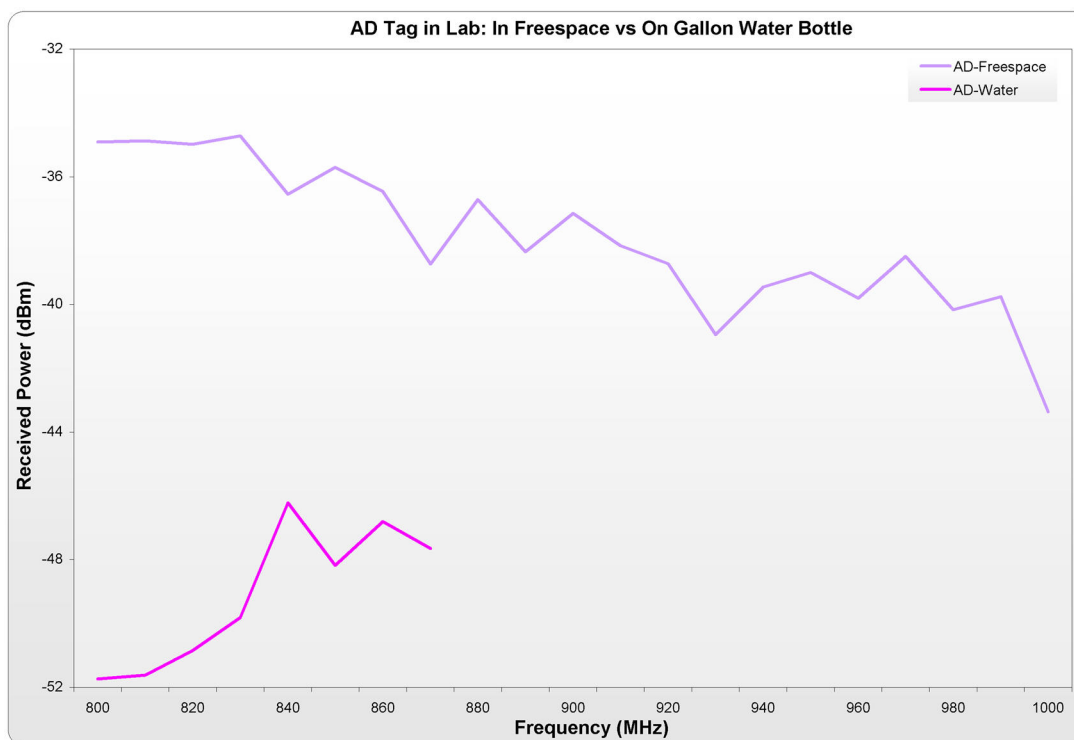
Figure 7.10. Lab: Water bottle vs Freespace: Frequency vs Received Power.

antenna for the tag on detergent in the lab (non-ideal environment) as opposed to the tag on detergent in the chamber (ideal environment).

The figures show the performance of Michelin rubber tag in freespace and on detergent in lab and chamber. The amount of power required to turn on the tag and respond is very high for the tag on detergent (around 27 dBm) against freespace (around 19.5 dBm) in the lab while it is quite low for the tag on detergent (around 17.8 dBm) as opposed to freespace (around 14.5 dBm) in the chamber as shown in figures 7.17 and 7.19. Also, the received power differential at the reader between the tag in freespace and on detergent is approximately 15 percent in the lab as compared to an 8 percent differential in the received reader power level between the tag in freespace and on detergent in the anechoic chamber at 866 MHz.
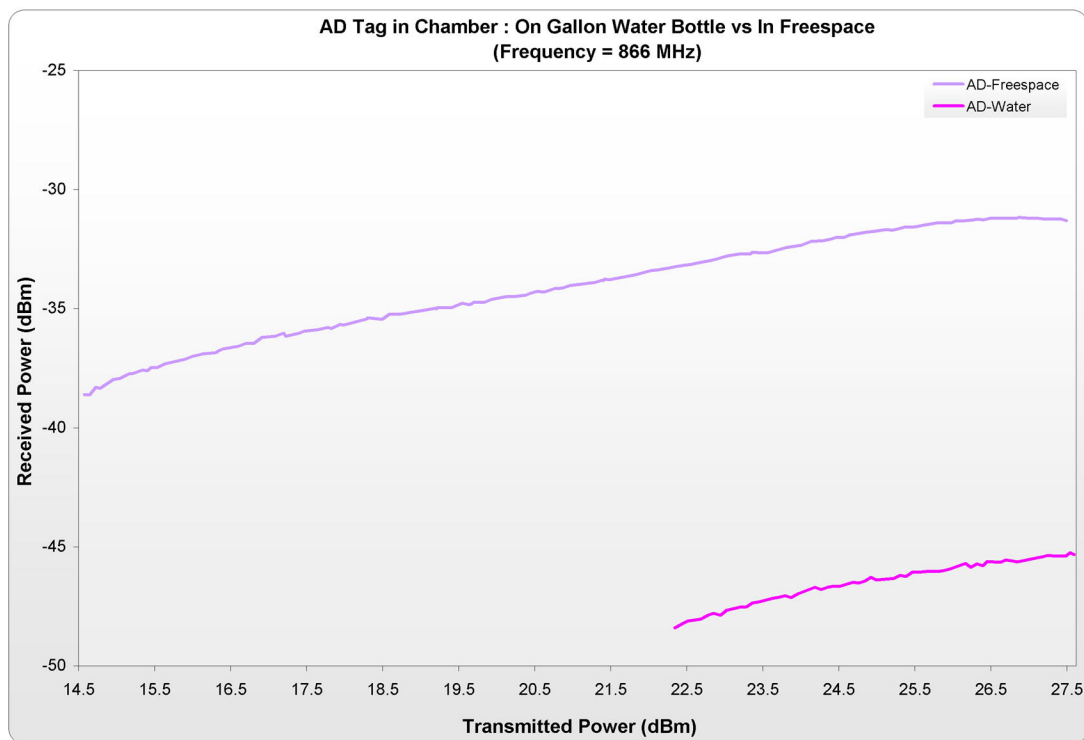
Figure 7.11. Water bottle vs Freespace (Chamber): Power.

Figures 7.18 and 7.20 show the frequency sweep from 800 - 1000 MHz for the Michelin rubber tag on detergent and in freespace in lab and chamber environments.

There are two peaks observed in the frequency sweep graph for the tag on detergent at 860 MHz and 970 MHz and for the tag in freespace at 865 MHz and 965 MHz. There are two peaks in the frequency sweep graph for the tag in freespace in the lab at 865 and 970 MHz, however there is only one peak observed for the tag on detergent in lab at 880 MHz.

These graphs not only show the performance of the tag in freespace as opposed on detergent, they also show the detuning effects of detergent (or any liquid) on the tag antenna. It can also be inferred that the amount of power delivered to the tag, the amount of power backscattered by the tag and the communication of the entire system is affected by the presence of liquids on passive UHF RFID tags.
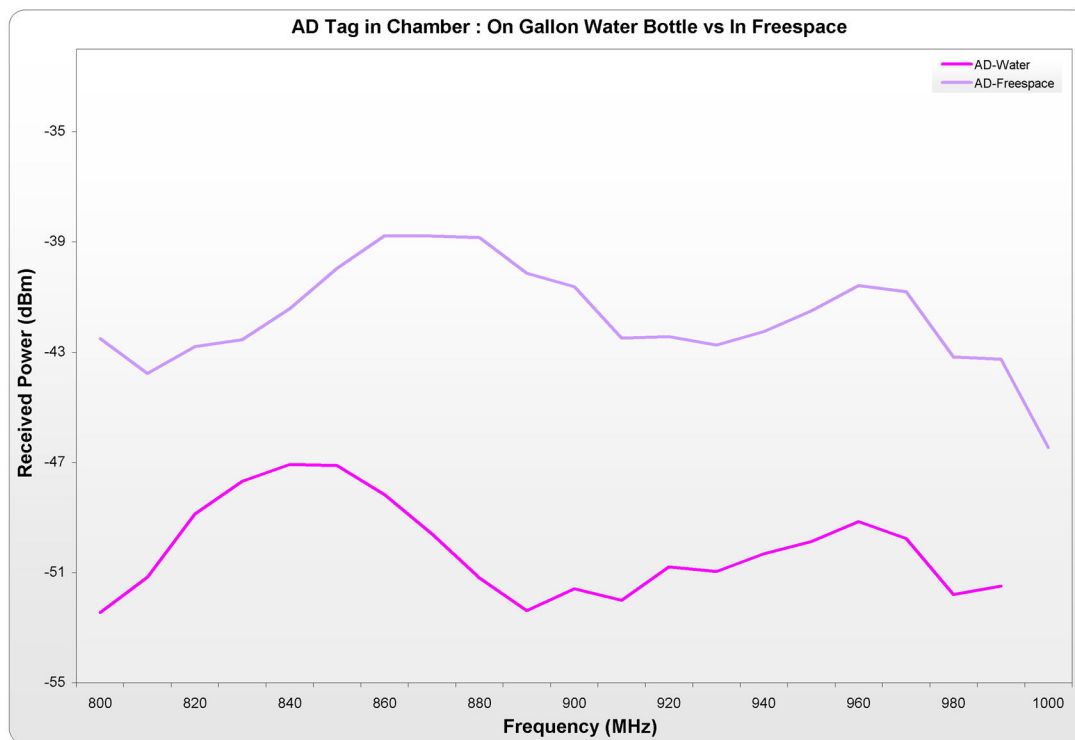
Figure 7.12. Water bottle vs Freespace (Chamber): Frequency vs Power.

7.6 Summary

Almost all applications require RFID tags to be read through environments with water or any other liquid and metal. With passive UHF RFID systems becoming very ubiquitous recently, it is very important that RFID tags are read even in the presence of water or metal. The significant hindrance to this is that passive UHF RFID systems use electromagnetic waves for propagation in the far-field for long communication ranges. Also, electric field in attenuated in the presence of dielectrics and hence does not perform very well around liquids. In this chapter, we have analyzed the performance of some commercial tags on water and detergent. Characterization of the lab and chamber environment are preformed and the results are interpreted. All the tests performed in the lab are also preformed in the anechoic chamber to compare and contrast the ideal versus non-ideal environments and a consistent percentage

Figure 7.13. Detergent vs Water Bottle: Transmitted vs Received Power.
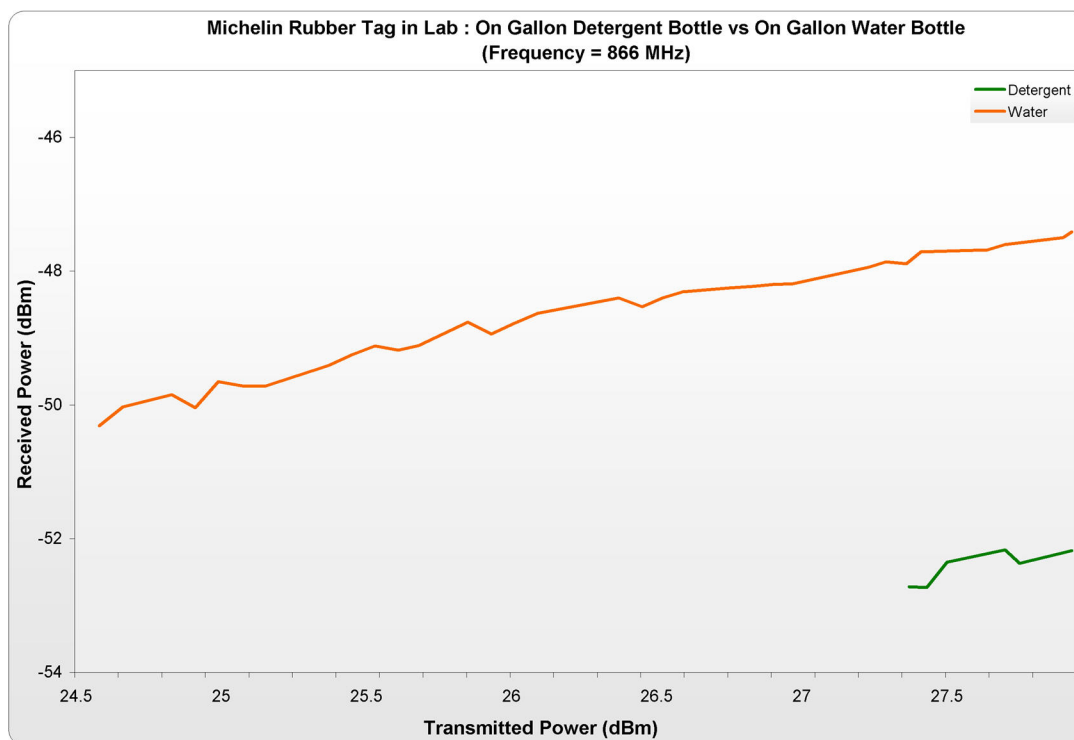
differential of 10 - 12 percent between the lab and chamber are highlighted. The tests in the anechoic chamber also validate the tests performed in the lab. The analysis shows the impact of liquids on the amount of power required to turn on the tag IC to respond, the amount of power backscattered by the tag and the communication range between the reader and tag.
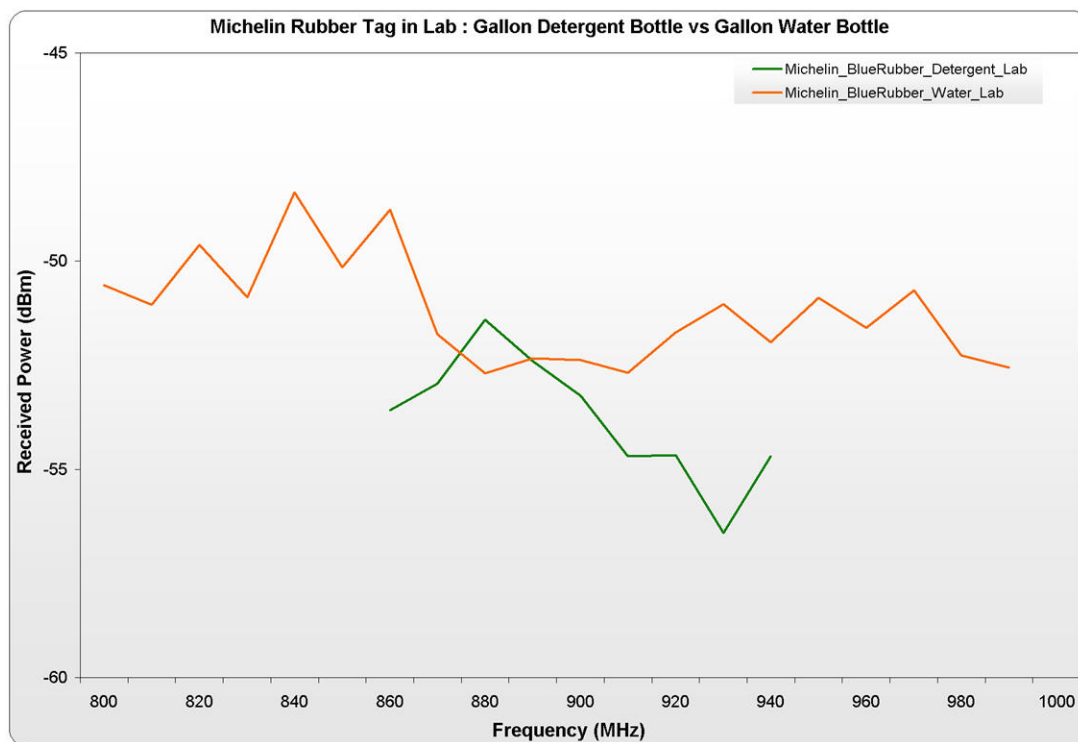
Figure 7.14. Detergent vs Water Bottle: Frequency vs Received Power.

Michelin Rubber Tag on Gallon Detergent Bottle Lab vs Anechoic Chamber
(Frequency = 866 MHz)
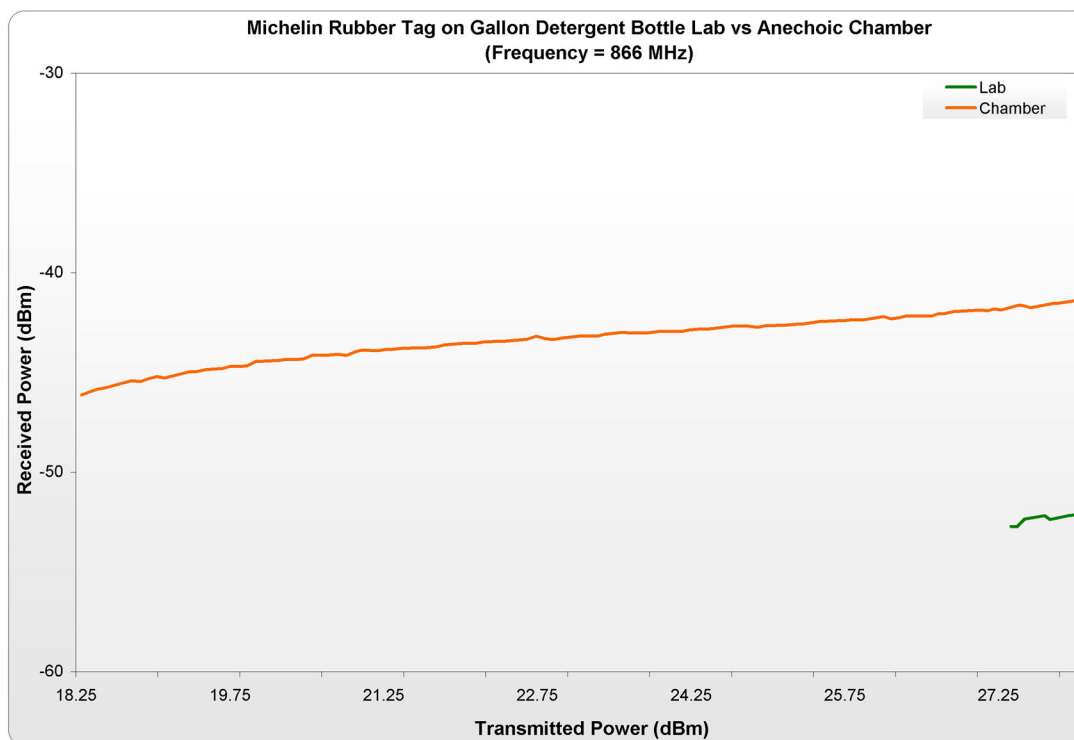
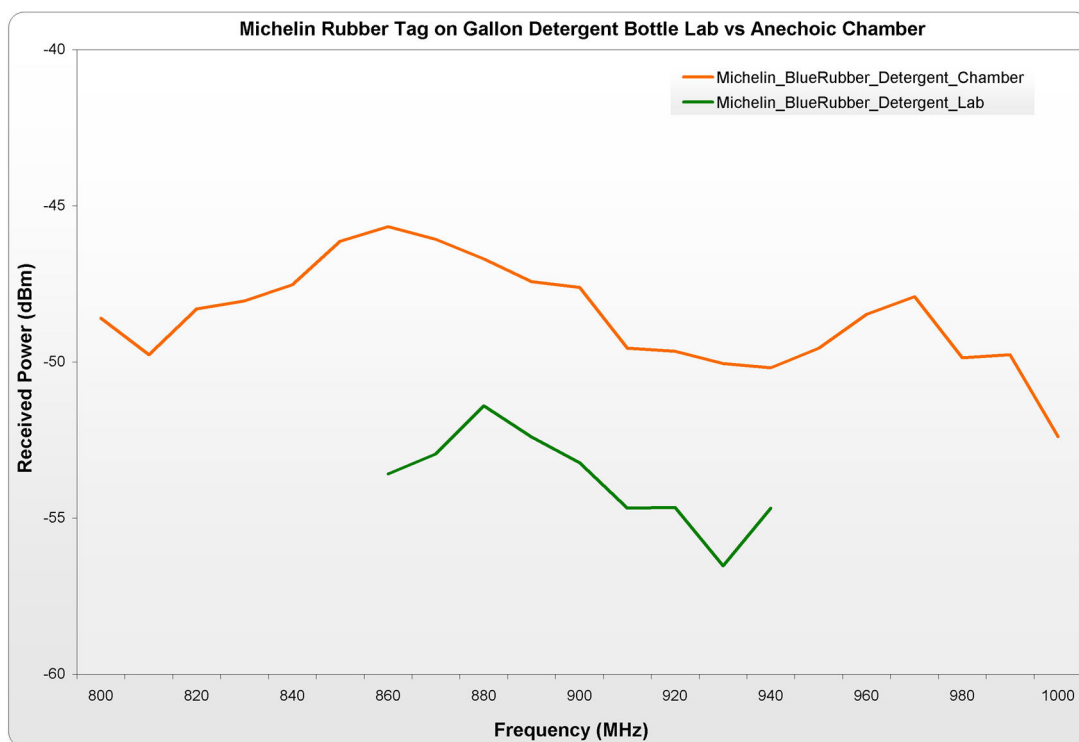Figure 7.15. Detergent bottle: Transmitted vs Received Power.

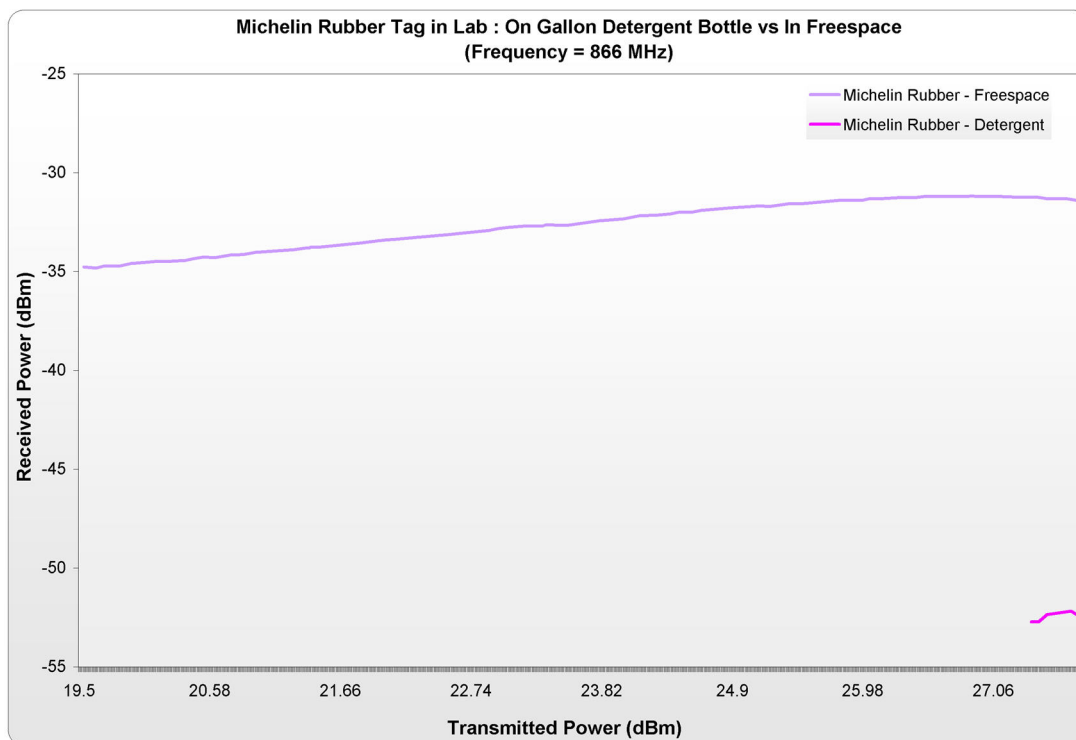Figure 7.16. Detergent bottle: Frequency vs Received Power.

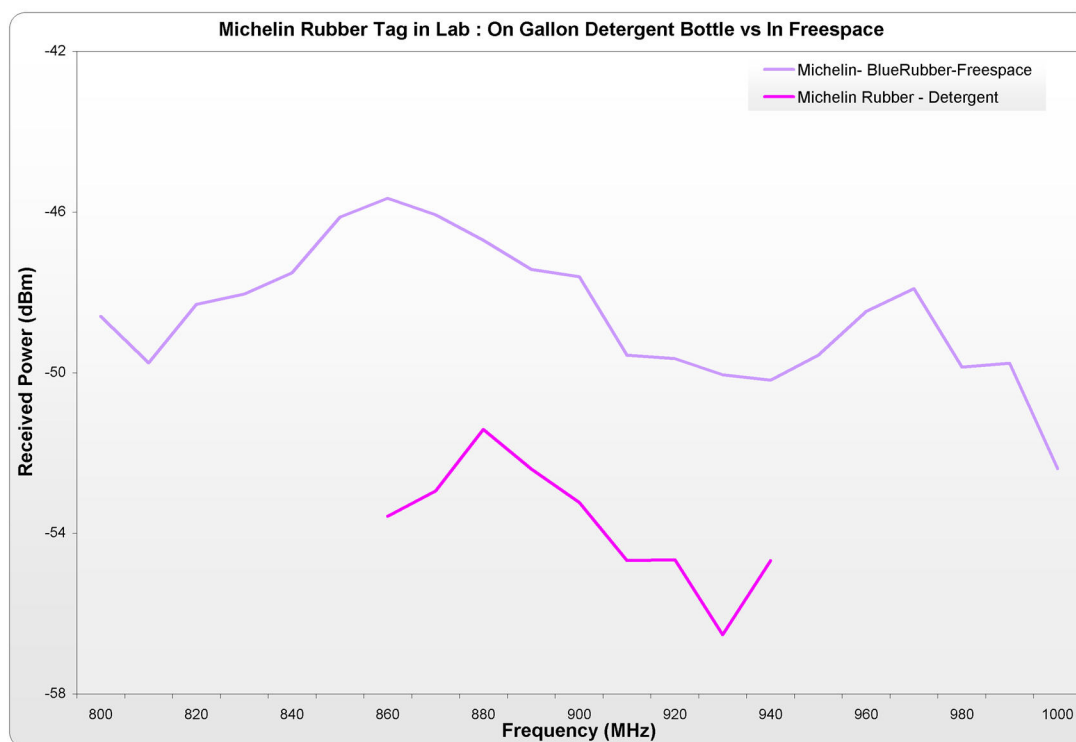Figure 7.17. Lab: Detergent bottle vs Freespace: Power.

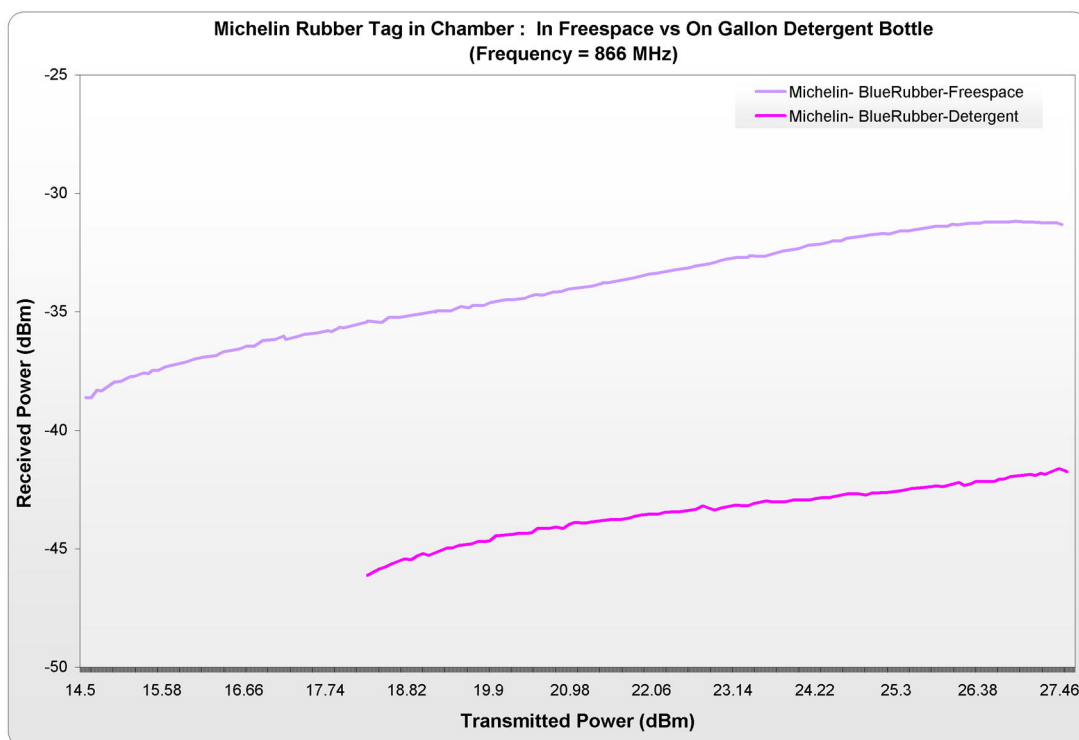Figure 7.18. Lab: Detergent bottle vs Freespace: Frequency vs Power.

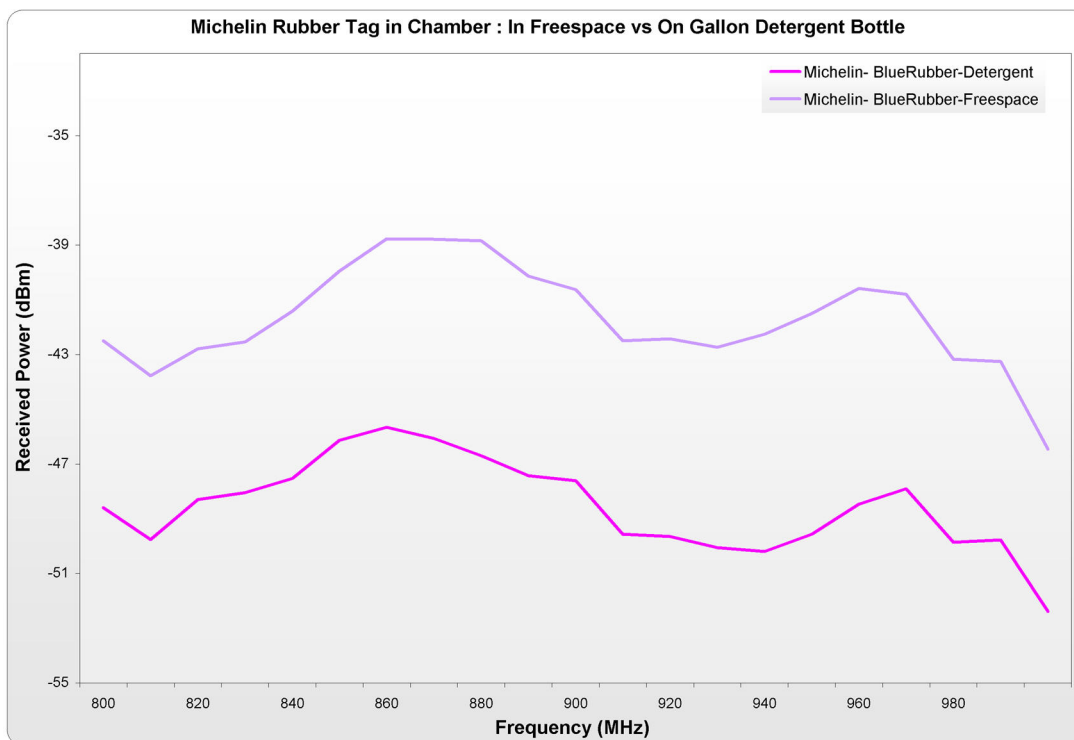Figure 7.19. Chamber: Detergent bottle vs Freespace: Power.

Figure 7.20. Chamber: Detergent bottle vs Freespace: Frequency vs Power.

CHAPTER 8

CONCLUSIONS

The RFID technology has ushered in a significant momentum in the consumer industry in the past decade [50]. Applications have broadened ranging from smart cards and labels for the supply chain to RTLS tags to track cargo containers [51]. The recent popularity of Passive UHF RFID technology is attributed to the low cost RF tags and the lack of on-tag power supply [52]. In this chapter, we discuss the future of RFID technology and its widespread adoption by several industries in a myriad of applications. We also examine the aspects of Tag Analysis that are not covered in this text and thus form a basis for potential future work in the evaluation and study of RFID tags.

8.1 Introduction

RFID technology has created an impact not only on the economy but also has the potential to change the standards of living. RFID has also created a buzz in the healthcare sector where it is possible to track patients and hospital equipment [53]. Technological advances such as the microchip and cutting edge modern antenna design led to the reduction in the prices of passive RFID tags while improving their performance and storage capacity. Recently, RFID chips have become as small as grains of sand that can be embedded in passports, drivers license and bank notes [54]. In the following sections, we discuss the trends and the future of RFID technology. We also provide ideas for future work on analysis and evaluation of passive UHF RFID tags.

8.2 Trends and Future of RFID Technology

The concept behind RFID systems originated during World War II and was adopted by the Germans to distinguish between identified and unidentified aircrafts. Research on RFID systems was a government sponsored endevor until the 1970's after which it was transferred to the private sector. Technological advancements open the door for new applications in this fast-paced technology [55]. It is important to reduce the price on tags due to the sheer volume of tags being used for every application. Thus adoption and success of RFID technology for any application will primarily focus on the cost of tags.

Innovations in chip and antenna designs for tags is an open-ended process. Cutting edge designs reduce the cost of the tags while improving the storage capacity and performance which makes the adoption of RFID technology possible. Future RFID technology will come up with tags as cheap as bar code labels. Chipless tags such as SAW (Surface Acoustic Wave) tags overcome the physical limitations of other RF tags as they do not have a tag IC and can be used with metal or liquids [56]. The Smart Active Label (SAL) technology provides a semi active tag that offers enhanced range and accuracy with less vulnerability near metal or liquids.

Manufacturing and tag packaging play a significant role in the practical use of RFID tags. Printed electronics has provided the lead in tag manufacturing. Printing the tag antenna and even the IC with conductive ink opens a new realm of possibilities [57]. Polymer electronics is another promising technology that can reduce the manufacturing cost of RFID tags. Another major issue in RFID tags is the low power. Power harvesting is extremely essential and critical for the effective operation of passive tags. New concepts and techniques to power the tags have become very important.

RFID systems enable automation at a very large scale where tags can be read at a range of several meters and with high speed. RFID systems play a critical role in the evolution of supply chain and inventory management. In determining the future of RFID, it is important to realize that hardware and software developments will never cease to exist. It is the demand and user-defined needs that drives the technology to evolve past its issues.

8.3 Potential areas for future work on Tag Analysis

Most commercial tags that are manufactured today provide high performance, low cost and increased srorage capacity. However, different tags have different characteristics due to the varying antennas and chips that are widely being used. Thus different tags may be suitable for different applications. In the RFID world of innumerable tag designs, it is essential to understand and analyze different tags to asses the performance of these tags to be used in certain environments and for specific applications.

There are certain aspects of tag analysis that are not covered in this text and thus they form the basis for future work on the same. Only limited number of commercial tags were used for testing purposes as this book is not a comprehensive study of all tags available in the market. Impact of the orientation of tags on the performance of the system can be undertaken and investigated. More specific propagation modeling relating to a spefic environment based on the data acquired can be accomplished. Software simulations to model propagation through different media can be developed. Extensive tests on the performance of tags on several other media other than the ones mentioned in this book can be carried out. More specific environment characterization can be implemented. Innovative antenna designs for different application can be developed based on the data on the performance of tags.

8.4   Summary

In this text, we have covered test procedures for the analysis of several factors that affect the performance of passive UHF RFID tags. All tests were performed under lab conditions except for the ones performed in an anechoic chamber. Test procedures and analysis guidelines to examine tag sensitivity, backscattering of tags and communication range are discussed in detail. Correlation and mutual relationship between the afore mentioned parameters are also developed and investigated in chapters 5 and 6. Performance of tags on three different media such as gallon water bottle, gallon detergent bottle and on a metal drum were tested and results studied. Tests were conducted in an anechoic chamber and the results were compared and used to validate our lab testing conditions. This thesis also provides complete testing methodology and analysis guidelines to asses the performance of passive UHF RFID tags.

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BIOGRAPHICAL STATEMENT

Ananyaa Gautham is a Researcher with the Texas Radio Frequency Innovation and Technology Center at the University of Texas at Arlington. She received her B.E in Electronics and Communication Engineering with honors and is pursuing her M.S in Electrical Engineering at UTA. She is currently a Graduate Teaching Assistant with the Department of Electrical Engineering providing research assistance, project guidance and technical mentoring to graduate students. Her interests include RFID system design, wireless and digital communication, wireless sensor networks, embedded system design, antenna design, image and signal processing. Her current research focuses on Analytical and Practical Evaluation of UHF Gen2 Tags, RFID Reader Design and Wireless propagation modeling for RFID systems. She is a recipient of several honors and awards as a part of her undergraduate and graduate programs. Her near term vision is to bring scientific and engineering innovation to find solutions to some of the most critical problems faced by the RFID industry.