Performance Benchmarks for Passive UHF RFID Tags

by

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Abstract

Passive radio frequency identification (RFID) systems are revolutionizing the way products and goods are tracked and traced in the supply chain. Various major retailers and government agencies have realized the potential of RFID systems and have released mandates and recommendations to their suppliers. The time constraints to meet the mandates and the lack of good, reliable, unbiased source of information has driven the need for developing a set of common benchmarks for comparing performance of tags. In this thesis, I present a comprehensive set of benchmarks developed for comparing the performance of Ultra High Frequency (UHF) passive RFID tags. Also, I present some experimental results and the key insights that these benchmarks have revealed about the current state of passive UHF RFID tags that are available in the commercial market.

To my parents

Acknowledgements

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Table of Contents

List of Figures

List of Tables

1. Introduction

1.1. Motivation

Automatic identification (Auto ID) of objects enables the organizations that manage global supply chains and vast trading partner networks to operate more efficiently and save cost. Auto ID includes a host of technologies like bar codes, smart cards, voice recognition, biometric technologies, optical character recognition, radio frequency identification (RFID), and others. Bar codes have been the primary means of identifying products since late 1960s. RFID offers many compelling advantages over bar-codes, including non-line-of-sight operation. Some of the large retailers and government agencies have realized the promise that RFID offers to businesses and have released mandates and recommendations to their suppliers to use RFID. The time deadlines for these mandates have resulted in a number of misleading claims from RFID vendors and confusion among RFID end-users. Hence, there is an immediate need for performance benchmarks of RFID products to give consistent information and to avoid confusion.

RFID is an Auto ID technology that enables products to be uniquely identified without the need for line of sight. RFID enables computers to sense objects and collect the identification codes that are assigned to objects. In combination with the Internet and associated infrastructure, RFID will enable companies to track and trace individual items through the supply chain, i.e. from the manufacturer, through the distributor, to the retailer, and finally to the consumer. RFID aims to provide retailers a near-perfect supply chain visibility. That is, companies would be able to know exactly where every item in their supply chain is at any moment of time.

In essence, RFID is revolutionizing the way products and goods are tracked and traced in the supply chain. Retailers consider RFID as an investment for the future providing advantages like cost reduction by maintaining correct amount of stock levels, increase in revenue by reducing the out-of-stocks, counterfeit protection, shrinkage protection, and real-time tracking of supplies. These benefits are pervasive throughout the supply chain. In a highly competitive business environment, RFID represents the next level of supply chain efficiency that many companies are striving to attain.

Realizing the importance and advantages of RFID to businesses, some of the largest retailers and government agencies have required their suppliers to use RFID to help their supply chain run more efficiently. Recent mandates and recommendations from various retailers and government agencies like U.S. Department of Defense (DoD) [1, 2] are requiring their suppliers to use RFID. Also, organizations such as Food and Drug Administration (FDA) are encouraging the pharmaceutical companies to use RFID [3]. This has caused RFID to become important to a large number of people who were unfamiliar with the technology. An estimated 14,000 companies supplying a major retailer and 50,000 suppliers to DoD have to meet aggressive timelines set by these mandates and recommendations. Few companies affected by these mandates have the necessary in-house RF expertise to deploy the technology. The majority of the companies generally resort to outside expertise for information and help. Even as late as 2004, there were not enough third party solution providers having access to good information. Hence, the companies that were mandated resort to employing the RFID vendors to investigate RFID performance in their environment. When companies employ vendors, there is an obvious risk of getting biased information. Although there are better third party solutions currently, still the risk of bias exists. Hence there is a need for unbiased, good, and reliable source of information for RFID products.

The companies that are affected by the mandates need to deploy RFID, which has created demand for RFID products. The ignorance of the majority of the market about the RFID technology and the enthusiasm of RFID vendors resulted in competing and misleading claims from the vendors. For example, a leading RFID tag vendor states in one of the web pages that *"Today's RFID tags have read rates varying from as low as 20 tags/second to over 1,000 tags/second"* [19]. We believe that this statement is false or at best misleading. Misleading claims and the lack of good, credible, unbiased source of information has created confusion among the RFID end-users. Hence, performance benchmarks for RFID products are needed to give consistent information and to avoid this confusion.

RFID Alliance lab [4] was created to provide unbiased, reliable, and independent source of information for performance of EPC-complaint ultra high frequency (UHF) RFID products. The lab provides objective benchmarking information that separates facts from hype. For example, we have observed tag read rates ranging between 0 and 65 tags per second (see Section 3.5 [4, 5]), not the 20 to 1000 as a leading RFID tag vendor claims. Benchmark information such as the tag read rates will help the end-users to make more informed decisions and deploy RFID technology successfully.

Benchmark measures that are presented in this thesis can be used to compare the performance of different tags in terms of distance, quality, and read rates in various situations. These measures are relevant and intuitive to the end users. The benchmark measures are repeatable providing a scientific way to compare performance, and also are an indication of the real-world performance of the tags. These measures, when combined provide the expectations in performance that can be realized in real-world scenarios and give information towards implementing better RFID systems.

This thesis presents the benchmark metrics that were developed for RFID Alliance Lab for comparing the performance of passive UHF RFID tags. In addition to the benchmarks, we also present a sample of the empirical results obtained from comparing 10 commercially available tags. We also project some interesting observations about the tag-reader system. The complete results are commercially available [5, 6]. These benchmarks provide a first step towards a common benchmark standard that aims to reduce confusion prevalent among the end-users of RFID products and provide consistent information using user-relevant performance measures.

1.2. Research Questions

The timelines for the mandates and the lack of good information sources in RFID has resulted in confusion among end-users. The ignorance of the market and the RFID vendor’s enthusiasm to capture the market caused competing and misleading claims from RFID vendors. In order to separate the facts from the hype, there is a need to measure performance. Since different end-users of tags have different requirements, there are various aspects of performance that needs to be measured. These various aspects of performance in RFID pose several research questions that need to be answered. Some of the research questions are listed as follows:

1. Maximum distance

   RFID vendors report tags readable up to a maximum of 20 feet. However, these claims are unverified. Furthermore, the RFID tag vendors do not mention the deterioration of performance of tags with distance. If the tag is within the maximum read range of the reader, can tags respond to all the read attempts from the reader at any distance within the maximum range?

2. Orientation sensitivity

   Some RFID vendors report that their tags are readable at all angles with the reader antenna. However, they do not mention the performance difference at various angles. Are the tags readable at all the angles? If so, what is the performance difference at various angles with respect to the reader antenna?

3. Variance in performance

   Tags within the same model are supposed to give similar performance. Consistency in performance in the same model is generally expected. However, are tags really consistent? If not, how should one measure the variance in the performance of the tags?

4. Read rates

   There can be only one tag present in the reader's field or there can be multiple tags present. Does the speed at which the tags are being read depend on the number of tags in the reader's field? Does the speed at which tags are being read depend on the air-interface protocol between the tag and the reader?

5. Metal / water effects in terms of distance

   Most of the common products used in supply chain have some form of metal or water in them. For example, common products like a bag of chips, dishwashing detergent or toothpaste have some form of metal either in the product or on the packaging. Thus, there is a real need to measure the effects of metal and water on tags. The maximum distance at which a tag is readable in the presence of metal or water is to be measured.

6. Metal / water effects in terms of frequency

The frequency of operation of UHF RFID is different across countries. For example, UHF RFID operates in 902-928 MHz in USA whereas 860-868 MHz in Europe. Thus, in order to achieve a globally visible supply chain the tags should operate well across all the UHF RFID frequencies. Does the presence of metal / water near the tag affect it frequency response? If so, what is the performance that one can expect at each frequency of operation?

The answers to these research questions would help the end-user to separate the facts from the hype and also give them the quantitative performance information about RFID tags. The objective of this thesis is to answer research questions such as the ones listed above. In order to answer the questions, we set out with developing benchmarks for RFID performance. In this thesis, we present the benchmarks that are developed to answer these questions. We also present select data[1] that give insight into some of the interesting aspects of tag performance. We describe the benchmarks, illustrate sample data, and discuss the observations.

1.3. Organization

The way this thesis is organized is as follows: Chapter 2 gives an overview of UHF passive RFID, discuss about the working of passive RFID, review some of the fundamental RF basics involved in UHF RFID communication and finally discuss about the factors that affect the performance of UHF RFID. Chapter 3 defines the benchmarks that were developed for read and write performance of tags. Also, some interesting results and insights from the comparison of the tags are mentioned. Chapter 4 consolidates some interesting observations with passive UHF RFID tags. These constitute characteristics of the RFID system and also for some specific protocols. Chapter 5 concludes the thesis and presents directions for future work. Appendix A includes pictures of some of the RFID tags and readers that are available in the commercial market.

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[1] Contractual constraints prohibit us from identifying particular RFID product by name, but this information is commercially available in [5, 6]. We believe that many lessons and trends can still be projected without identifying products.

2. Background

RFID systems provide an automatic means to identify physical objects without the need for line-of-sight communication. The main components of a RFID system are tags, readers, and host computer. RFID tags are attached to physical objects as a means to identify them. RFID readers convert the radio waves sent from the tags to get the digital data and send the collected data to the host computer. RFID tags used in supply chain carry a unique serial number called Electronic Product Code (EPC) [7]. Mandates require that the tags deployed in the supply chain to be primarily passive UHF EPC-compliant tags. The time constraints of these mandates have driven the need for good source of information for comparing UHF EPC-compliant tags. Hence, in this thesis we are concerned about the benchmark metrics for passive UHF EPC-compliant tags.

The passive UHF RFID tags used in the supply-chain form only a small portion of a variety of RFID systems that have been developed. For perspective, a brief history of RFID and the broad classifications of the RFID systems are given before describing passive UHF RFID and passive RFID performance in more detail. In this chapter, we will also discuss a basic background on UHF RF that is relevant to this thesis.

2.1. History of RFID

RFID is a term that refers to a family of technologies that has existed since 1940s. It has been suggested that the first RFID related technology was invented by the British in 1939, and was routinely used by the allies to identify airplanes as friend or foe. This technology was called as Identify Friend or Foe (IFF).

Since the invention in 1939, RFID has undergone significant development with advances in different fields. In the 1960s and 1970s, various governments developed identification technology to track military equipment and personnel [16]. By the late 1970s this identification technology was used for identification and temperature sensing of cattle. However, the wide use of the technology was possible only by late 1980s and 1990s when the semiconductor companies were able to achieve improved performance with size and cost reduction. This enabled RFID systems to be used in many new practical applications. From then on, passive RFID has found its use in access control and security, airline baggage handling, inventory management and asset tracking, and smart cards.

There has been continued work on finding innovative methods for achieving low cost and high performing technologies. However for wide scale adoption of RFID such as in the supply chain, RFID systems from different vendors must be compatible with each other and also must be able to operate under regulations from various countries. In order to make different vendors use the same specifications standards are essential. EPCglobal Inc. has been leading the development of industry-driven standards for using RFID in the supply chain.

2.2. Taxonomy of RFID systems

Through the development of RFID to its current state, there have been many different varieties of RFID systems. A classification of the existing RFID systems would help us understand the larger universe of RFID. This will enable us understand the various possibilities with RFID systems and the reason for using UHF passive RFID tags in the supply chain.

The variety and the operating principles of RFID systems have enabled classification along several dimensions. Passive UHF RFID used in supply chain forms only a small part of a larger universe of RFID systems. In this section, we give the description of the larger RFID universe before going into the specifics with passive UHF RFID.

2.2.1. Chip and Chip-less tags

RFID tags can be classified as chip and chip-less tags based on the way the tags store data. The chip tags contain an integrated chip (IC) to store the unique data. The power needed to operate the integrated chip is derived either from the reader's RF signal or from an on-board battery source. Chip-less tags do not contain an integrated chip, but they encode unique patterns on the surfaces of materials. These patterns constitute the data that is reflected back to the readers. An example of chip-less tags is the Surface Acoustic

Wave (SAW) RFID tags which are based upon the piezoelectric effect and on the surface-related dispersion of acoustic waves at low speed [8].

Although chip-less tags seem to provide the minimum of functionality – a read-only device with a unique number, the technology is not mature enough for adoption in supply chain. Though chip-less technology show tremendous promise in the future, the chip tags offer the most near-term solution for the majority of track and trace in supply chain.

2.2.2. Auto-ID Class Structure

Auto-ID center was founded in 1999 to develop an open standard architecture for creating seamless global network of physical objects. Auto-ID center has provided a layered class structure [9] to classify UHF RFID tags based on their operation and functionality. The class structure classifies various mutations of tags into a class structure ranging from the least sophisticated Class 0 to the most sophisticated Class 5. Class 0/1 tags both represent basic capability. They are read only passive identity tags. The passive tags derive the power needed for operation from the reader's RF signal. They communicate back with the reader using backscatter modulation. The Class 0 protocol uses out-of-band signaling while Class 1 protocol uses in-band signaling. Class 0 tags are read-only, programmed by the manufacturer, whereas Class 1 tags are generally viewed as write once and read many where the writing can be done either by the manufacturer or by the user. Class 2 tags are passive tags with additional functionality like encryption or memory. Class 3 tags are semi-passive tags. These tags have a battery source for operating the internal circuitry, whereas they do not have a transmitter for sending back the information. All the tags from Class 0 to Class 3 use backscatter techniques to communicate to the reader at UHF frequencies. Class 4 tags are active tags, which have a battery source and a transmitter. They may be capable of broadband peer-to-peer communication with other active tags in the same frequency band or other readers. Class 5 tags are devices that can power other tags as well as communicate with other Class 4 tags. An example is a RFID reader that is capable of powering up the other Class 0/1 tags. Since the tags used in supply chain will be used on almost every product/case, the tags must cost as less as possible. Of all the tags it is possible to achieve lower costs in near-term with Class 0 /Class 1 tags. Thus, the mandates require Class 0/1 passive tags to be deployed in the supply chain.

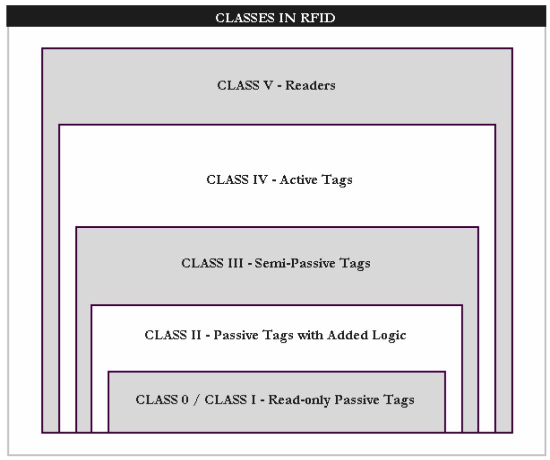

Figure 1 Class Structure for RFID classification

2.2.3. Frequency of Operation

Another major classification dimension is the frequency at which the RFID systems operate. RFID systems generally operate in specific Industrial Scientific Medical (ISM) bands that occupy portions of spectrum from low frequencies like 125 kHz to microwave frequencies like 5.8 GHz. The mandates require that the RFID systems be operated in the UHF (Ultra High Frequency) frequencies occupying the ISM bands in 860 – 960 MHz according to frequency restrictions in different countries. The read range offered by UHF RFID makes this frequency the most attractive for supply chain implementations.

2.3. Components and Functions

As was described at the beginning of Chapter 2, the RFID system consists of three components: tags, readers, and host computer. The general working of passive RFID system is as follows: the reader transmits a query for all the tags to respond. The tags that are powered and which have recognized the query from the reader respond back to the reader. Both the tags and readers typically implement a command protocol necessary for the identification of a single tag or multiple tags within the reading range of the reader.

These protocols have anti-collision algorithms that reduce the occurrence of multiple simultaneous transmissions from different tags to a single query from the reader.

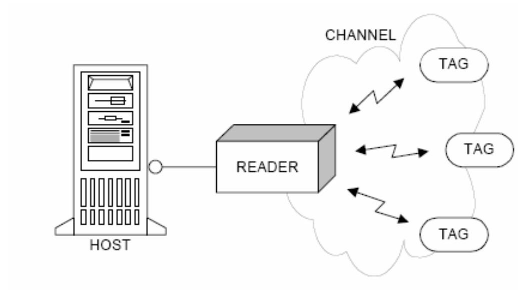

Figure 2 RFID system components

Readers are generally radio transceivers with antennas connected to them. These radio transceivers typically implement a variety of protocols meant for tag-reader communication. Passive RFID tags are attached to objects and the RFID tags contain an identification code (ID). EPC-compliant tags used in the supply chain are programmed with an ID called as electronic product code (EPC). EPC generally consists of a unique identifier, a cyclic redundancy check, and a short password [13]. Physically, a passive RFID tag is composed of a chip, an antenna on top of a substrate, and may contain a label (adhesive paper for attaching to the product). Figure 3 shows the components of a sample passive UHF RFID tag.

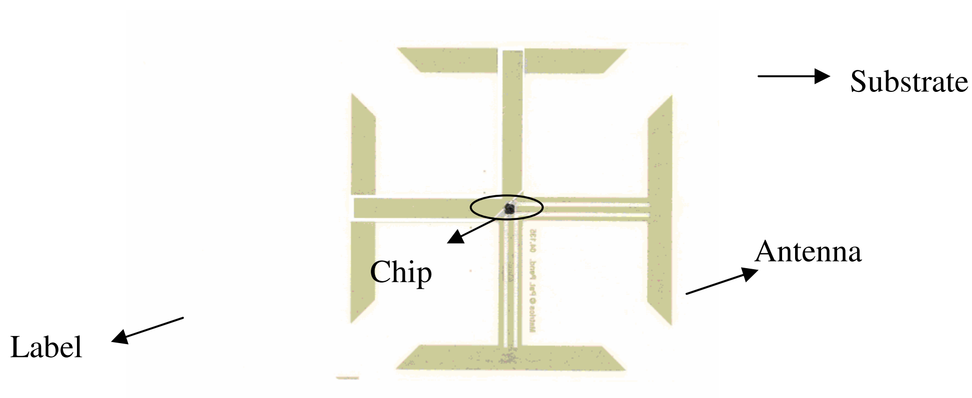

Figure 3 Sample Passive RFID tag

The other component in the RFID system, the host computer is meant for collecting all the raw EPC numbers from the reader. A middleware can be used in the host computer to convert the raw EPC numbers to the objects to which they are attached. Different kinds of logistical analysis can be realized through consolidation of the outputs from the middleware.

Before explaining in detail about the way passive UHF RFID works, it would be helpful to discuss the principles involved in the tag-reader communication and vice-versa.

2.4. UHF RF Communication Principles

The communication between the reader and the tags in UHF take place in the ISM band of UHF in various countries. UHF communication between tags and readers take place through the electromagnetic (EM) waves that propagate through the environment. In this section, we will discuss the principles involved in communication between tags and readers in UHF and vice versa.

2.4.1. Reader to Tag communication principles

In supply chain, RFID tags are typically used in the far-field region of the reader antenna. Hence, the reader to tag communication takes place using far-field communication principles. Far field distance from an antenna is estimated using Rayleigh distance or far field distance. For different radiating structures, it has been estimated that the far field distance is given as:

$$r > \frac{2D^2}{\lambda}$$

where D is the maximum dimension of the radiating structure and r is the distance from the antenna. It should be noted that this is only an estimate and the transition from near-field to far-field is not abrupt. Typically D for reader antennas is 1 foot. The far field distance in UHF ISM band in USA (915 MHz) can be estimated to be 56 cm.

In general, the reader and tag are separated by a distance of 2 foot to ensure that the tag is placed in the far-field of the reader antenna. As is common in most of the wireless communication systems, the coupling takes place using the transmission, propagation, and reception of EM waves. The power received by an antenna from in terms of the power transmitted by another antenna separated at a distance of r is given by Friss transmission formula:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi r)^2}$$

where P_r, P_t are the received and transmitted power of the antennas, G_r, G_t are the gains of the receiving and the transmitting antennas, and λ is the wavelength. The above formula assumes that there is no polarization mismatch between the transmitting and the receiving antennas. Also, the power available to the load must include the impedance mismatch between the load and the antenna impedances. Thus, the power available to the load in the receiver is given as:

$$P_r = pq \frac{P_t G_t G_r \lambda^2}{(4\pi r)^2}$$

where p denotes the polarization mismatch factor between the transmitting and receiving antennas and q denotes the impedance mismatch factor between the load and receive antenna impedance. The fraction of the received power $1-q$ is not delivered to the receive load and is scattered. The above equations show the amount of power delivered to the tag from the reader at a given fixed frequency.

The frequency of operation for the reader to tag communication in passive UHF RFID is not fixed. Reader does a frequency hopping in the ISM band in UHF for communicating with the tags. The frequency hopping avoids interference that might occur due to other devices using some part of the spectrum in ISM band. Also, the modulation schemes used in the reader to tag communication depend on the type of the protocol being read.

2.4.2. Tag to Reader communication principles

The passive tags do not have a transmitter to communicate back with the reader. The tags communicate back to the reader by changing the load impedance. The variation of the tag's load impedance causes a mismatch between the tag's antenna and load. This causes some amount of power to be reflected back and scattered through the antenna. The return scattered signal from the tag is detected and demodulated by the reader. The variation of load impedance causes different amount of powers to be reflected back to the reader. This method of communication is called as *backscatter modulation*.

Figure 4 Illustration of Backscatter Modulation

Figure 4 shows the extreme case of backscatter modulation for illustration purposes. When the load (red) and antenna (black) are perfectly matched, the antenna delivers the received power to the load. When the load and antenna are mismatched, the power received by the antenna is reflected and radiated back. The change between these two extreme conditions is used to modulate the response back to the reader. In practice, the load variations are not this drastic. Typical value of impedance for a UHF RFID chip produced by Philips is 16 – j350 Ω [17].

2.5. Passive UHF RFID System – Working

A passive RFID system consists of passive RFID tags and a reader capable of reading them. The principles mentioned in Section 2.4 are used for communication between the passive tags and reader. In this section, we put all these principles together and explain the basic working of passive RFID system.

The primary working principle of a passive RFID system can be explained using Figure 5. Figure 5 shows a part of the circuit for a simple passive RFID chip. The RFID reader sends out RF energy in attempt to read tags. The tag antenna is tuned to receive the RF energy. The bridge rectifier charges a capacitor using the RF energy that the antenna receives. Once the capacitor is charged to a certain voltage, the combination of the capacitor and Zener in breakdown serves as a voltage source. If enough energy is available to drive the internal circuitry of the RFID chip, the tag begins to perform the demodulation and processing the commands sent by the reader. The tag responds to the issued commands by switching the load at the antenna terminals from matched to unmatched conditions according to the tag response signal. The switching of the load between matched and unmatched conditions would absorb and reflect the signal transmitted from the reader. When there are multiple tags responding to a command, the RFID air-interface protocol has an anti-collision algorithm to detect collisions [7].

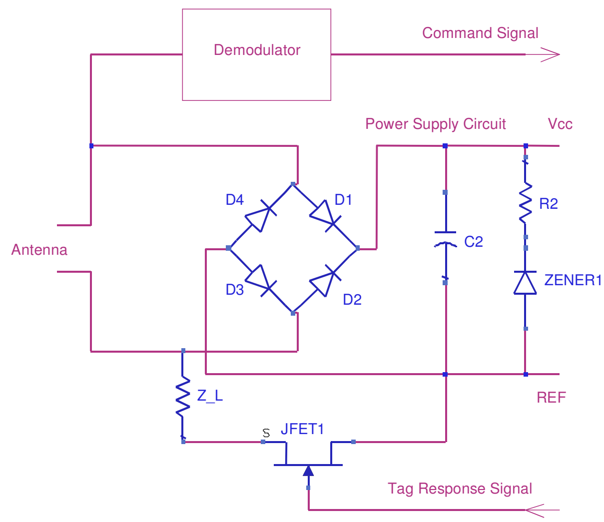

Figure 5 Part of the circuit for a RFID tag

The mandates require the use of EPCglobal Class 0 and Class 1 passive RFID tags. EPCglobal is a leading standards body for RFID involved in the development of industry driven standards. EPCglobal Inc. standardizes the specifications of the Class 0 and Class 1 protocols. The reader and the tag talk with each other using these protocols. These protocols are briefly summarized in the next section.

2.6. EPCglobal Class 0 and Class 1

The Class 0 protocol is meant for implementation of read-only passive RFID tags [12]. Reader to tag communication is accomplished through an amplitude-modulated carrier. Tag to reader communication is accomplished through passive backscatter of the tag to reader carrier already described to produce widely separated sub-carrier tones. A population of tags to be read by the reader can be represented as a binary tree. The reader scans the tree from the root to leaf to fully define an EPC. The process of finding a single tag in a population by scanning the tree is called as *tag singulation*.

The Class 1 protocol [13] is meant for implementation of read/write tags. Reader to tag communication is accomplished using amplitude shift keying (ASK). Binary data from reader to tag is encoded as pulse width modulation of the low level pulse. The tag to reader communication use passive backscatter that follows a scheme where two transitions are observed for a binary zero and one transition for binary one. When a population of tags is to be read by the reader, the reader puts the tags that are already read to *sleep* so that the reader can focus on reading the difficult-to-read tags [14]. These difficult-to-read tags can be at the edge of the read field or on an RF-absorptive material. In practice, RFID reader performs a sequence of *wake up*, *read*, and *sleep* cycles to ensure that all the tags in the field have been read.

2.7. Performance of UHF Passive RFID

Until now, we have been considering the behavior of EM fields and waves in free space (environment is uniform and there is no objects to interfere transmission and reception). In practice, the environment is not truly free space and there are various factors that might affect the performance of the RFID system.

The main factors that affect the performance of a RFID system are the tags, readers, and the environment in which they are operating. The medium over which the tags and the reader communicate is called the *channel*. The channel affects the communication between the tags and reader due to effects such as attenuation, multi-path, and interference from other readers and RF devices. The physical objects to which the tags are attached also affect the tag's performance. Many common materials that the tags are attached such as metal and water have considerable effects on the performance of the tags. Changes in impedance bandwidth, detuning of the antennas, and reduction in the efficiency of the antenna are some of the factors that change the amount of power being delivered from the antenna to the chip. The environmental effects observed at UHF frequencies can be classified into material effects observed with conductors, dielectrics, and in free air. In this thesis, we separately analyze the environmental effects of tags near metal, water, and free-air and develop different performance metrics.

Another factor that affects the performance of RFID system is frequency of operation. It should be noted that all the performance metrics of the tags are frequency dependent. Also, the ISM band in UHF frequencies varies among countries. For example, the ISM band frequencies are 860 – 868 MHz in Europe, 902 – 928 MHz in USA and Canada, and 950 – 956 MHz Japan. Thus if the tag is to be read globally, it should operate well across the spectrum. In this thesis, we have also developed benchmarks for the frequency dependency of tags near metal and water.

Although RFID performance is a concern for those who are deploying RFID, we are not aware of any published standard or recommendations towards a well-defined set of performance measures. EPCglobal Inc has realized that RFID performance is an issue and is taking steps towards a performance standard. We are aware of a group in EPCglobal Inc working towards a performance standard. But it is currently not visible to the public and there has been no published recommendation towards performance. The only published previous work in this area was [10]. This essentially lists out a set of simplistic approach for comparing different RFID product offerings by end-users. Although it lists a broader view on the performance issues, it does not provide well-defined measures that would be user-relevant for comparison. In this work we not only provide well-defined set of measures for performance comparison of RFID tags but also provide empirical results based on those measures.

3. Performance Benchmarks

The time constraints to meet the mandates and the lack of good, reliable, unbiased source of information has driven the need for developing a set of benchmarks for comparing performance of tags. The performance benchmarks developed for RFID Alliance Lab to compare passive UHF RFID tags are presented in detail in this chapter.

The two functions that are commonly performed with passive tags are read and write. Generally, tags are read much more often than they are written. The benchmarks presented in this thesis cater only to these two functions. While it would be ideal to have a single overall number that defines performance of tags, the reality is different end-users of tags have different requirements. Hence, multiple benchmarks are needed to measure the performance of tags.

Read Performance Benchmarks

In the first part of this chapter, we describe the benchmarks for read performance of tags when the tag is in free-space, near metal, and near water. Tags occur in a wide variety of scenarios. For example, there can be only one tag or multiple tags in the reader field. If there is only one tag in the field, the tag is referred to be in isolation whereas when there are multiple tags in the field, it is called as tags in population. Also, another scenario is when the tags are used in free-air or attached to materials. Thus, a number of benchmarks can be defined to characterize read performance. Some of the characteristics of tags that we considered for each of the scenarios were:

Free-air / Material

- Readable distance
- Orientation sensitivity
- Consistency among tags
- Read speeds in isolation
- Read speeds in population
- Frequency response

Static / In Motion

- Read range
- Read speed in isolation
- Read speed in population

For each of the characteristics listed above, two different benchmarks can be defined depending on the scenario in which tags are present. For example, read distance can be measured in free-air or in front of a material. In order to define, a useful set of benchmarks for end users, we chose a relevant sub-set of these benchmarks which are simple, repeatable, and that would provide an indication of the real-world performance of tags. The chosen benchmarks are listed in Table 1. The benchmarks were chosen based on what are useful for the end users and how tags are currently being used in real-world. It can be noted from Table 1 that we do not list a benchmark for reads on conveyors, portals, dock-doors etc. There has been considerable work on conveyor testing across the industry. For example, University of Arkansas [18] has been providing application level analysis for conveyor testing. Since there are many unconstrained variables in conveyor testing, it is hard to characterize tags and their behavior using conveyor tests. Since the focus of this thesis is to provide repeatable, simple, baseline measures that characterize the tags and compare them, we do not include a benchmark for reads on conveyor. The benchmarks given in Table 1 provide end-users with enough data for predicting real-world performance of tags. We believe that these benchmarks quantify all the relevant aspects of tag read performance.

Table 1 Read Performance Benchmarks

Benchmarks	**Measured Characteristic**
Response Rate vs. Attenuation	Distance
Orientation Sensitivity	Orientation
Variance of Tags	Consistency
Read performance in front of metal / water	Material effects
Read in isolation	Speed
Read in population	Throughput

Table 1 shows the benchmarks developed for read performance of tags. The benchmarks developed for tag performance in free-air are:

- Response rate vs. attenuation
- Orientation sensitivity
- Variance of tags,
- Read rate in isolation, and
- Read rate in population

The benchmarks developed for performance of tags in front of materials are:

- Maximum read distance of tags
- Changes in frequency response near water and metal

Write performance Benchmarks

In the last part of this chapter, we discuss the write performance benchmarks for tags. The tags are written only a few times (lesser than 100 times) compared to the number of times they are read. As noted in Section 3.7, there are additional constraints that have to be observed when writing to tags. For example, tags are generally written individually and are placed at a much closer distance from the reader antenna. The benchmarks for write performance of tags are:

- Reliability
- Write speed

In this chapter, the benchmarks are explained as follows:

1. We begin by stating the objective of each benchmark.
2. An accurate description of the test procedure that should be adopted along with the test parameters for each benchmark is discussed.
3. The test metrics that should be measured from the test procedure are listed. The test procedure and the test metrics constitute the formal definition of the benchmark.
4. We provide the explanation of one of the experiments that we conducted using this benchmark.

5. Sample results from the experiment are included along with some of the interesting lessons learned when the metric was used among a wide variety of tags.

Appendix A shows pictures of some of the tags that are available in the commercial market and the readers that were used for our experiments. It is to be noted that all the developed benchmarks are based on the tag-reader system. Thus, changing the reader model may affect the results observed from the benchmarks. The reader model used is one of the parameters that should be mentioned along with the benchmarks. In fact, there are several other parameters or conditions that might affect the results from a benchmark and have to be mentioned along with the results. These are parameters / conditions are summarized in Section 3.1. All the experiments mentioned in this thesis were done using the commercial readers along with the default antennas sold with the reader. The commercial reader used for each experiment is listed along with the parameters / conditions for that experiment.

3.1. Default Test Parameters

The test parameters describe the equipment and the conditions under which the measurement was taken. The test parameters are important to understand the implications of the results. In order to attain the same results when the benchmark is repeated, the test parameters have to be mentioned along with the benchmark results. The benchmarks along with the test parameters provide the user with the information to analyze, which is the better performing tag under the user's constraints. Some of the test parameters are common across all the benchmarks. Table 2 includes the common test parameters that are to be mentioned with a benchmark along with the default values for the test parameters.

All the default values in Table 2 are self-explanatory. It should be noted that in USA, Federal Communications Commission (FCC) limits the maximum output transmitter power to 30 dBm. However, the default maximum output power is listed as 32.5 dBm. The reason is that the default maximum output power accounts for the loss in the cable loss. The measured cable loss for the factory default cable is 2.5 dB for one of the readers and hence, the output power is raised the same amount to account for the loss.

Table 2 Common test parameters and default values

Test Parameter	Default Value
Environment	Anechoic Chamber
Reader Model	Factory Reader model
Reader firmware and software version	Current firmware and software version on reader
Antenna Type	Bi-static and circular polarized
Number of Antennas	1
Combining with multiple antennas	Disabled
Protocol of the tag	Protocol of the tag e.g. EPC Class 0, EPC Class 1, ISO
Multi-protocol Reader settings	List of scanned protocols
Cables to connect antenna and reader	Factory default
Maximum Power	32.5 dBm
Application	Demo application
Separation between reader and tag	3 feet

It is noted that Table 2 is not an exhaustive list of parameters. The common parameters should include all the parameters that might affect the outcome of the benchmark. For example, temperature and humidity might affect some measurements. If this is the case, it has to be included in the above set of parameters. All the listed parameters are necessary for the end-user to understand the implications of the results from an experiment. In the following sections, we discuss the benchmarks in detail.

3.2. Response Rate vs. Attenuation

The most common question about tags and readers is the maximum distance at which a tag can be read. This benchmark addresses that question indirectly. This benchmark uses attenuation of power levels as a means to simulate distances. We know that, in an ideal channel Friss transmission equation describes the amount of power received (see Section 2.4.1). The reduction in the transmit power reduces the extent of reader field. Thus in order to achieve repeatable results, the power levels was attenuated to simulate distance.

Also, it should be noted that this benchmark forms one of the fundamental characteristic of tag-reader system and is the basis for the benchmarks such as orientation sensitivity, variance of tag performance, and read performance in front of metal/water.

3.2.1. Benchmark Objective

The objective is to determine the maximum distance at which a tag is readable by a RFID reader.

3.2.2. Test Procedure

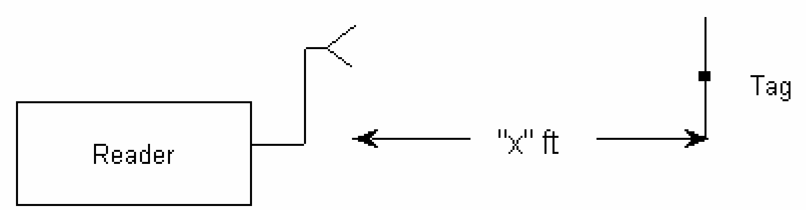

Figure 6 Free Space experimental Setup

Figure 6 shows the setup that should be used for this benchmark where x is the separation between the tag and the reader. Since UHF tag-reader communication takes place in the far-field as seen in Section 2.4, the separation x should be such that the tag is in the far-field of the reader antenna. Both the forward channel (reader to tag) and the reverse channel (tag to reader) should be attenuated for simulating distance. However, for large tags (> 2x2 inches) attenuating the forward channel is sufficient in non-noisy environments (see Section 4.1). Ideally, the tag and the reader should be placed in an anechoic chamber or at least in a non-noisy environment for this benchmark.

The ratio of number of times a tag is read to the number of reader attempts to read the tag is measured for increasing attenuation levels at fixed increments. Attenuation is increased until the tag is not read. The following configurable test parameters should be included along with the common parameters mentioned in Table 2:

- Attenuation range
- Attenuation steps – increments in attenuation
- Number of attempts made by the reader at each attenuation level
- Separation x between the reader and tag

It should be noted that at least 100 read attempts are needed to get valid conclusions from data. For statistical accuracy, 1000s of read attempts on a single attenuation level should be performed.

3.2.3. Test Metric

Response rate is the ratio of the number of times a tag is read to the number of times the reader attempts to read the tag. Response rate is measured for increasing attenuation levels on both the forward and reverse channels. Attenuation is increased until the response rate goes down to 0%.

3.2.4. Our Experiment

We placed the tag and the reader in a non-noisy environment. We placed the tag in free-air at a separation of 34 inches above the reader antenna as shown in Figure 6. Since a bi-static antenna was used for reading tags, the tags were aligned with respect to the transmit antenna. It was observed that tags give better performance when they are aligned with the transmit antenna (see Section 4.2). Table 3 shows the parameters that were used for this experiment.

We developed a custom software module that interacts with the reader to measure response rate vs. attenuation. We have translated the attenuation levels in dB to distances in feet using the Friss transmission equation. These give us good, quantitative, relative performance data. The response rate was recorded until it goes down to 0%. We repeated the experiment with Class 1 tags also.

Table 3 Parameters for response rate vs. attenuation experiment

Test Parameter	Parameter Value
Environment	Free-air
Reader Model	Thingmagic Mercury 4
Reader software version	2.4.22
Antenna Type	Bi-static and circular polarized
Number of Antennas	1
Protocol of the tag	EPC Class 0 / EPC Class 1
Multi-protocol Reader settings	Scans only Class 0 / Class 1 depending on protocol of the tag
Cables to connect antenna and reader	Factory default
Maximum Power	32.5 dBm
Application	Custom software on reader
Separation between reader and tag	34 inches
Attenuation Range	0 to 20 dB
Attenuation Step Size	0.1 dB
Number of read attempts	5000

3.2.5. Results and Lessons Learned

Figure 7 shows an example of a response rate against attenuation for a commercial UHF RFID passive Class 0 tag. We performed 1 million read attempts over 200 different power settings to obtain this data.

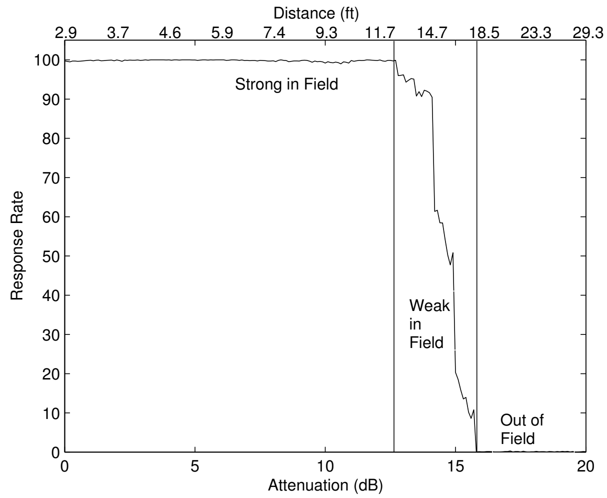

Figure 7 Typical Response rate vs. Attenuation for a tag

With Class 1 tags, there were two types of behavior that were prevalent. It was observed that there were two sections in Class 1 tags. Depending on the speed at which they respond the sections were called Class 1 "fast" and Class 1 "slow" tags. The Class 1 "fast" tags show a slightly different behavior in response rate from the Class 0 and Class 1 "slow" tags. Figure 8 shows the behavior that we had observed with Class 1 "slow" and Class 1 "fast" tags. This behavior was consistent across tags belonging to the same protocol and type.

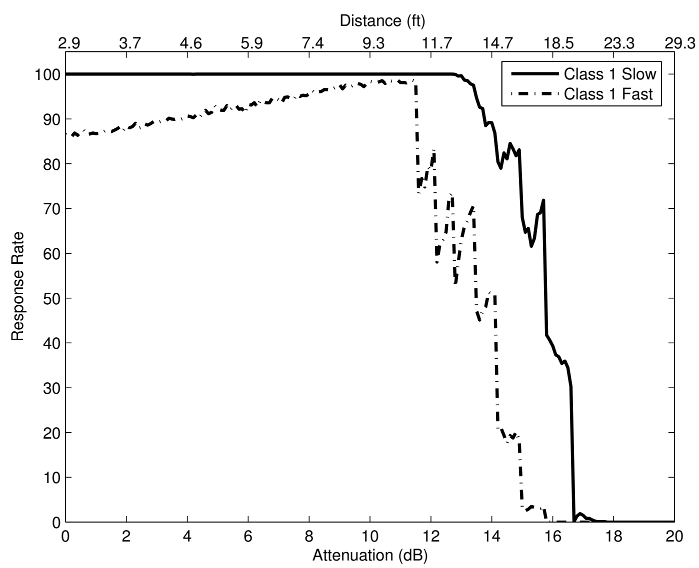

Figure 8 Class 1 Slow vs. Fast Response rate Behavior

From Figure 7 and Figure 8, we can observe three regions of operation: strong-in-field, weak-in-field, and out-of-field. Typically, the response rate is nearly 100% when the tags are in the strong-in-field region, but we have observed response rate go down to as low as 85% as shown by the Class 1 "fast" tag in Figure 8. When the tag is in the weak-in-field region, the tag exhibits a non-monotonic decrease in response rate. Figure 7 shows a tag that exhibits a relatively smooth decrease in the response rate but other tags as the Class 1 "fast" in Figure 8 have shown us a much more "bumpy ride down". In the out-of-field region, the tag does not respond to the reader queries and the response rate goes down to 0%. Early experiments showed response rates slightly larger than 0 %, which we determined to be the result of "ghost reads" (See Section 4.4).

3.3. Orientation Sensitivity

The radiation pattern of a RFID tag antenna determines the ability to read the tag in any orientation. This benchmark determines the ability of the tag to be read when the tag is rotated with respect to a single reader antenna.

3.3.1. Benchmark Objective

The objective of this benchmark is to determine the orientation sensitivity of a tag antenna.

3.3.2. Test Procedure

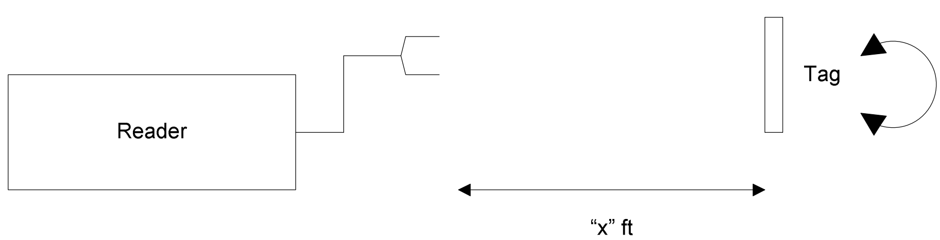

Figure 9 Test setup for orientation sensitivity

The tag and the reader should be separated at a fixed distance as shown in Figure 9. The tag should be rotated at fixed angle steps with respect to a single reader antenna along two perpendicular directions, the E-plane and H-plane for a dipole. For tags that are not based on dipole design, E-plane is considered to be the horizontal as the tags are shown in Appendix A. At each angle, measure the attenuation level at which the tag is unreadable. At each attenuation level, the reader attempts to read for a number of times before it determines that the tag is unreadable. The following configurable test parameters should be included along with the common parameters mentioned in Table 2:

- Fixed angle steps
- Number of attempts before declaring unreadable
- Attenuation step size – increments in attenuation
- Separation x between the reader and tag

Since the metric is a single attenuation value along a particular angle, it is recommended to perform at least a few hundred read attempts before assuming that the response rate has gone down to 0%. This benchmark should be done in non-noisy environments. Ideally, an anechoic chamber is preferred.

3.3.3. Test Metric

The power level of the reader is reduced until the response rate goes down to 0%. The attenuation level where tag becomes unreadable at various angles is the test metric.

3.3.4. Our Experiment

We suspended the tag at a distance of 34 inches above the reader antenna in free-air. To determine the radiation pattern or orientation sensitivity of different tags, the tag antenna was rotated in free-space at 20° steps along two perpendicular directions, the E-plane and H-plane for a dipole. The power level of the reader was attenuated until the response rate went to 0%. The response rate was assumed to be 0% only after 300 read attempts were performed at a certain attenuation level. Table 4 lists the parameters used for our experiment with Class 0 tags. Different readers for reading Class 0 and Class 1 tags were used.

Table 4 Parameters for orientation sensitivity experiment

Test Parameter	Parameter Value
Environment	Free-air
Reader Model	Matrics AR 400
Reader software version	03.01.09
Antenna Type	Bi-static and circular polarized
Number of Antennas	1
Protocol of the tag	EPC Class 0
Multi-protocol Reader settings	Scans only Class 0
Cables to connect antenna and reader	Factory default
Maximum Power	32.5 dBm
Application	Custom software on reader
Separation between reader and tag	34 inches
Fixed angle steps	20°
Attenuation Step Size	0.5 dB
Number of read attempts	300

3.3.5. Results and Lessons Learned

We have found that most of the tested tags can be classified into two categories: the "long, thin" tags and the "squarish" tags. The "long, thin" tags are typically a variant of a dipole or slot antenna e.g. Alien ALL-9250, Symbol I2010 (see Appendix A) while the "squarish" tags are dual dipole e.g. Symbol X2040, Avery Triflex (see Appendix A). We know that dipole antennas receive and emit radiation at best when perpendicular to its axis and not at all along that axis (called the null). A dual dipole tag has two dipoles oriented in perpendicular directions so that if we are looking at the null of one antenna, the second antenna is at the best receiving orientation [15]. The radiation patterns of these two tags are obviously different.

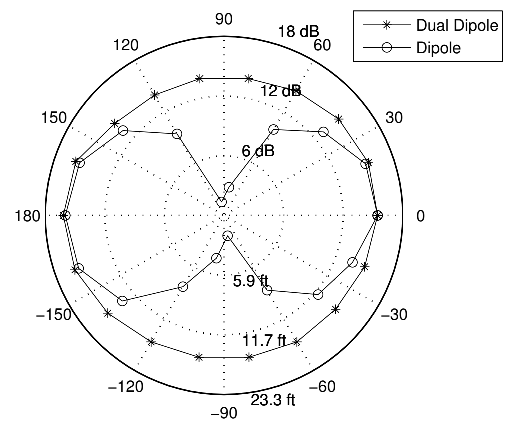

Figure 10 Orientation Sensitivity of Two tags along E-plane

Figure 10 shows the radiation pattern of a dipole tag and a dual dipole tag along E-plane. In H-plane, all the tested tag antennas had nearly circular patterns and thus we provide no sample data. In E-plane, these two types of radiation patterns were more prevalent. In Figure 10, the concentric circles are labeled with dB of attenuation (top) and an approximate distance in feet (bottom). It can be seen that dual-dipole tag performs equally well in all the directions whereas the dipole tag performs differently with varying orientations. Some of the dual dipole designs had a nearly uniform radiation patterns.

3.4. Variance of Tag performance

One might assume that two tags of the same model would exhibit nearly identical performance behavior. We have observed that this is not the case and tag performance varies considerably. In this benchmark, we set out to determine the variance of tags in terms of performance.

Before comparing a number of tags with each other, we present a way to compare the performance two tags. We consider response rate vs. attenuation (see Section 3.1) as a basic performance characteristic for a given tag. To compare tags against each other, it would be easier to find an identifiable point along this curve, such as 50% response rate. However, the non-monotonic nature of the response rate against attenuation behavior of tags makes it difficult to find such an identifiable point. Even the attenuation at which the response rate goes 0% requires large amount of reads to avoid observing a false 0% point. We believe that a better way to compare tags against each other a one-norm metric for minimization of areas between two curves was sufficient.

$$\Delta = \min_{\delta} \left\| f_1(x) - f_2(x+\delta) \right\|$$

f_1 and f_2 are the response rate vs. attenuation for two tags and Δ is the norm-metric that indicates the amount of shift δ needed so that the area between the curves is minimum. We found 1-norm to be sufficient. We used 1-norm metric to quantify the variance across a number of tags.

3.4.1. Benchmark Objective

The objective of this benchmark is to determine the variance of tag performance in the same model across a number of tags.

3.4.2. Test Procedure

The test setup shown in Figure 6 should be used to determine the variance of performance of tags. The tags should be oriented in the best possible orientation with the reader antenna. Measure the response rate vs. attenuation for the same attenuation range for a fixed number of tags of the same model. The attenuation should be increased until the response rate goes to 0% for each of the tags. The following test parameters should be mentioned in addition to the ones in Table 2:

- Best orientation of tag model
- Attenuation range
- Attenuation step size – increments in attenuation
- Number of attempts at each attenuation level
- Separation x between the reader and tag
- Number of tags in the tag model

It is recommended that orientation be determined in (Theta, Phi) as shown in Figure 11. The orientation specifies the angle of the tag with respect to the reader antenna.

For statistical accuracy, the number of tags tested in the same model should be high. It is recommended that the variance is measured across at least 50 tags of each model. Higher the number of attempts, higher is the statistical accuracy of the data collected for each tag.

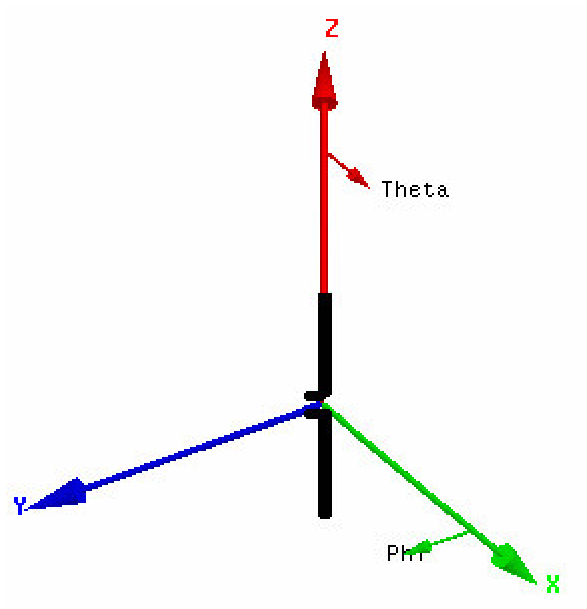

Figure 11 Determination of angle of the tag with respect to reader antenna

3.4.3. Test Metric

The 1-norm metric quantifies variances across a number of tags of the same model. Once we measure the response rate vs. attenuation for all the tags in a tag model, they are ranked to obtain 0% corresponding to worst performing tag to 100 % corresponding to the best performing tag in that model. The 1-norm metric can be used across any two tags (say 0% and 100% or 10% and 90% or 20% and 80%) to determine the variance across that band. The 1-norm metric quantifies the variance in performance of all the tags within the chosen range in that particular model.

3.4.4. Our Experiment

We placed the tags from the reader at a separation of 34 inches in free-air. To determine the variance in performance of tag models, we measured the response rate vs. attenuation at least for 100 tags of a single tag model. The tags were oriented in the best possible orientation (0, 0) and the response rate against attenuation is measured in the experimental setup shown in Figure 6. To expedite the testing process, a small sample of tags on each model was first compared to identify an interesting region of power levels for each tag model. The interesting region for a tag model would include all the three regions in the response rate for most of the tags of that model (strong-in-field, weak-in-field, and out-of-field). Then for each of the tags in that model, we varied the power levels in steps of 0.5 dB through the interesting region and performed between 50 and 100 read attempts at each of the power setting. Table 5 consolidates all the parameters used for this experiment.

Table 5 Parameters for variance experiment

Test Parameter	**Parameter Value**
Environment	Free-air
Reader Model	Thingmagic Mercury 4
Reader software version	2.4.22
Antenna Type	Bi-static and circular polarized
Number of Antennas	1
Protocol of the tag	EPC Class 0 / EPC Class 1
Multi-protocol Reader settings	Scans only Class 0 / Class 1 depending on protocol of the tag
Cables to connect antenna and reader	Factory default
Maximum Power	32.5 dBm
Application	Custom software on reader
Separation between reader and tag	34 inches
Best orientation angle	(0, 0)
Attenuation Range	Interesting region varies from tag to tag
Attenuation Step Size	0.5 dB
Number of read attempts	100
Number of tag in a model	At least 100

3.4.5. Results and Lessons Learned

The above experiment was done across 9 different commercial tag models. In this section we discuss three tag models, model with best variance (low), model with worst variance (high), and also a model whose variance was typical among the 9 tag models that we compared. We start with the discussion of the model with typical variance in performance among the tested 9 commercial tags.

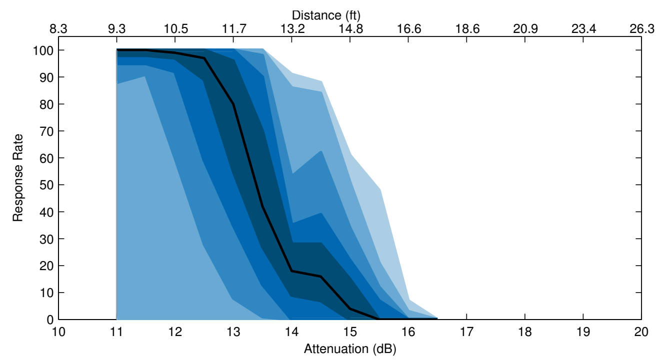

Figure 12 Typical variance of performance among tested commercial tag models

Figure 12 shows the typical amount of variance in performance that one can expect from a commercial tag model. In Figure 12, we calculated various ranges in tag performances. All the tags tested in each tag model were ranked from 0% corresponding to worst performing tag to 100 % corresponding to the best performing tag in that model. The black line depicts the median tag (50%) in this tag model. The darkest band near the median tag shows the middle 40 % of tags of the tag model that we had tested. The middle 70% is shown in the next lighter color band. The middle 87% and 98% are shown in the next two bands. The lightest band encompasses all the tags that are tested.

In the Figure 12, there is a considerable performance difference between the best performing tag and the worst performing tag. It can be seen that the lightest band extends all the way up to 11 dB. This means that the bottom 1 % of the tags were unreadable at 11 dB of attenuation while a number of tags are readable up to 16 dB.

Figure 13 and Figure 14 show the best tag model and worst tag model among the tested 9 commercial tag models. We analyzed all the variance plots observing the following two qualities:

1. Well performing tag models are readable in strong-in-field region at high attenuation levels. This represents models in which majority of tags are readable in strong-in-field region at high attenuation values.
2. Narrow bands denote lower variation in performance of that tag model.

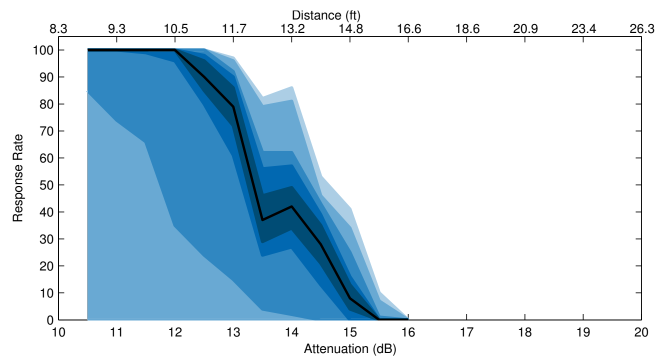

Figure 13 Best variance of performance among tested commercial tag models

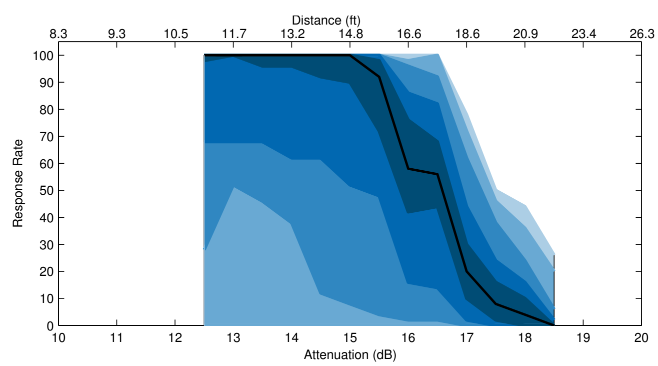

Figure 14 Worst variance of performance among tested commercial tag models

As shown above, we observed considerable variation in performance across tag models also. It should be noted that in real-world situations, the worst performing tag limits the performance. Thus, even though the tag model in Figure 14 is readable to high attenuation levels, the variance is poor and hence limits performance. Among the 9 commercial tag models tested, even the best performing tag model had a variance of about 3 dB.

Apart from quantifying the variance, the end users can use this data to arrive at their own conclusions. For example, an end-user might be concerned about the number of tags satisfying a minimum performance level from a tag model. While another end user might be interested in the consistency of the tag performance from a model to prevent a reader from reading tags going through an adjacent dock door. Also, one can quantify the variance values using the 1 norm-metric.

3.5. Read Rate

Read rate is defined as the ratio of the number of times a tag is read to the number of seconds read was performed. This is second of the two fundamental characteristics of the RFID tag-reader system and it measures the speed at which the reader can read a tag. The benchmarks that are based on read rate metric are read rate in isolation, tag read rate in population, time to first read, and total tag read rate.

3.5.1. Read Rate in Isolation

When the reader detects only a single tag, the tag is said to be in isolation. This benchmark is intended to measure the speed at which a tag in isolation is read using a single reader antenna.

3.5.1.1. Benchmark Objective

The objective is to find the speed at which a reader can read a tag in isolation using a single reader antenna.

3.5.1.2. Test Procedure

The tag should be placed in the setup shown in Figure 6. A median-performing tag identified for each tag model from performing the study as in Section 3.4 should be used for this benchmark. The tags should be oriented in the best possible orientation. The reader should be programmed to read tags as many times as possible within certain duration of time. The benchmark is repeated for a fixed number of times for each model.

It should be noted that some of the settings on a reader affects the read rates. In certain readers, there is a factor called "timeout" which when varied would give different results for read rates. Factors similar to timeout that affect the read rates should be included as parameters. The following configurable test parameters that are to be mentioned in addition to the ones in Table 2:

- Duration of Time
- Best orientation of tag
- Reader Settings – Timeout factor
- Number of repetitions
- Separation x between the reader and tag

For greater statistical accuracy, the duration of time should be higher. It is recommended that the duration of time should be at least 30 seconds. Also, it is recommended the reader settings are determined from the guidelines given with the reader.

3.5.1.3. Test Metric

The test metric is the number of tag reads recorded through the entire duration of the time. Read rate in isolation should be computed as the ratio of the number of times a single tag is read to the number of seconds read was performed.

3.5.1.4. Our Experiment

We placed the tag at a distance of 34 inches from the reader antenna. We measured the number of times the tag was read over duration of 60 seconds. The reader was set to search only for Class 0 or Class 1 tags, depending on the type of tag being read and the timeout (a configurable parameter in the reader) was determined using the reader guidelines. The experiment was repeated for 10 times for each tag model. Table 6 lists the test parameters for the experiment conducted.

Table 6 Parameters for read rate in isolation experiment

Test Parameter	Parameter Value
Environment	Free-air
Reader Model	Thingmagic Mercury 4
Reader software version	2.4.22
Antenna Type	Bi-static and circular polarized
Number of Antennas	1
Protocol of the tag	EPC Class 0 / EPC Class 1
Multi-protocol Reader settings	Scans only Class 0 / Class 1 depending on protocol of the tag
Cables to connect antenna and reader	Factory default
Maximum Power	32.5 dBm
Application	Custom software on reader
Separation between reader and tag	34 inches
Best orientation angle	(0, 0)
Duration of time	60 seconds
Timeout factors	Reader guidelines Timeout factor: 250 ms
Number of repetitions	10

3.5.1.5. Results and Lessons Learned

The read rates observed with three different commercial readers are shown in Table 7. One of the interesting findings was that we found two types of Class 1 tags "Slow" and "Fast". The tag read rates were consistent within the same type across tag models, but the difference in the tag read rates across the types were considerable. Class 0 tags and Class 1 "Slow" tags had similar tag read rates. The standard deviation of the read rates indicates that the read rates are robust within a tag type.

Table 7 shows that absolute value of read rate across various reader manufacturers changes to as much as 250 %. However, different readers showed similar trends. Thus, the values of tag read rates were dependent on the tag- reader system.

Table 7 Read rates in isolation

Tag Class	Type	Read Rate	Standard Deviation
Class 1	"Slow"	7.0	0.24
Class 1	"Fast"	24.1	1.29
Class 0	-	6.5	0.04

It should be noted that some readers implement a feature for EPC Class 1 protocol called "Global Scroll". This feature is an implementation of a command called "ScrollAllID" defined in the Class 1 protocol. This feature bypasses collision detection in the readers, and thus the read rates could be as high as 300 reads per second. Since the "Global Scroll" avoids collision detection, it is not generally used in practice. When the reader tries to read multiple tags in the field with a "Global Scroll" feature, all the tags in the field will respond at the time resulting in collisions. This means the reader would detect the tag with the strongest response signal. Table 7 shows the read rates variation from 6 to 60, which is considerably smaller than the 20 to 1000 cited, by some vendors [19].

3.5.2. Read Rate in Population

In general, there can be multiple tags present in the reader's read field. This is called *tags in population*. Typical applications include reading tagged items that are in a container and reading tagged containers in a pallet. This benchmark analyzes the effect of tags in population for Class 0 and Class 1 tags. As seen in Section 2.6, Class 0 and Class 1 protocol follow different approaches in handling collision detection and resolution, which becomes apparent with this benchmark.

3.5.2.1. Benchmark Objective

The objective of this benchmark is to determine the speed at which tags are read and also the speed of each individual tag when tags are in population using a single reader antenna.

3.5.2.2. Test Procedure

The reader field is populated with as many tags as possible. Placing the tags close to each other was challenging because of the tags close to each other can detune themselves or the tags can mask each other. The tag size and interference between the tags being unique for each tag model, the placement in the space was also unique and thus the results are not completely reproducable.

As we know, population of tags can occur in a wide variety of scenarios. Hence it is difficult to generalize a test setup for tags in population. Thus, we explain the approach we have adopted and follow it up with the different test metrics developed from the experiment. Only one reader antenna should be used for this benchmark. As mentioned in Section 3.5, the reader settings affects the read rate and should be noted along with the parameters. The following parameters should be noted down in addition to the common test parameters (Table 2):

- Test Setup
- Number of tags in population
- Reader settings – Timeout factors
- Duration of time
- Number of repetitions

3.5.2.3. Our Experiment

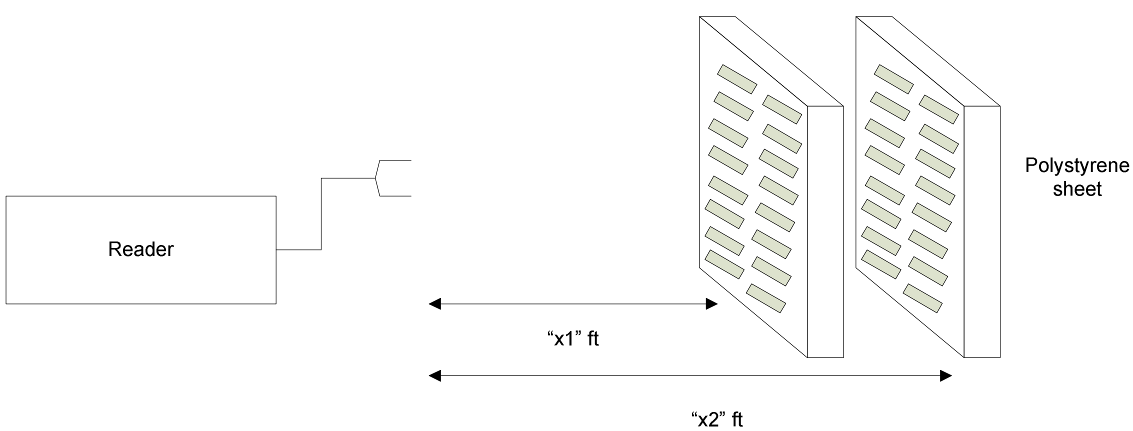

Figure 15 Class 0 tags and Class 1 tags setup for read rates in population experiment

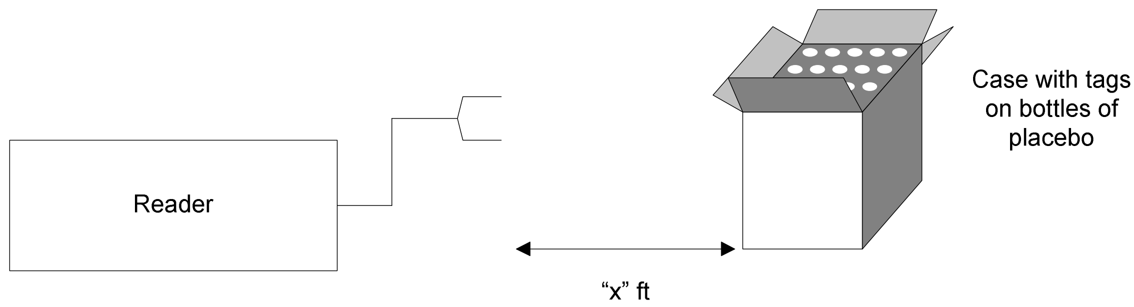

Figure 16 Class 0 item-level tags setup for read rates in population experiment

Table 8 Parameters for tags in population experiment

Test Parameter	Parameter Value
Environment	Free-air
Reader Model	Thingmagic Mercury 4
Reader software version	2.4.22
Antenna Type	Bi-static and circular polarized
Number of Antennas	1
Protocol of the tag	EPC Class 0 / EPC Class 1
Multi-protocol Reader settings	Scans only Class 0 / Class 1 depending on protocol of the tag
Cables to connect antenna and reader	Factory default
Maximum Power	32.5 dBm
Application	Custom software on reader
Duration of time	5 minutes
Number of repetitions	10

This experiment was done with three different tag models, a Class 1 tag, a Class 0 tag, and a Class 0 item tag. The Class 0 and Class 1 tags were placed on two polystyrene sheets placed at 36 and 48 inches respectively as shown in Figure 15. The Class 0 item tag with 48 item-level tags on bottles of placebo stacked in a cardboard box as shown in Figure 16. The experiment was repeated 10 times for each of the tag models. The test metrics time to first read (TTFR), total tags read rate, and tag read rate in population deduced from this experiment are described along with the various inferences about the underlying protocols. The test parameters common for all the tag models are consolidated in Table 8. The three different test setups and reader settings used in each setup is listed in Tables 9, 10, 11. Our experiment showed some consistent trends in the underlying air-interface protocols for passive RFID tags.

Table 9 Parameters for first test setup – population experiment

Protocol	Class 0
Test Setup	Two Polystyrene sheets separated from reader antenna at 34 inches and 48 inches respectively. Tag locations are such that maximum number of tags is readable.
Tags in Population	120
Reader Settings	Timeout factor: 10 seconds

Table 10 Parameters for second test setup – population experiment

Protocol	Class 1
Test Setup	Two Polystyrene sheets separated from reader antenna at 34 inches and 48 inches respectively. Tag locations are such that maximum number of tags is readable.
Tags in Population	140
Timeout Factors	Timeout factor: 10 seconds

Table 11 Parameters for third test setup – population experiment

Protocol	Class 0 Item
Test Setup	48 item-level tags on bottles of placebo stacked in a cardboard box
Tags in Population	48
Timeout Factors	Timeout factor: 600 ms

3.5.2.4. Test Metrics

3.5.2.4.1. Time to First Read (TTFR)

Each of the tags takes different amount of time to read. Some were read within a fraction of second whereas others were not read in the allotted time. Time to First Read (TTFR) defines the time it takes for the n^{th} tag to be a read when there are multiple tags in the reader field.

3.5.2.4.2. Total Tag Read Rate

In order to find the throughput of the tag-reader system, the total number of reads in population is measured. Total tag read rate should be measured as the ratio of the number of times any tag in the population is read to the number of seconds the read was performed.

3.5.2.4.3. Individual Tag Read Rate

When the tags are read in population, each tag is read at a different rate. Individual tag read rate in population should be measured as the ratio of the number of times each of the individual tag is read to the number of seconds the read was performed in population.

3.5.2.5. Results and Lessons Learned

Although different setups were used for Class 0 and Class 1 tags, this experiment revealed trends on the underlying technology and the protocols for passive RFID tags were inferred. We compare the general trends of Class 0, Class 1 tags based on the metrics mentioned above.

3.5.2.5.1. Time to First Read (TTFR)

Time to First Read was measured for each of the tags detected across all the repetitions. The maximum allotted time for the experiment was 5 minutes. Figure 17 shows the average TTFR for a Class 0 and Class 1 tag (the Class 0 tag which was on placebo is not shown). The total read time period was limited to 300 seconds (5 minutes) and if a tag was not read after 300 seconds, we assigned a value of 1000 seconds as TTFR (so that the tag could be plotted). A horizontal line representing the total duration of read for each experiment is also shown for perspective. It should be noted that although some of the tags were not read in a repetition, all the tags were read at least once in at least one of the repetitions.

Figure 17 shows the average time taken for the identification of tags of both Class 0 and Class 1 tags. Although there was a small variance in the time measured for each of the tags across repetitions, it was not plotted to keep the figure clear. The standard deviation is small and does not affect any conclusions drawn from the experiment. Figure 17 shows that for the first two-thirds of the tags, the TTFR of Class 0 is considerably smaller than the TTFR of Class 1. This matches the general observation that Class 0 generally performs much better than Class 1 in population.

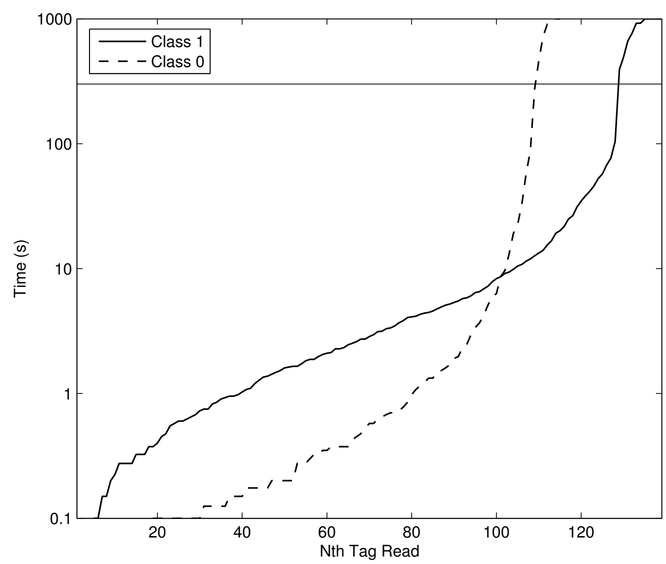

Figure 17 Time to First Read (TTFR) for Class 0 and Class 1

Also, it can be seen from Figure 17 that for both Class 0 and Class 1 the first few tags were read quickly, about two-thirds of the tags were read linearly in time and the last one-thirds of the tags took more time to read matching exponential growth in TTFR. In general, for all the regions of the plot Class 0 tags seemed to perform better than Class 1.

3.5.2.5.2. Total Tag Read Rate

The total tag read rate indicates the overall throughput of the tag and reader system. We observed total tag read rate for Class 0 tags to be between 4.7 and 5.8 times the total tag read rate for the Class 1tags.

Table 12 Total Tag Read Rate in Population

Tag Type	Total Tag Read Rate	Standard Deviation
Class 1	45.6	0.99
Class 0	265.5	8.77
Class 0 Item	212.3	4.80

As can be seen, in population the Class 0 total tag read rate is considerably higher than Class 1 tags. In contrast for the isolation case, the Class 0 tag read rate was smaller than Class 1 tag read rate as seen in Section 3.5.

3.5.2.5.3. Individual Tag Read Rate in Population

Figure 18 shows the individual tag read rate in population for three different experiments on tags in population. We sorted the tags in descending order of individual tag read rate in population.

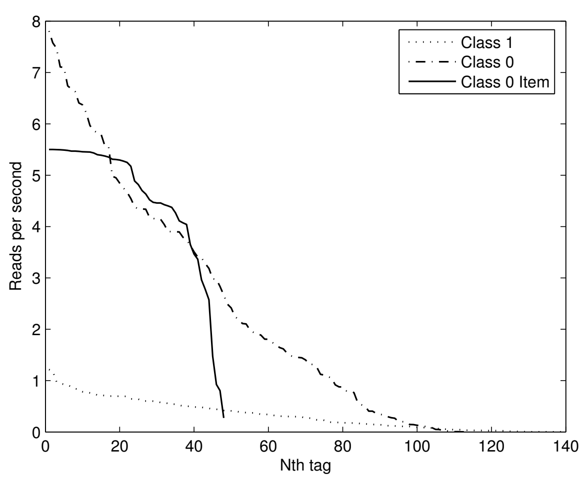

Figure 18 Tag Read Rate in Population

In the Figure 18, Class 1 tag and Class 0 tag follow the same nature with Class 0 tag being faster. The nature of the Class 0 item tag is follows considerably different curve. We speculate that the concave nature of Class 0 item indicates that most of the Class 0 item tags are in the strong-in-field region, while only a few where in the weak-in-field region. The nature Class 0 and Class 1 tags indicate that only a few where in the strong-in-field region and most were in the weak-in-field region.

Another inference that can be made about Figure 18 is to compare the values of read rate to that in the Table 1. It can be seen that the individual read rates of Class 0 tags that are in the strong field region in the population case is almost close to the Class 0 tags in isolation. In the case of Class 1 tags, the read rate in population is considerably smaller than the read rate in isolation (decreased from 24 to 1).

Our population experiments show that the read rates of Class 0 tags scale much more gracefully than Class 1 tags. We observed through all our population experiments that reading last few tags takes considerably longer time than reading the first. This may result in unfortunate consequences when reading large number of tags, whether it is in item-level tags or cases in a pallet.

3.6. Read Performance near Metal and Water

Up to now, we have discussed benchmarks that were developed in “free air”. Free air benchmarks can be used as baseline measurements for tag performance. But in real world situations, the tags are attached to various materials that have different characteristics. The presence of a material near tags changes the characteristics of the antennas. Some of the materials that are common and pose greater challenges to tag are metal and water. Water and metal affects tag performance in a number of ways. They provide multi-path, create fading zone. In fact, metals can be used to boost the performance of tags. The presence of high-dielectric material in the near field of the tag causes detuning of the antenna, so the antenna would resonate at a lower frequency. The presence of material changes the impedance bandwidth of the antenna and reduces the power transfer efficiency. The benchmarks in this section are aimed at studying the effects of tag performance near these materials.

3.6.1. Performance in front of Materials

3.6.1.1. Benchmark Objective

The objective is to determine the maximum distance at which a tag is readable, when there is a small separation between the material and the tag.

3.6.1.2. Test Procedure

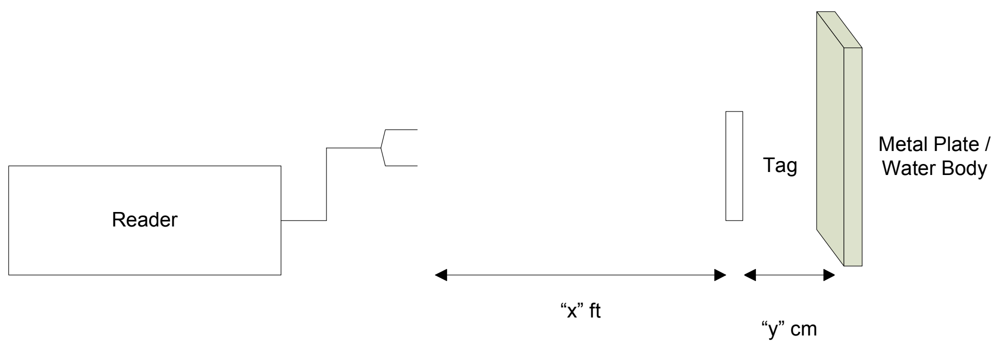

Figure 19 Test setup for performance in front of materials

The tag-reader setup given in Figure 19 should be used. The median tag from each tag model should be oriented at their best possible orientation in front of a metal plate whose size is comparable to wavelength. If the testing is done in front of water, a water body whose size is again comparable to wavelength should be used. The attenuation at which the tag becomes unreadable should be measured at various separations from the metal/water.

Small separations between the tag and the material are the most interesting and most useful regions where the benchmark should be measured (as the tags are generally stuck on the materials). The attenuation is increased slowly until the tag becomes unreadable. This attenuation value should be measured for different separation between tag and material. The following test parameters should be mentioned in addition to those in Table 2:

- Separation Range
- Separation step size
- Number of attempts done by the reader
- Attenuation step size – increments in attenuation
- Best orientation of the tag
- Separation between the reader and tag

Since the metric is an attenuation value at a particular separation, it is recommended that at least a few hundred read attempts are to be performed before assuming that the response rate has gone down to 0%. For statistical accuracy, the number of attempts should be higher. The testing should be done in non-noisy environments. Ideally, anechoic chamber is preferred.

3.6.1.3. Test Metric

The test metric is the power level of the reader at which the response rate goes down to 0%.

3.6.1.4. Our Experiment

We placed the tag in front of the reader antenna at a distance of 3 feet as shown in Figure 6. The tag and the material were separated in free-air. The material was a large flat piece of steel ($\approx 2\lambda \times 1.5\lambda$) for the experiment in front of metal while it was a 10-gallon aquarium filled with water for the experiment in front of water. The separation was varied from 0 to 2 cm in steps of 2.5 mm from the material. It should be noted that the thickness of the glass plate (0.55 cm) has to be taken into account when the experiment is done in front of an aquarium. The attenuation at which the tag became unreadable at each separation was noted. Table 13 lists the parameters that were used for both the experiments in front of metal and water. Different readers were used for reading Class 0 and Class 1 tags.

Table 13 Parameters for read performance in front of metal / water

Test Parameter	**Parameter Value**
Environment	Free-air
Reader Model	Class 0 – Matrics AR 400 Class 1 – Alien 9780
Reader software version	Class 0 – 03.01.09 Class 1 – 3.7.3
Antenna Type	Bi-static and circular polarized
Number of Antennas	1
Protocol of the tag	EPC Class 0 / EPC Class 1
Multi-protocol Reader settings	Scans only Class 0 / Class 1 depending on protocol of the tag
Cables to connect antenna and reader	Factory default
Maximum Power	32.5 dBm
Application	Custom software on reader
Separation between tag and reader	34 inches
Separation range from materials	Metal – 0 to 2 cm Water – 0.55 cm to 2.55 cm
Separation Step size	0.25 cm
Number of attempts	100
Attenuation Step size	0.1 dB
Best orientation of the tag	(0,0)

3.6.1.5. Results and Lessons Learned

Tags in front of metal

Figure 20 shows the comparison of performance for 4 Class 0 tags in front of metal.

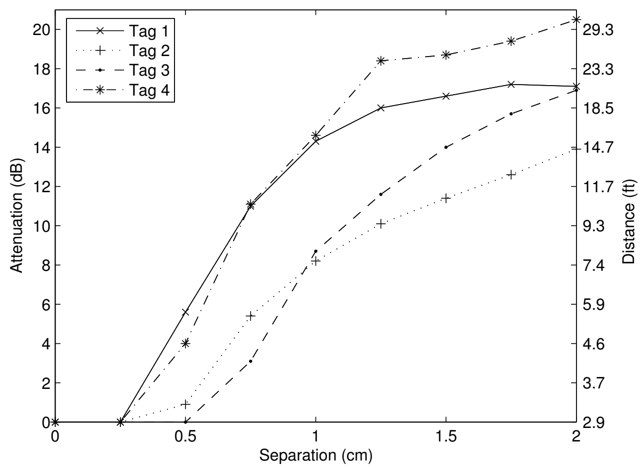

Figure 20 Tags in front of metal

As seen in the Figure 20, Tag 1 and Tag 4 have better performance than the other two tags starting from a separation of 5 mm. It should be noted that Tag 1 design is supposed to work better in reflective environments and as can be from the experiments it turns out to be the best in front of metal among the Class 0 tags compared. The performance of Tag 4, a dual dipole design is comparable to Tag 1. Even in our free-air experiments, Tag 4 was a fundamentally better tag compared to other tags.

It can be seen that, all the tested tags were unreadable at a separation of 2.5 mm from metal. Some of the tags had a good performance at a separation of even 5 mm from metal.

Tags in front of water

Figure 21 shows a selection of Class 1 tags that we had tested in front of water. As can be seen, Tag 4 is the best performing in front of water at a distance of 0.8 mm. But it should be noted that the same tag is not the best performer in free air. Tag 3 is a better performer in free air but is highly detuned when it comes in front of water. Tag 2 is the worst among the compared Class 1 tags. This showed that some of the tags were tuned to work in front of water but it should be noted that all the tested tags did not work at a separation of 0.55 mm from water (when the tags were directly on the container).

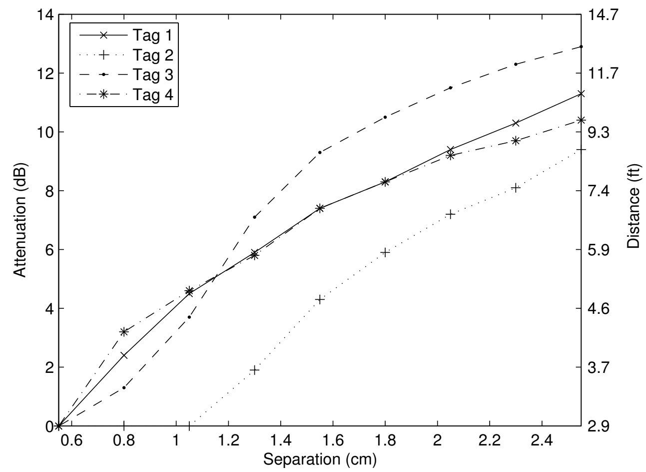

Figure 21 Tags in front of water

3.6.2. Frequency Dependent Performance

As seen in Section 3.6, presence of materials near tags affects the frequency response of the tags.

3.6.2.1. Benchmark Objective

The objective of this benchmark is to determine the changes in the frequency response of tags near materials.

3.6.2.2. Test Procedure

The same test procedure described in Section 3.6.1.2 should be used for this benchmark. The tag should be read at a fixed frequency and then the frequency is varied. The attenuation at which tag is unreadable is measured across all the frequencies of interest. The following parameters should be added along with the default parameters mentioned in Section 3.1:

- Separation Range
- Separation step size
- Number of attempts done by the reader
- Attenuation step size – increments in attenuation
- Fixed frequencies of interest
- Separation between the reader and tag

- Best orientation of the tag

Higher the number of frequencies under consideration, higher would be the resolution of the frequency response.

3.6.2.3. Test Metric

The test metric is the attenuation at which the tag became unreadable at each of the frequencies under consideration.

3.6.2.4. Our Experiment

Table 14 Parameters for frequency response in front of materials

Test Parameter	**Parameter Value**
Environment	Free-air
Reader Model	Thingmagic Mercury 4
Reader software version	2.4.22
Antenna Type	Bi-static and circular polarized
Number of Antennas	1
Protocol of the tag	EPC Class 0 / EPC Class 1
Multi-protocol Reader settings	Scans only Class 0 / Class 1 depending on protocol of the tag
Cables to connect antenna and reader	Factory default
Maximum Power	32.5 dBm
Application	Custom software on reader
Separation between tag and reader	34 inches
Separation range from materials	Metal – 0 to 2 cm Water – 0.55 cm to 2.55 cm
Separation Step size	0.25 cm
Number of attempts	1000
Attenuation Step size	0.1 dB
Best Orientation of the tag	(0,0)
Frequencies	902, 915, 928, 955 MHz

The experiment described in Section 3.6.1.4 was repeated when the reader was programmed to do the reads in a single, fixed frequency and then the frequency was varied. The parameters used for this experiment are listed in Table 14.

3.6.2.5. Results and Lessons Learnt

Tags in front of Metal

It was seen in Chapter 2 that the ISM band in UHF frequencies varies between different countries. The ISM band frequencies in various countries are 860-868 MHz in Europe, 902 to 928 MHz in USA, and 950 to 956 MHz in Japan.

Most of the antennas that are used for tags are resonant antennas. It is widely known that the presence of high dielectric like water near antennas changes their resonant frequency. Thus, if a tag is to be read globally, they should perform well across all these frequencies. In this benchmark, the experiment was performed at 902 MHz, 915 MHz, 928 MHz, and 955 MHz. We measured the attenuation at which the response rate goes down to 0% across different frequencies. Figure 22 shows the frequency dependent performance of two different tags in front of metal.

It should be noted that Tags 1 and 2 are readable at all the frequencies in free-air. In front of metal, Tag 1 performs better at lower frequencies and degrades a little bit as the frequency is increased. This is typical performance of most of the tags near metal. However, as can be seen with Tag 2 there are drastic changes in performance with increase in frequency. At 2 cm separation, Tag 2 performs better than Tag 1 at 902 MHz but as can be seen, Tag 2 is unreadable at 955 MHz near metal. This means that say if a metal product with Tag 2 on it is shipped from USA to Japan. It would be readable and would work when it is shipped but would be completely unreadable in Japan.

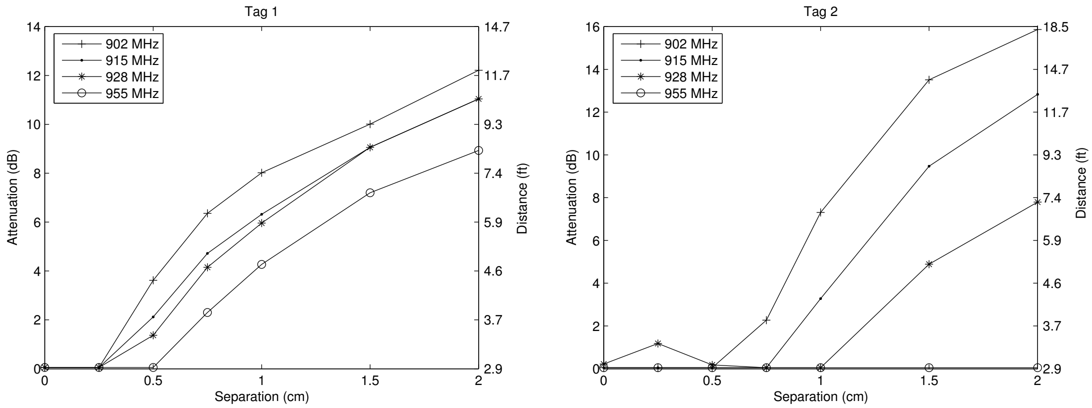

Figure 22 Comparison of tags in front of metal based on Frequency

Tags in front of water

A similar observation was made with the above tags when they are in front of water. However, we observed one more interesting behavior of the frequency response in front of water.

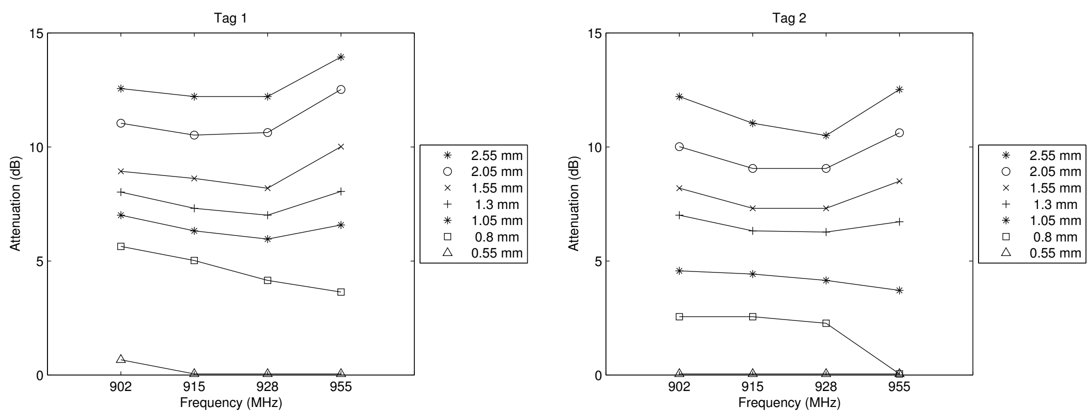

Figure 23 Comparison of tags in front of water based on Frequency

Figure 23 shows two tags that have a similar behavior but different performance levels. In Figure 23 the performance of the tags at different separation from water container are shown. It can be clearly seen that both the tags have good performance at 955 MHz at a separation of 2.55 mm. As the separation is decreased, the performance degrades rapidly at 955 MHz compared to moderate decrease at other frequencies. This is a common behavior that we have observed for all the tags when the tags are in front of water. The performance rapidly decreases at higher frequencies whereas there is comparatively gradual decrease in performance at lower frequencies.

Another observation about performance is that at small separations, Tag 1 still has some link margin at which the tag is still readable. Thus, it is quite evident that Tag 1 is better in terms of performance than Tag 2. It is possible to arrive at the same conclusion by generating the attenuation plots similar to Figure 22.

Frequency dependent analysis gives insight into the detuning effects of the antennas, permits a way to analyze better antenna designs for specific materials, and provides a performance criterion through which a globally visible tag can be developed.

3.7. Write Performance

Before discussing about the write performance, it should be noted that only certain types of tags can be written. As seen in Section 2.6, EPCglobal Class 1 protocol is meant for read/write tags. A few manufacturers have extended Class 0 protocol to build a read/write tag based on their own proprietary protocol called Class 0+ and Class 0 Read/Write. Thus, the tags that we could test for writing ability are Class 0+ and EPC Class 1 Generation 1 tags.

The constraints for writing tags are greater than reading tags. For example, the tag requires more power for writing purposes. Hence the writing range is much smaller than the reading range. When the tag is being written there should be only one tag in the write field at a time. It takes more time to write a tag and there is a possibility of failure to write also. The benchmarks for write performance were write failure rate and time it takes to write tags.

3.7.1. Benchmark Objective

The objective is to measure the reliability and the time it takes for writing to tags.

3.7.2. Test Procedure

The tag should be separated from the reader antenna at a distance recommended by the reader guidelines. Ideally, an anechoic chamber is preferred. In all cases, at least a non-noisy environment for placing tags is crucial for good performance with writing to tags. Each tag is written with different IDs so that a wide variety of combinations are written to the memory in tag.

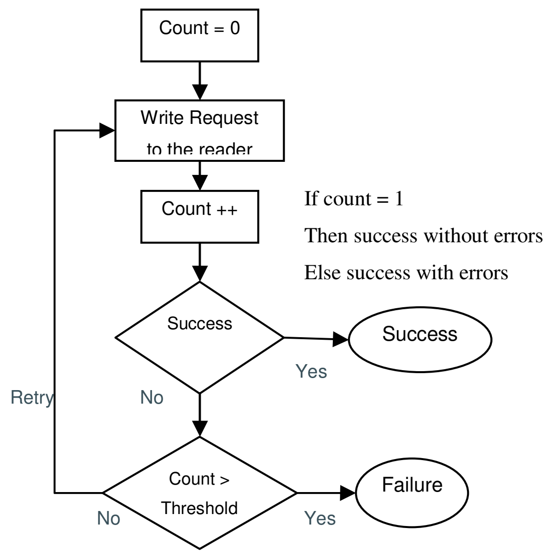

Figure 24 Write Attempt Procedure

The tags should be written using the procedure shown in Figure 24. First, a request to the reader through the API to write a tag is performed. This is termed as *write request.* After the request, the tag was verified if it was correctly written. If the write was not successful, it is declared as a *write error*. If a write error was encountered, write request is repeated for a specified number of times called threshold repetitions. If all the write requests did not succeed, then it is declared as a *write failure*. The entire process starting from the first write request and ending with a write success or a write failure is termed as *write attempt*. The write attempts should be timed and also the outcome of each of the write requests. The following parameters are essential and should be mentioned in addition to the default parameters mentioned in Table 2:

- Separation between the reader and tag
- Number of tags

- Threshold repetitions
- Number of IDs to be written

It is recommended that in each tag model at least 10 tags have to be tested to make valid conclusions from the data.

3.7.3. Test Metrics

3.7.3.1. Write Success Rate

Write Success rate is defined as the ratio of the number of tags that resulted in a write success to the total number of tags tested. This would indicate the number of tags that are writeable.

3.7.3.2. Percent successful write requests

It is the ratio of the sum of write-requests that were successful to the number of write-requests performed for that tag.

3.7.3.3. Write Timing

The average time of all the successful write attempts of a tag is called *write timing*.

3.7.4. Our Experiment

The tags that we used for writing were all Class 1 tags because the reader did not support writing to other protocols at the time of testing. The tags and reader were separated in free-air. The tags were placed at a separation of around 19.5 inches above the reader antenna. The reader guidelines recommended that tags be placed between 1 and 2 feet from the reader antenna. Ten different tags from each model were selected for our experiment. Each tag was written with ten different IDs. The IDs included all zeros, all ones, alternating ones and zeros, and the remaining were randomly selected IDs. Table 15 shows the parameters that were used for our experiment on write performance of tags.

Table 15 Parameters for write performance

Test Parameter	Parameter Value
Environment	Free-air
Reader Model	Thingmagic Mercury 4
Reader software version	2.4.22
Antenna Type	Bi-static and circular polarized
Number of Antennas	1
Protocol of the tag	EPC Class 1
Cables to connect antenna and reader	Factory default
Maximum Power	32.5 dBm
Application	Custom software on reader
Separation between tag and reader	19.5 inches
Number of tags	10
Threshold repetitions	10
Number of IDs written	10

3.7.5. Results and Lessons Learned

3.7.5.1. Write Success Rate

Among the tested 4 different Class 1 tags, two tags performed at 100% write success rate. Another tag performed as low as 80 % write success rate.

3.7.5.2. Percent successful write requests

Among the tested Class 1 tags, only one had a Percent successful write request greater than 95%. Also, another tag had Percent successful write request as low as 35 %.

3.7.5.3. Write Timing

Write timing had a direct correlation with the number of write attempts it takes for a successful write. Again one of the tags had a consistent low write timing of 0.48 s whereas another Class 1 tag had a write timing of 2.12 s.

It should be noted that we are attempting to write tags at least 10 times before declaring a tag as a write failure. Therefore, the write timing values are on the order of seconds. If lesser write requests were used before a tag is declared as a failure then it would result in better timings but at the cost of less success rate. It is likely that label printers that are used to write tags in production environments will have lesser number of maximum write requests until a tag is declared dead. In fact, the write success rate variation observed by the companies using label printers in practice ranged from 95% to as low as 70 %.

One of the conclusions that were noticed out of the write performance was that none of the tags performed flawlessly. It was observed that with more readers in the vicinity, the interference from the other readers causes writing to be more difficult. In fact, the electrical interference from other devices has been observed to affect writing to tags.

4. Interesting Observations

RFID tags are used for several applications in the supply chain ranging from tracking cases/pallets to tracking items. The cases/pallets are tracked generally using “large tags” (> 2x2 inches) and items inside a case are tracked using “item-level tags” (< 2x2 inches). In general, large tags have measured maximum read distances of up to 20 feet [5] while small tags have measured maximum read distances of up to 7 feet [6]. Apart from the read distances, we have observed certain interesting characteristics of the tag-reader system for these two kinds of tags.

In this chapter, we present observations that would help to understand the limitations in the performance of the tag-reader system for item-level tags. We also discuss the other benchmarks on the RFID system and interesting observations that we have noticed with passive RFID system.

4.1. Transmit and Receive Channel Sensitivity

The aim of transmit and receive channel sensitivity experiment was to determine how much the passive RFID system performance is dependent on the forward channel (reader to tag) and the reverse channel (tag to reader). The results indicate the constraints involved in the tag-reader system in the current UHF passive RFID systems. This experiment also provides a way to verify whether attenuating the transmit power level is an effective way to simulate distance. Results show that there are significant differences between large tags and item-level tags.

4.1.1. Objective

The objective of this experiment is to determine the sensitivity of performance to attenuation on forward and reverse channel for large and item-level tags.

4.1.2. Test Procedure

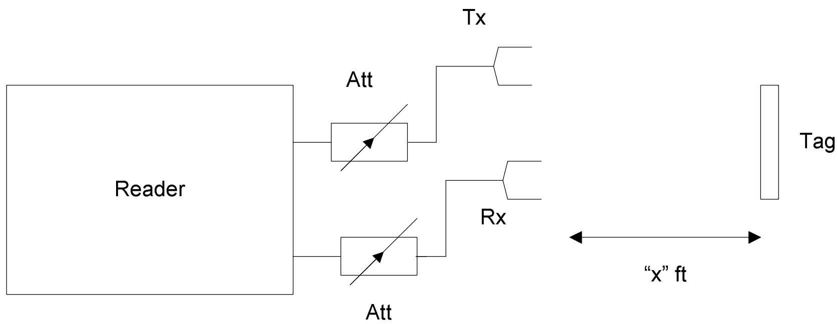

Figure 25 Test setup for channel sensitivity

The tag should be separated from a single reader antenna as shown in Figure 25. A median tag in a given model should be used for this benchmark. The forward channel and the reverse channel should be attenuated in fixed steps across a range of attenuation values. The response rate should be measured at each attenuation level of the forward and back channel. The following parameters should be noted in addition to those mentioned in Table 2:

- Attenuation range on forward and back channel
- Attenuation steps on forward and back channel
- Separation between the tag and the reader
- Number of read attempts

It should be noted that higher the number of read attempts, higher is the statistical accuracy of the response rate measured.

4.1.3. Test Metric

The test metric is the response rate at each attenuation level on the forward and back channel. The attenuation is increased until the response rate goes down to 0%.

4.1.4. Our Experiment

Table 16 Parameters for channel sensitivity experiment

Test Parameter	**Parameter Value**
Environment	Free-air
Reader Model	Thingmagic Mercury 4
Reader software version	2.4.22
Antenna Type	Bi-static and circular polarized
Number of Antennas	1
Protocol of the tag	EPC Class 0
Multi-protocol Reader settings	Scans only Class 0
Cables to connect antenna and reader	Factory default
Maximum Power	32.5 dBm
Application	Custom software on reader
Separation between tag and reader	Large tags – 3 feet Item-level tags – 18 inches
Transmit attenuation range	Large tags – 0 to 20 dB Item-level tags – 0 to 15 dB
Receive attenuation range	Large tags – 0 to 20 dB Item-level tags – 0 to 15 dB
Attenuation Step size	Large tags – 0.5 dB Item-level tags – 1 dB
Number of attempts	Large tags – 50 Item-level tags – 100

For this experiment, we use a median tag from Section 3.4 on the setup shown in Figure 25. We connected a variable inline attenuator between the antenna and the reader. Then, we varied the attenuation on transmit and the receive lines using the attenuators at steps of 0.5 dB. The forward channel attenuation was varied between 0 and 12 dB and the back channel attenuation was varied between 0 and 20 dB. At each power setting, 50 read attempts were performed and the response rate was recorded. We repeated the same experiment with an item-level tag. The item-level tag was separated at a distance of 1.5 feet from a reader as in Figure 25. The separation was reduced because the general item-level tags are designed to be readable up to 7 feet [6]. The experiment was repeated with the item-level tag with 100 read attempts at each attenuation level. Both transmit and receive lines are attenuated in steps of 1 dB. The transmit line was attenuated between 0 and 15 dB, and the receive line between 0 and 15 dB. Table 16 shows the parameters for both the experiments.

4.1.5. Results and Lessons Learned

4.1.5.1. Large tags

Figure 26 shows the results where "TxAtt" represents the attenuation in the forward channel and the "RxAtt" represents the attenuation in the reverse channel. Figure 26 shows the results of the experiment done with a Class 0 tag. Similar results were observed with Class 1 tag also.

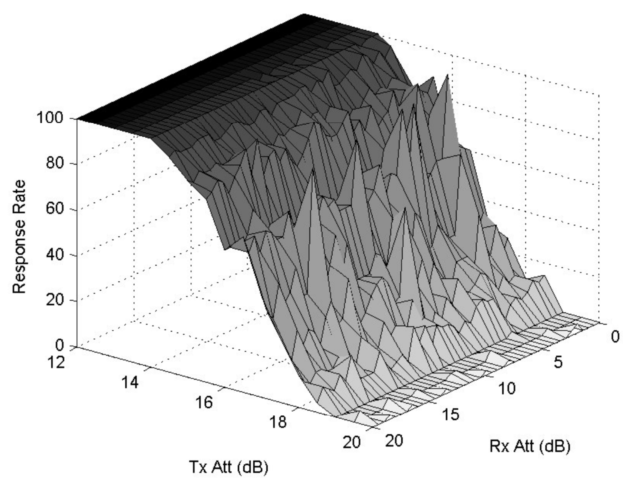

Figure 26 Channel Sensitivity for Large tags

Although there is some statistical noise, it is clear that the response rate showed no sensitivity to receive attenuation. This shows that the forward channel power transfer or the ability to transfer power from the reader to the tag is the dominating factor for the tag-reader system for large tags. This implies that for large tags, the forward channel attenuation is sufficient for simulating increase in the distance between the tag and the reader.

The tag-reader system studied has virtually no sensitivity on the response rate in the back channel, which indicates that the tag-reader system studied is a *strongly forward link limited system*. This means that the passive RFID systems are currently limited by the amount of power that the tag receives. If the tag receives enough energy to drive the chip, the reader should be able to detect the backscatter from the tag.

This result also indicates the differences in the choice of antenna configurations. In general, the antennas that are used with RFID readers can be bi-static or mono-static. In a bi-static antenna, the reader uses separate antennas for transmit and receive. Since the antennas are not exactly at the same location, the forward and reverse channel can be slightly different. In a mono-static antenna, the reader uses a single antenna for transmit and receive. The forward and reverse channel between the reader antenna and the tags are identical. A mono-static antenna normally uses a directional coupler to achieve separation to transmit and receive signals. Depending on the design, the directional couplers include some form of attenuation on the receive line. These results indicate that for a modest level of attenuation in the receive line will not affect the performance of the large tags with the passive RFID system.

This experiment practically validates the approach adopted in Chapter 3 of attenuating only the forward channel for simulating distances for large tags.

4.1.5.2. Item-level tags

Figure 27 shows the results for a Class 0 item-level tag. It can be clearly seen that the response rate shows considerable sensitivity to attenuation on the receive line as opposed to the large tags. We can infer from this that the reader sensitivity to detect the tags plays a major role. Thus, the forward and the reverse channel have to be attenuated simultaneously in order to simulate distances for item-level tags. Thus, not only the ability to transfer power to the IC is a constraint, but also the sensitivity of the reader to detect the tag response plays a major role in affecting the performance with item-level tags.

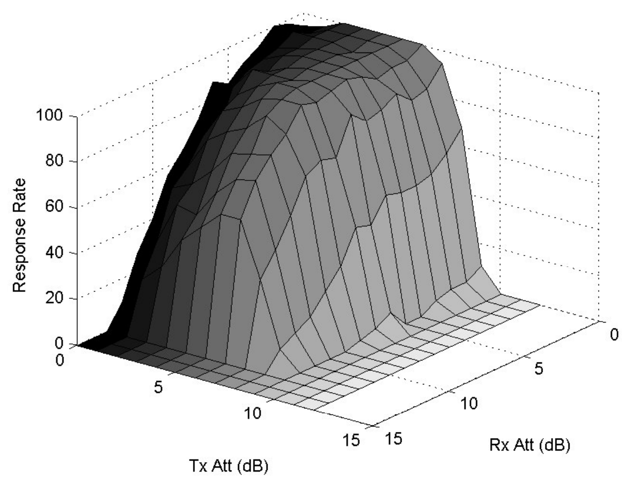

Figure 27 Channel Sensitivity for Item-level tags

4.2. Placement of Tags for Performance

In Chapter 3, most of the experiments were done with the tags being aligned with the transmit antenna. It was mentioned that transmit aligned gives better performance. A simple experiment was done to determine the best placement (better performance) of tags in front of a bi-static antenna.

4.2.1. Objective

The objective is to determine the placement of tags in front of a bi-static antenna, which would give better performance.

4.2.2. Test Procedure

The tag should be separated from a single bi-static reader antenna as shown in Figure 6. A median tag in a given model should be used for this benchmark. The tag should be aligned in front of transmit of the bi-static antenna as shown in Figure 28. The tag should be rotated in fixed steps and the attenuation level at which the tag becomes unreadable is measured. The following parameters should be noted in addition to those mentioned in Table 2:

- Angle step size
- Rotation plane
- Attenuation steps on forward and back channel
- Separation between the tag and the reader
- Number of read attempts

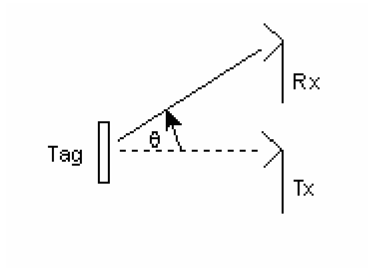

Figure 28 Setup for placement of tags

The measurement is repeated when the tag is aligned at the center of transmit and receive and when aligned directly in front of receive of the bi-static antenna.

4.2.3. Test Metric

The test metric is the attenuation level at which the tag becomes unreadable at various angles.

4.2.4. Our Experiment

Two separate experiments were done one with large tags with the setup described in Section 3.1 and the other with item-level tags with the same setup at a distance of 1.5 feet from the bi-static antenna (due to the smaller range of item tags). A large tag with dipole design was aligned directly in front of the transmit antenna. The dipole tag was rotated in 10° steps along its E-plane. The attenuation at which the tags became unreadable was measured at various angles. The experiment was repeated when the sample tag model was aligned with the receive antenna and the center of transmit and receive antenna. Table 17 lists the test parameters used for the large tags and the item-level tags.

Table 17 Parameters for placement of tags experiment

Test Parameter	Parameter Value
Environment	Free-air
Reader Model	Thingmagic Mercury 4
Reader software version	2.4.22
Antenna Type	Bi-static and circular polarized
Number of Antennas	1
Protocol of the tag	EPC Class 0
Multi-protocol Reader settings	Scans only Class 0
Cables to connect antenna and reader	Factory default
Maximum Power	32.5 dBm
Application	Custom software on reader
Separation between tag and reader	Large tags – 3 feet Item-level tags – 18 inches
Angle Step size	10°
Rotation plane	E-plane
Attenuation Step size	0.1dB
Number of attempts	1000

4.2.5. Results and Lessons Learned

4.2.5.1. Large tags

Figure 29 shows the radiation pattern of a large tag as its alignment is moved from transmit through the center and receive of a bi-static antenna. As can be seen large tags give better performance when they are aligned with transmit of a bi-static antenna. Also, it should be noted that the performance difference for large tags in all the three placements is considerably small (approximately 1 dB). The reason for small performance difference is that the tag is placed at a distance where the gain of transmit and receive antenna is approximately same.

Another interesting observation is that when the tag is aligned with transmit of the bi-static antenna the radiation pattern is aligned along 0° axes. There is a tilt in the radiation pattern in the clock-wise direction as the tag is moved towards receive of bi-static antenna. In all the cases, the performance is maximum at an angle where the tag is facing transmit of the bi-static antenna. This confirms the results in Section 4.1.5.1 that the tag-reader system performance is dominated by the forward channel transfer of power to the IC.

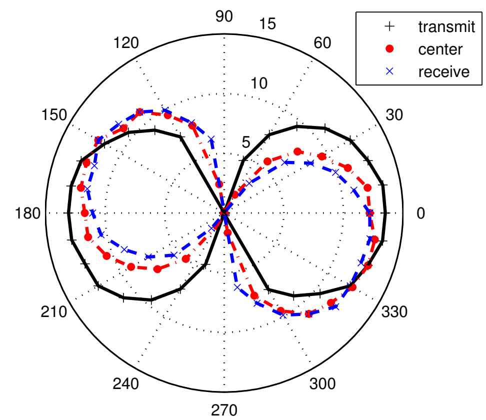

Figure 29 Test Setup Comparison for Large tags

4.2.5.2. Item-level tags

Figure 30 shows the radiation pattern of an item-level tag as the placement in front of a bi-static antenna was changed. As can be seen the item tags also give better performance when they are aligned with transmit of a bi-static antennas. There is a considerable performance difference (approximately 5 dB) for item tags among the three placements. The reason for this is: as the distance between the tag and the reader changes, the angle between the tag and the transmit antenna changes and also the angle between the tag and the receive antenna changes. The gain of transmit and receive antenna changes with angle of reception. When the tag is closer, there will be a greater change in the gain due to angle of reception. The change in the gain when tag is closer becomes prominent in the item-level tag and this is the reason for high performance difference.

Figure 30 also shows that when the tag is aligned with receive of the bi-static antenna the radiation pattern is aligned along 0° axes. Similar to the large tags, it can be seen that there is a tilt in the radiation pattern in the clockwise direction when the tag is moved towards receive of the bi-static antenna. But the performance is maximum at an angle where the tag is facing receive of the bi-static antenna.

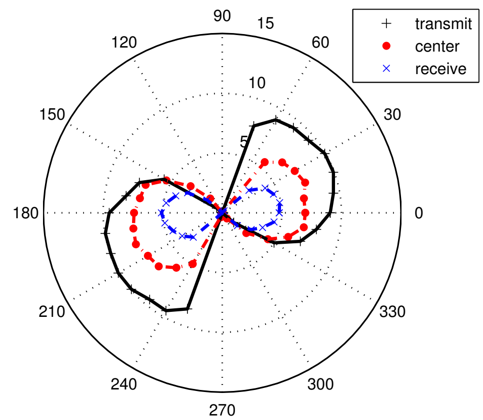

Figure 30 Test Setup Comparison for Item-level tags

4.3. Constructive Effect of Materials

In Section 3.6, we discussed the performance of tags in front of metal up to a distance of 2 cm. We noted that it is possible to get better performance out of a tag when it is in front of a metal at a particular separation. The better performance is due to constructive interference between the backscattered signal from the tag and the backscattered signal reflected from the metal. This section describes an experiment conducted using the benchmark for performance of tags in front of metals. In this experiment, we determine the performance of tags at larger separation values (> 2 cm) in front of metal.

4.3.1. Objective

To determine the maximum distance up to which tags are readable when they are separated in front of metal at various distances.

4.3.2. Our Experiment

The tag is separated from the reader antenna at a distance of 3 feet as in Figure 6. We placed the tag at its best orientation in front of a metal plate whose dimensions are comparable to wavelength. We varied the separation between the tag and the metal plate from 0 to 16 cm. The separation steps were not of fixed size. We chose the various separation values as {0, 1, 2, 4, 8, 12, 16 cm}. We measured the attenuation value at which the tag becomes unreadable in 100 read attempts for each separation of tag from metal. Table 18 shows the test parameters for this experiment.

4.3.3. Results and Lessons learned

Figure 31 shows the increase in performance at a separation of 4 cm due to the multi-path enhancing the transmission between reader and tag by constructive interference. We observed similar nature of curves from all the tags. This experiment shows practical measurements that metal plates can be used to enhance the performance of tags. The enhanced performance occurs when the tag and metal plate are separated such that the multi-path results in a constructive interference.

Table 18 Parameters for tags in front of metal experiment

Test Parameter	Parameter Value
Environment	Free-air
Reader Model	Class 0 – Matrics AR 400
Reader software version	Class 0 – 03.01.09
Antenna Type	Bi-static and circular polarized
Number of Antennas	1
Protocol of the tag	EPC Class 0
Multi-protocol Reader settings	Scans only Class 0
Cables to connect antenna and reader	Factory default
Maximum Power	32.5 dBm
Application	Custom software on reader
Separation between tag and reader	34 inches
Separation range from materials	Metal – 0 to 16 cm
Various separation values	0, 1, 2, 4, 8, 12, 16 cm
Number of attempts	100
Attenuation Step size	0.1 dB
Best orientation of the tag	(0,0)

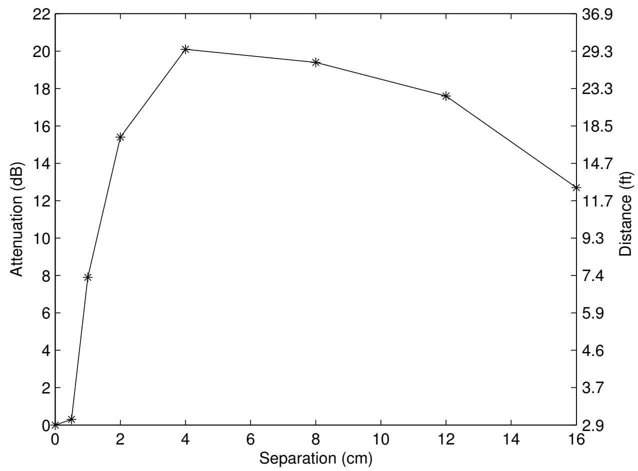

Figure 31 Better Performance of a tag in front of metal

4.4. Ghost Reads

In section 3.1 we had mentioned that ghost reads occurs with Class 0 tags in the out-of-field region. When the tested RFID reader was programmed to read only Class 0 tags, the reader reported tags that were not present in the field. This phenomenon is called *ghost reads* or *phantom reads*. This phenomenon occurred in one of the tested readers.

4.4.1. Objective

The objective is to determine the percentage of ghost reads observed with one of the tested readers.

4.4.2. Our Experiment

In this experiment, we configured the reader to read any Class 0 tag for a time period it would take to perform 100,000 Class 0 reads. There were no tags in the field of the reader during the duration of the experiment. We recorded the tag IDs and the number of times the reader reports each tag.

Table 19 Parameters for ghost reads experiment

Test Parameter	Parameter Value
Environment	Free-air
Reader Model	Thingmagic Mercury 4
Reader software version	2.4.22
Antenna Type	Bi-static and circular polarized
Number of Antennas	1
Protocol of the tag	EPC Class 0
Multi-protocol Reader settings	Scans only Class 0
Cables to connect antenna and reader	Factory default
Maximum Power	32.5 dBm
Application	Custom software on reader
Tags	No tag in the field
Number of attempts	100,000

4.4.3. Results and Lessons Learned

We observed that 90 distinct Class 0 RFID tags were read in the 100,000 attempts or 0.9 per 1000. All the tag IDs were read only once and were evenly distributed between 64 and 96 bits. We also observed that the rate at which ghost reads occur in the reader was consistent across all other Class 0 experiments. From other experiments, we estimated that 677 ghost reads had occurred in a total of 515,000 Class 0 reads or 1.3 per 1000.

Apparently the reason seems to be that, when the readers are reading Class 0 tags, they are susceptible to interpreting noise as a signal. As mentioned in Section 2.3, the tag ID in the passive tags contains a 16-bit CRC. In theory, a random tag ID along with a matching CRC should be rare. Since a tag ID contains a 16-bit CRC, a random ID and CRC can match only 1 in 2^{16}. Based on the data that we have collected, the ghost reads occurs approximately at the rate of 1 per 1000 read attempts or 1 in 2^{10}. Thus, it can be seen that for every 1 read attempt the reader discards approximately 64 tags with invalid CRCs. We find this alarmingly high. This data points out a flaw in the design and/or the implementation of the Class 0 protocol on the reader used for our experiment.

One of the ways to get rid of ghost reads is to put a *software filter* on the reader. If a tag ID is read only once in certain duration of time, then it can be considered as a Ghost read. But this approach will filter the tags that are correctly read also. Another approach is to introduce a filter in the middleware where the tag IDs is mapped to products. If the tag ID is not mapped to a particular product in the inventory then that read can be considered as a Ghost read. But both of these options are not ideal.

We are also aware that there have been recent attempts from vendors to control and reduce the ghost rates. It should be noted that with the impending release of "Gen 2" (EPC Class 1 Second Generation) products, Class 0 protocol will soon become obsolete. It should be noted that we have not observed ghost reads with Class 1 tags and we have looked at a data from 1 million read attempts. This interesting observation provides information on the behavior of tags and also affects the way the data from the readers are handled.

5. Conclusion

5.1. Conclusions

During the course of the development of RFID Alliance Lab benchmarks, we have inferred several conclusions and interesting observations. In this section, we summarize the conclusions from the experiments conducted using the benchmarks.

1. Maximum distance

   We conclude that a typical commercial tag model is readable up to a maximum of 18 feet. However, the tag does not respond to all the read attempts from the reader within this maximum range.

2. Three regions of operation of passive RFID tags

   We conclude that all the passive RFID tags have three distinct regions of operation. The three distinct regions of operation are: strong-in-field, weak-in-field, and out-of-field. In the strong-in-field region, the tag responds to most of the attempts from the reader. Thus, the response rate in strong-in-field region is close to 100%. The tag performance degrades rapidly with increasing attenuation in the weak-in-field region. In the out-of-field region, the response rate goes down to 0%. We observed the three regions of operation in passive RFID tags for all the three tested readers.

3. Orientation sensitivity

   We conclude that only a few tags available in the commercial market are orientation insensitive. Out of 10 tested commercial tag models, we have observed only 2 to be orientation insensitive.

4. Variance in tag performance

   We conclude that one cannot expect two tags from the same model to have identical performance. In fact, depending on the tag model the variance in performance of a tag model can be 6 dB or even more. This variance in dB when translated to distance would result in a factor of two or more. Thus, the worst tag is readable only up to half the distance of the best tag in that model. In order to avoid inconsistency of tags, the end-user has to reject the tags that do not perform well before applying them on a product.

5. Read rates in isolation

- When there is only one tag in the reader field, Class 1 tags are read much faster than Class 0 tags.
- There are two sections in Class 1 tags depending on the read rate.
- Absolute values of read rates are dependent on tag-reader system whereas the behavior of read rates across various sections of protocols was consistent for all the three tested readers.

6. Read rates in population
   - While reading multiple tags using the tested reader, the last few tags took exponential time to get read. Although we did not collect data using other readers, we observed the same to be true for the other two readers.
   - Class 0 tags scale up considerably better than Class 1 tags for the tested reader. Although we did not collect data using other readers for this experiment, our observations indicate the same.
7. Distance of tags in front of metal / water

   All the tested commercial tag models were unreadable within 2.5 mm of separation from metal and water. We repeated the experiment across all the three readers and observed that none of the tags work within 2.5 mm separation from metal and water.
8. Frequency response of tags in front of metal / water

   It is to be noted that the ISM band used by RFID is not unique across all the countries. In order to realize globally visible supply chain, tags must operate well at the UHF ISM bands across all the countries. Some of the tags are unreadable at certain ISM bands when the tags are near metal even though they are readable at all the frequencies in free air. Frequency dependent analysis on tags is essential to establish a globally visible supply chain.
9. RFID system is a forward link limited system for large tags

   The tested passive RFID system for large tags (physically > 2x2 inches) is limited by the amount of power that the tag receives. Thus, for large tags RFID is a forward link limited system. We repeated the experiment with another commercial reader and observed that RFID is forward link limited system for that reader also. Thus, if the tag is able to receive enough energy to drive the integrated circuit, the reader should be able to detect the backscatter from the tag.

The conclusions listed above show the current state of passive UHF RFID tags. It also shows some of the characteristics of passive UHF RFID tags. Although most of the results presented in this thesis are from the experiments conducted with a single commercial reader, we have observed similar trends across readers. Some of the interesting observations that we have noted through the course of this work are:

- Observed read rates are considerably less than the read rates cited by the RFID vendors. The RFID vendors cite read rates ranging from 20 to 1000 [19] whereas we have observed a range of 0 to 62.
- Item-level tags (physically < 2x2 inches) have more frequency-dependent performance. They do not respond at certain frequencies even in free air.
- "Ghost reads" or fake reads on Class 0 protocol were observed with one of the tested readers.

The conclusions and observations listed above help us to understand and analyze RFID performance in a better way. Understanding and analyzing RFID performance is essential when deploying real-world systems to track and trace the entire supply chain. The objective set out for this thesis was to develop a set of simple benchmarks to evaluate the performance of passive UHF RFID tags. In this thesis we explain the benchmarks, illustrated some of the sample data obtained from our experiments, and discussed the lessons learned from the results. The sample results indicate the drastic differences in performance across various tag models and also tags in the same model. The benchmarks have shown substantial differences between Class 0 and Class 1 tags behavior. The benchmarks presented in this thesis mark the first step towards common performance benchmark standards for RFID tags. Though it does not answer all the questions, it provides baseline information from where the end-users can start. It enables end-users to make informed decisions regarding RFID products and sort out marketing hype. We believe that the results from our testing give a better idea to the end-users about which tags would meet their individual needs and implementing better RFID systems.

5.2. Future Work

Through the course of this research work, we have observed several areas in RFID performance benchmarks deserving future work and attention.

The benchmarks presented in this thesis were developed using commercial RFID readers available in the market. There are pros and cons in using a commercial reader. The merit is that one would be able translate all the results directly to real-world. But on the negative side, there are unknown variables with a commercial reader. For example the variation in reader sensitivity is not known for a commercial reader. Also, there is no direct control provided to the end-user for doing a single read attempt. These unknowns in commercial readers are common and these have to be included when interpreting the results. Developing a custom reader would enable us to have more control over all the parameters of the reader and help us in reducing the unknowns.

Also, we have noted that the performance of tags is frequency dependent. Analyzing frequency dependent behavior of tags in detail would enable designing tags that work globally. We have seen that the item tags have more frequency dependent behavior compared to the large tags. A faster way to analyze the frequency dependent performance of tags has to be developed.

Developing analog measures such as change in impedance bandwidth of tags would make it easier to analyze the frequency dependent behavior of the antenna. The detuning of antennas in front of products can be analyzed in a better way with such a benchmark. The change in performance of tags due to materials and their free-air performances would give a good insight into the performance of tags when the tags are used in real-world.

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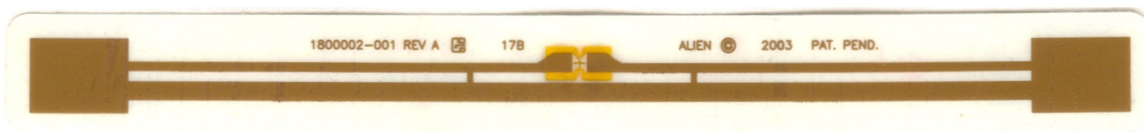
Appendix A

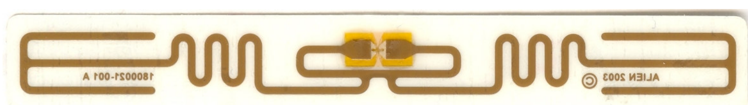
Tags, Readers, and Antennas

In this appendix, some of the tags that are available in the commercial market are shown. For perspective, the tags are shown in their real size. We also show pictures of some of the readers available in the market and that were used for the development of benchmarks. The testing was done with commercial RFID readers along with mono-static / bi-static antennas that came along with the commercial readers.

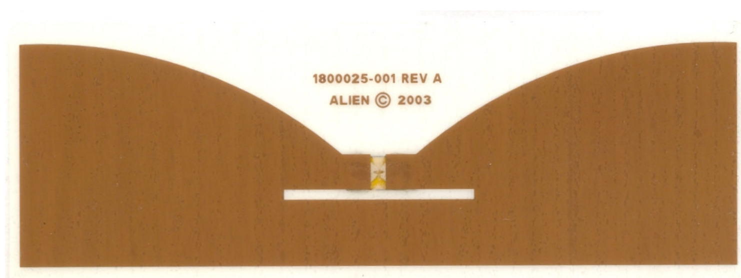
Some of the Passive Tag Models in commercial market (to scale)



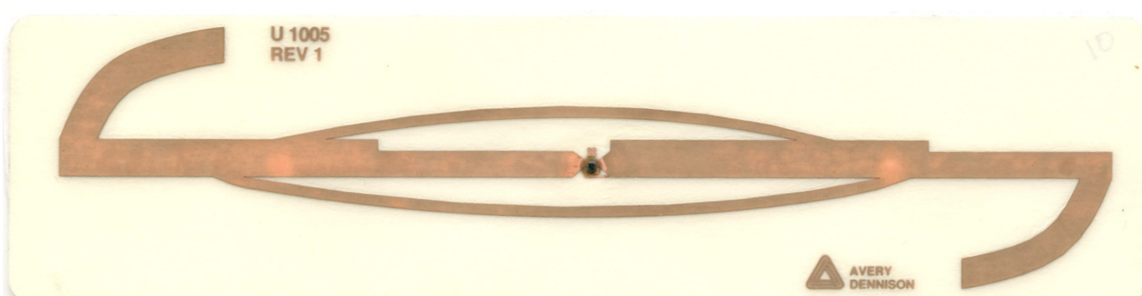
Alien ALL-9250 "I2"



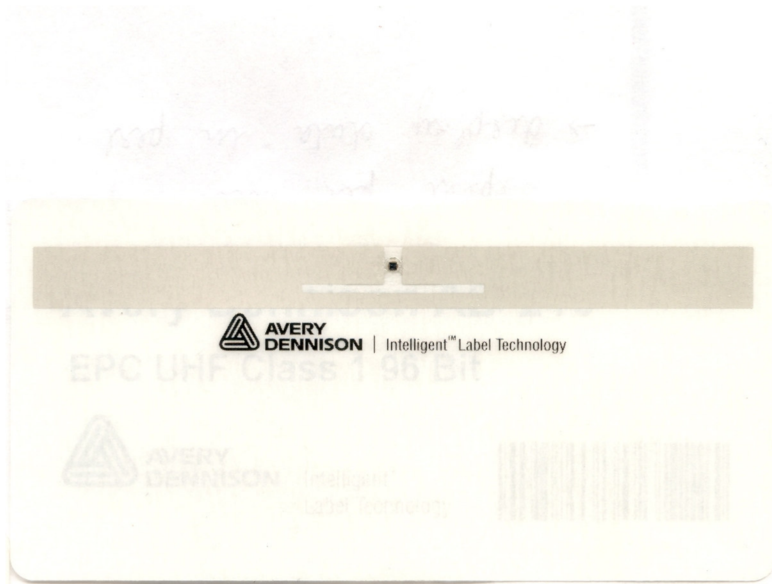
Alien ALL-9338-02 "Squiggle™"



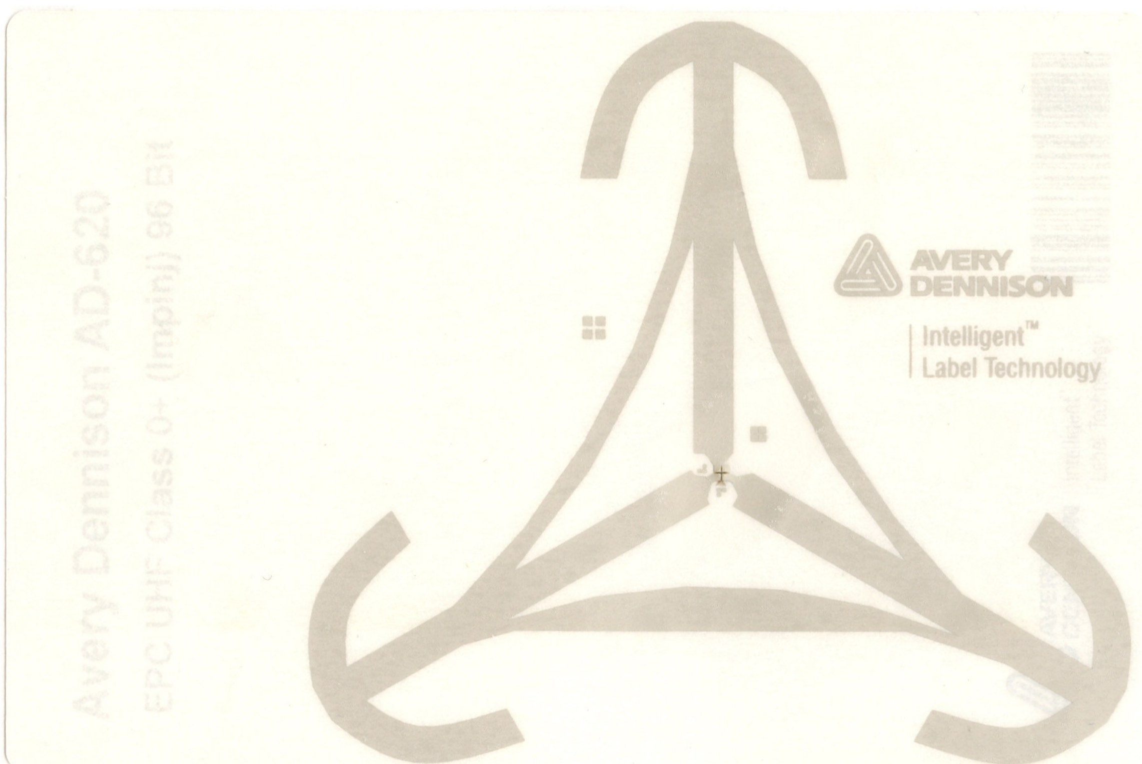
Alien ALL-9254 "M"



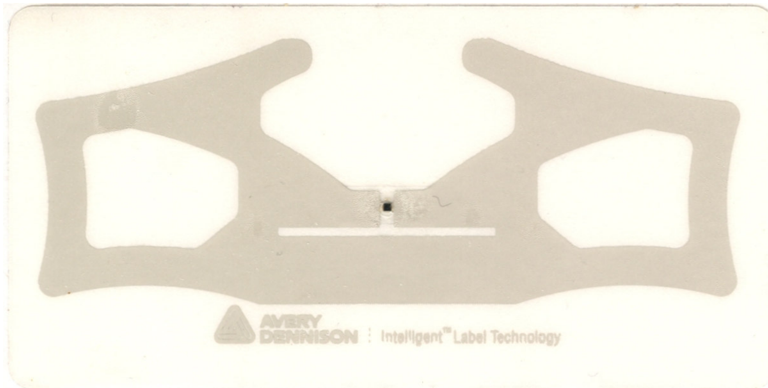
Avery DS1



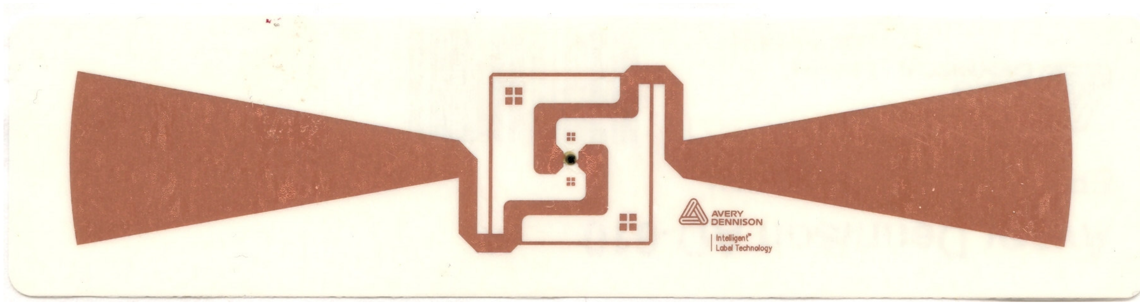
Avery Strip



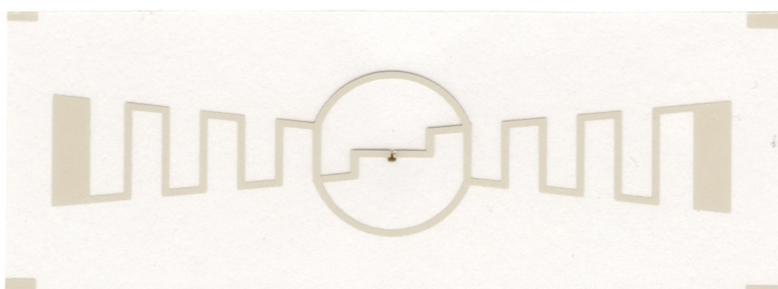
Avery Triflex



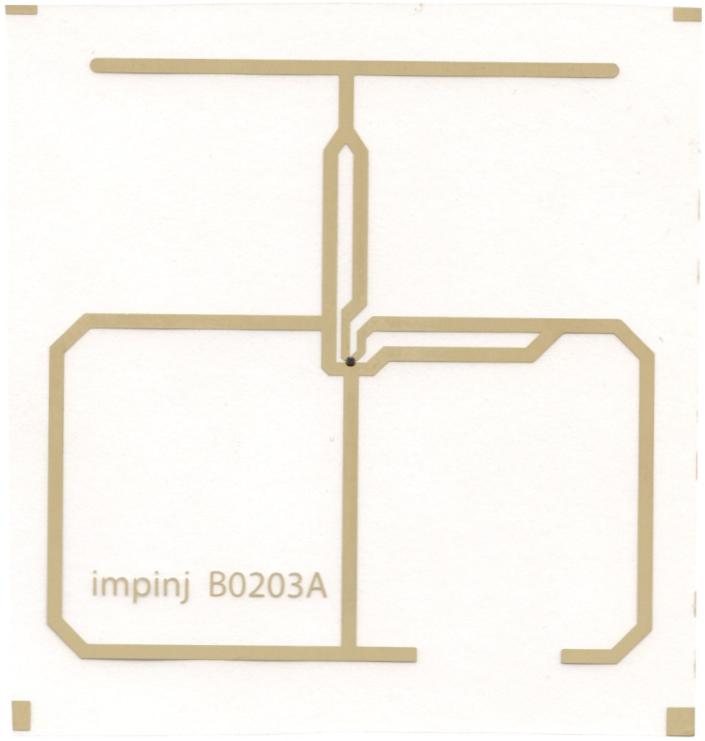
Avery AD 410



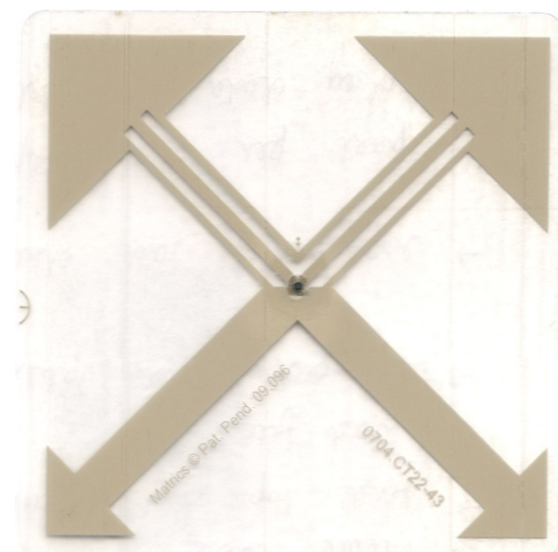
Avery AD 610



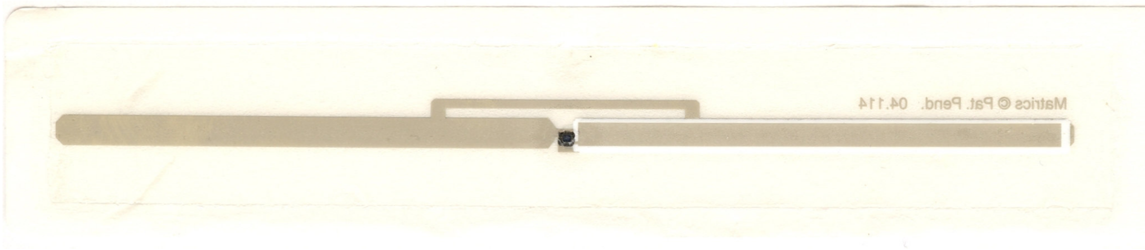
Impinj Single Antenna



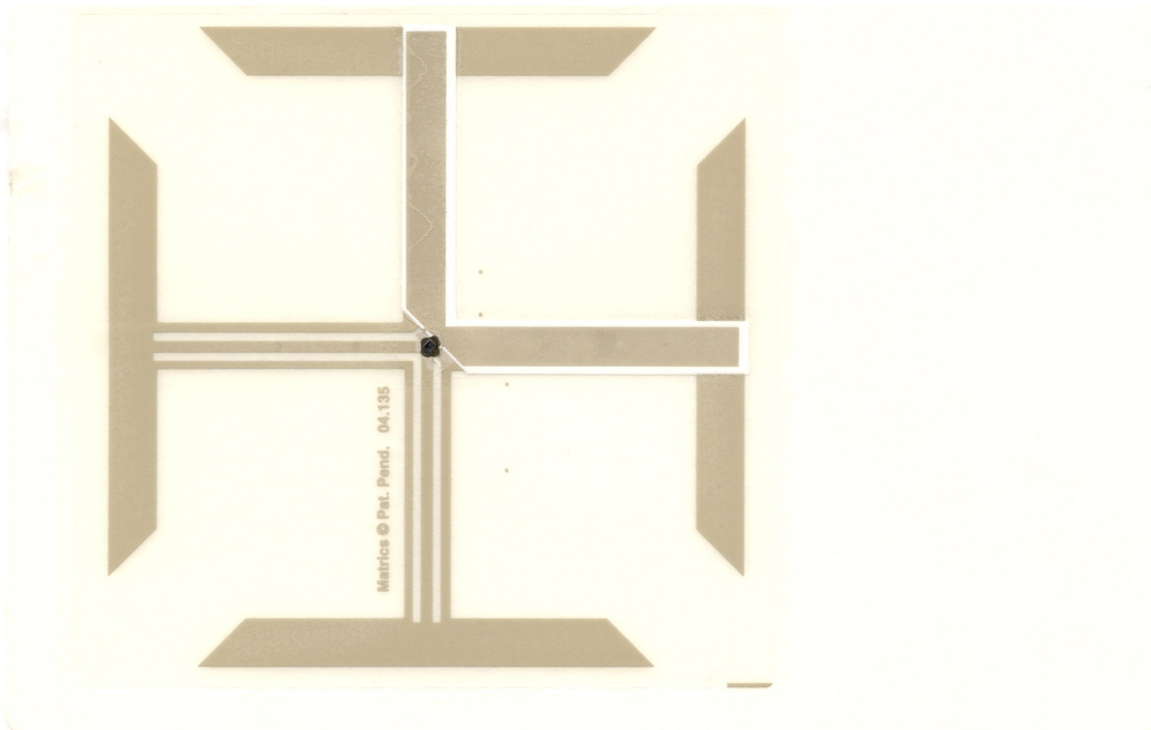
Impinj Dual Antenna



Symbol Arrow

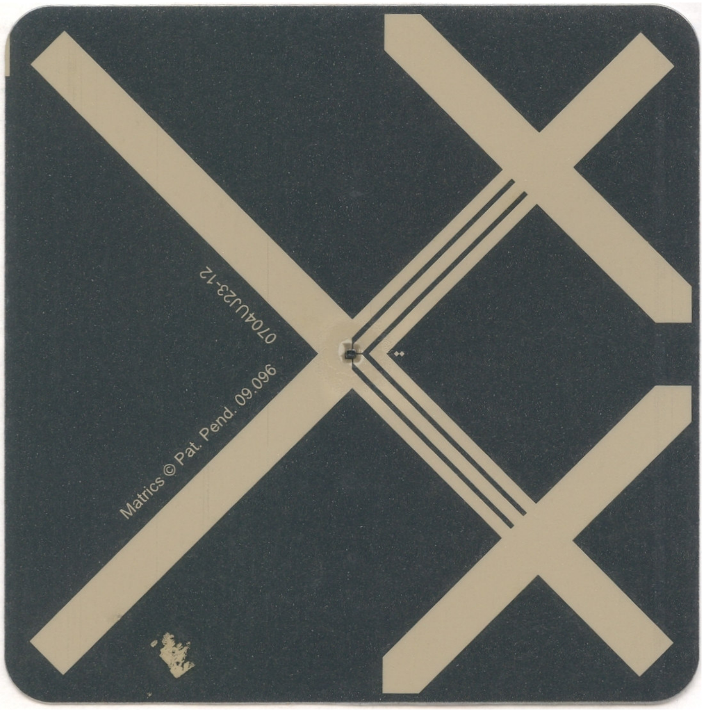


Symbol I2010

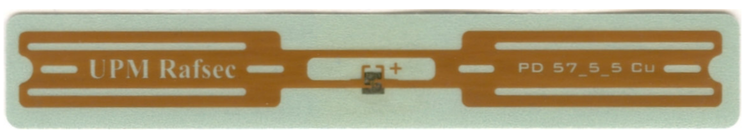


Symbol X2040

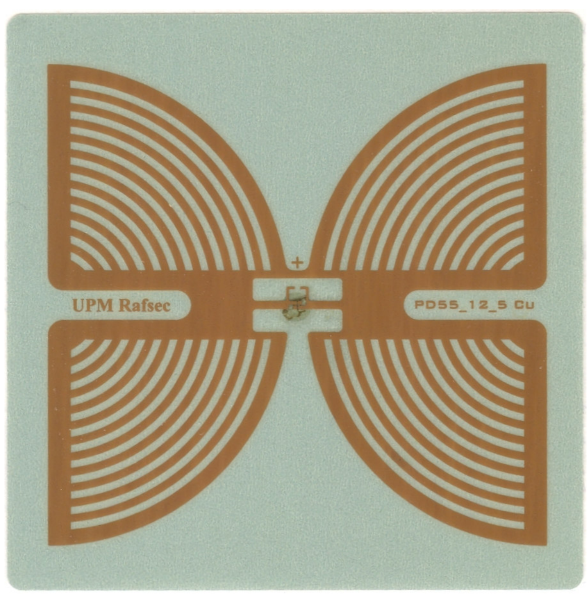
Symbol Dipole



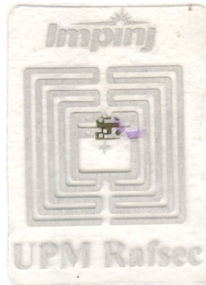
Symbol Dual Dipole



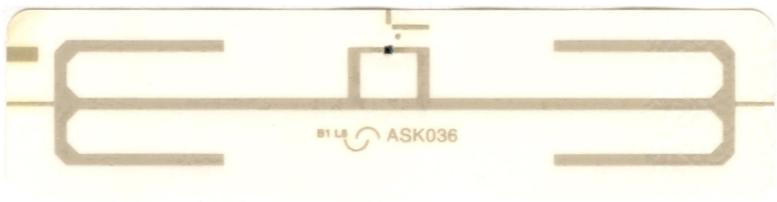
Rafsec 457



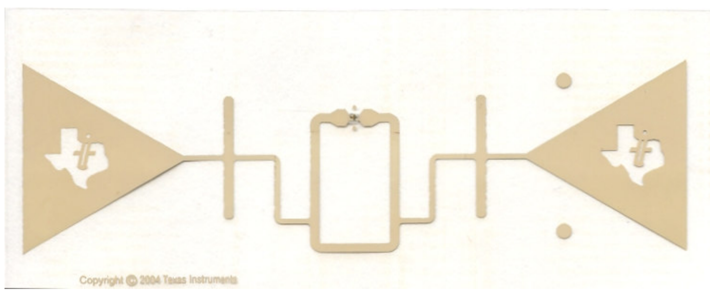
Rafsec 432



Rafsec Gen2 Onetenna

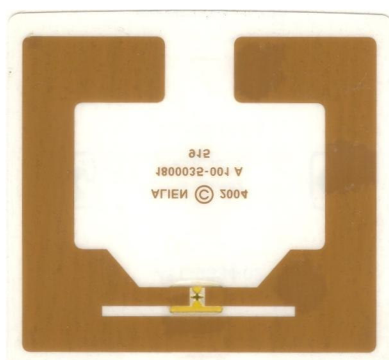


ASK 036

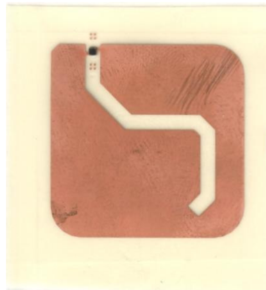


TI Gen2 RX-UHF-00C01-03

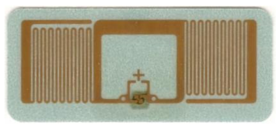
Some of the Passive Item-level Tag Models in commercial market (to scale)



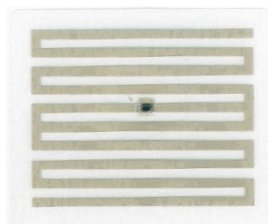
Alien ALL-9334 "2x2"



Avery AD-810

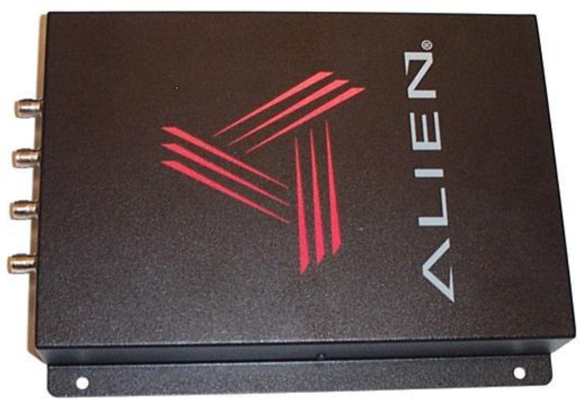


Rafsec 518

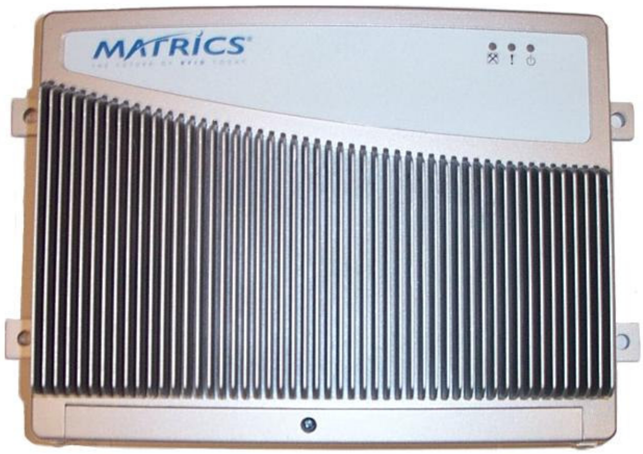


Symbol I1030

Some of the RFID readers available in the commercial market



Alien 9780 Reader



Symbol AR400 Reader

ThingMagic Mercury 4