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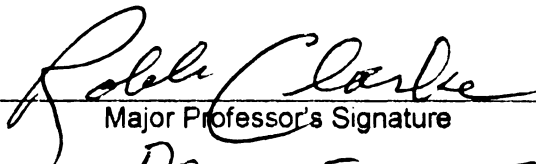
THE EFFECT OF ANTENNAE CONFIGURATION, PRODUCT
AND TAG TYPE ON THE READABILITY OF PASSIVE UHF
RFID TRANSPONDERS

presented by

THOMAS JOHN SILVER CRAWFORTH

has been accepted towards fulfillment
of the requirements for the

M.S. degree in Packaging


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**THE EFFECT OF ANTENNAE CONFIGURATION, PRODUCT AND TAG TYPE ON
READABILITY OF PASSIVE UHF RFID TRANSPONDERS**

By

Thomas John Silver Crawforth

A THESIS

**Submitted to
Michigan State University
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ABSTRACT

THE EFFECT OF ANTENNAE CONFIGURATION, PRODUCT AND TAG TYPE ON READABILITY OF PASSIVE UHF RFID TRANSPONDERS

By

Thomas John Silver Crawforth

Many advances are being made in the supply chain world at this time. One of the more prevalent additions is the use of radio frequency identification (RFID). With mandates being issued by powerful retailers and government agencies, numerous companies are being forced into implementing this technology. The use of 915 MHz RFID systems is rapidly growing and there is a need to better understand its use in certain applications.

The purpose of this research is to determine if the number of read antennae used and the location of these antennae has an effect on the readability of passive UHF RFID tagged cases on a stretch wrapper. The variables for this testing were number of read antennae, location of read antennae, case contents (empty, rice and water), and tag type (Alien Class 1 and Symbol Class 0).

The research found that there was a significant difference in the read rate of reads for both number and location of antennae. There was also a significant difference in the read rate of reads for different case contents with both rice and water decreasing reads, though water was shown to have the greatest impact. The tag type was not found to have a significant difference with respect to total reads; however there were differences seen within specific combinations of variables.

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CHAPTER 1 - INTRODUCTION

It is generally accepted that Radio Frequency Identification (RFID) has taken great strides in finding a place in everyday life. The technology is being successfully implemented in many areas, and some are taken for granted. Certain gas stations are using it as a contact-less method of payment; it is being used on highways as a method of high-speed toll collection, in buildings and parking lots as access control, and even in sports applications as a method of race timing. While these applications are in place, there is an ongoing push for the technology to be used for asset tracking within the supply chain. Before it is considered a success in this area, there is still much developing to do.

The benefits of implementing RFID into the supply chain are numerous. Inventory management, accurate order picking and delivery, reduced labor, decreased theft, smaller and more focused recalls, and a streamlined supply chain are all areas that RFID can potentially help. Improvement in any of these areas, let alone multiples, can create a significant competitive advantage for a company.

Initially, these benefits may be most easily realized in a large supply chain situation. There are two examples of extensive supply chains that would benefit greatly from implementing RFID. The first is the United States Department of Defense (DoD). The DoD has over 43,000 suppliers^[1], shipping to locations all across the world. Organizing and streamlining a supply chain such as this is an ideal application for RFID. The second example of an extensive supply chain is the retail giant Wal-Mart. Wal-Mart is the largest retailer in the world, with sales for 2004 surpassing \$250 billion^[2], and has a supply chain to match. Implementing RFID could dramatically alter these supply chains for the better. For this reason Wal-Mart has issued a mandate that its suppliers begin

implementing RFID, and the DoD issued a similar mandate shortly after. Wal-Mart undoubtedly knows that the requirements in the mandate are difficult at best, yet they also know that the industry would be less active in this area if not given some strong motivation. Certainly Wal-Mart is a large enough company to put pressure on the suppliers to accept a requirement for RFID adoption.^[2] As expected, Wal-Mart's competitors in the retail industry, and other companies from different industries are following suit and have issued mandates of their own, not wanting to be left behind. With these mandates in place, the technology is being advanced much more rapidly than it would have if the retail giants had not stepped in and forced the issue.

Implementing RFID technology is not a simple thing. That is likely a reason why Wal-Mart felt the need to push this onto its suppliers because, while the success of the technology will benefit both sides, its difficulties are a strong deterrent. Issues such as cost of equipment, availability of tags, standardization of information, and the physics of the technology will be difficult to overcome. With of the nature of the technology, there will not be a simple implementation procedure that can be used across industries, or even across some companies. Each implementer will have to look at the situation individually and make several decisions specific to their own requirements and limitations. For this reason, there has been much testing done, at the industry level and at the university level, looking at the effects of many different variables. While this testing has been done, there are a few areas that have grown in importance as a result of this testing. The purpose of this research is to cover, in depth, one of these resultant areas.

Prior research at the Michigan State University School of Packaging has led to this specific study. Since RFID study began at MSU in 1999, many areas have been

studied; material, environmental, and product issues have all been assessed; tags, readers, antenna read patterns, tagged cases and case loads, pallets and pallet loads have all been evaluated. A unit load is defined as “assembly of goods on a pallet for handling, moving, storing and stacking as a single entity” and may include homogenous and mixed loads, and may be made up of a multitude of smaller items or may be very few. An evaluation of a unit or pallet load is relevant for several reasons. On the surface it may appear to be irrelevant because of the Wal-Mart mandate and the details of Wal-Mart’s supply chain. Wal-Mart typically breaks a pallet apart upon arrival to one of its storage distribution centers, and the individual cases are loaded onto a high-speed conveyor, where they are read by RFID equipment. Reading a unit load in this case is not necessary, (although it is read as a unit load as it is unloaded from the truck anyway) however this system is unique to Wal-Mart. Many other supply chains do not implement this same read point because they store their product as unitized loads, and therefore would be highly interested in reading a unit load. Another reason that unit loads are relevant is that in many distribution centers mixed pallets are constructed and shipped on an order-by-order basis. Since each order and pallet make up differs, it becomes very important to read the entire pallet load to know what is included therein.

Previous Master’s theses at MSU have looked at many of the aforementioned areas^[3, 4, 5]. Different test methods have resulted in seemingly varied outcomes, in which many variables have been found to have an impact. Some of these variables are tag location and orientation, product content, and read point. With respect to unit loads, studies have been conducted in which a pallet load, with varying tag locations and products, is walked through an RFID portal with constant antennae location. This

research will examine if the same (or better) results can be achieved by altering the number and location of read antennae situated around a stretch wrapper.

Due to the importance of reading an entire unit load, and the poor results obtained in portal walk through testing^[3], a different read point was selected to increase read rates. A stretch wrapper has many applications in which RFID could be utilized. Unit loads of mixed product cases coming out of a warehouse headed to an individual store are stretch wrapped, homogeneous loads of product to be shipped and homogeneous loads that orders are picked from are also stretch wrapped. The stretch wrapper used throughout the testing consists of a vertically moving wrap carriage, and a flat turntable on which the pallet load sits. The difficulties of reading a unit load are combated using the stretch wrapping method because the method allows the tagged product to be in the read field for an extended time period, and multiple views from the rotations allow for maximum penetration of the RF signal to the interior cases. Based on this new set-up, the hypotheses for this research are:

- The case contents will have a similar effect on the read rates of RFID tags at the stretch wrapper as they did at the portal.
- The tag type will not have an effect on the read rates of RFID tags.
- The number of read antennae utilized will not affect the read rates of RFID tags.
- The location of the read antennae utilized will not affect the read rates of RFID tags.

The significance of this research lies in the fact that while much has been made of the product interactions, tag location effects, tag orientation effects, package system interactions, frequency effects, antenna type effects, etc, there has not been a focus on the

location and number of antennae needed to obtain ideal reads. The results show how significant this variable is when implementing an RFID system. Instead of relying on guesswork or a generic configuration, companies will now have some solid answers to utilize when configuring RFID into their business.

CHAPTER 2 – LITERATURE REVIEW

In today's highly competitive world of retail and consumer packaged goods (CPG), every company is looking to get a leg up on the competition. Increased revenue, higher market share, and larger profits are all goals of this rapidly growing industry. There is no specific business model for each and every company to follow in order to do this, but there is a lot of follow-the-leader going on. In this particular industry, that leader is Wal-Mart. "Wal-Mart Stores Inc. is the world's largest retailer, with \$285.2 billion in sales in the fiscal year ending Jan. 31, 2005."^[2] One of the ways that Wal-Mart is gaining a competitive advantage is through increased supply chain efficiency. An efficient supply chain can help decrease manual labor, shipping costs, and inventory holding costs, while increasing inventory visibility and turnover. An in-depth analysis of this is found in Chapter 9 of "The Wal-Mart Way" by Don Soderquist.^[6]

While it is easy to say that the supply chain needs to be more efficient, this is not the easiest thing to do. One way that this issue is being addressed is through the use of information technology (IT). Virtually every major company now has an IT department for the sole reason that as a business grows, there is more and more information to be gathered and an electronic means of obtaining, sorting, storing and retrieving is necessary. Automatic Identification and Data Capture (AIDC) technologies are one of the main ways that this is accomplished. There are many AIDC technologies in use today that are a part of our every day life; magnetic strips and barcodes are two of the simplest and most common. Others include biometrics, optical character scanning and RFID. The main goals of these technologies are the elimination of human error associated with manual data entry, and increased speed of data capture^[7].

One of the most rapidly growing AIDC technology is Radio Frequency Identification (RFID). RFID is defined as “A wireless data collection technology that uses electronic tags for storing data. Like bar codes, they are used to identify items. Unlike bar codes, which must be brought close to the scanner for reading, RFID tags are read when they are within the proximity of a transmitted radio signal.”^[8] The trend in CPG and retail is moving toward this technology as an answer to the problem of how to increase supply chain efficiency. “ ‘Supply chain event management is the largest application of RFID technology in industry today,’ says John Fontanella, senior VP of supply chain services at Boston-based AberdeenGroup”.^[9] A Master’s thesis from the University of Texas at Arlington provides a further justification for using RFID technology in mobile asset tracking. It provides the framework for how to implement the technology into the supply chain.^[10] Further examples of how the technology is gaining a foothold can be found at virtually every turn. As companies look to break away from established business models and revolutionize the way their business operates, RFID is coming to the forefront as illustrated in a Master’s thesis from the Massachusetts Institute of Technology. “RFID in the supply chain represents an enabling technology that will allow warehouse operations to break away from traditional methodologies and adopt revolutionary techniques, such as location-relaxed storage.”^[11] Location-relaxed storage is made possible through the use of RFID by allowing for a less rigid organizational system. RFID tagged goods can be stored anywhere in the warehouse, and when a worker needs to locate a specific item, RFID readers will notify them of the location.

RFID technology utilizes radio frequency waves to energize tags in order for them to release their information, also in the form of radio band energy. The radio bandwidth

portion of the electromagnetic spectrum is extremely wide, ranging from 3 kilohertz (kHz) to 300 Gigahertz (GHz), and the Federal Communications Commission (FCC) has allocated all the bandwidths across this spectrum for different uses in the United States. RFID has been allocated a few separate frequencies. The major frequency allocations for RFID in the U.S. are 134 kHz, 13.56 MHz, 433 MHz, 915 MHz, and 2.4 GHz.^[12] 134 kHz is considered low frequency (LF), 433 MHz and 13.56 MHz are considered high frequency (HF), 915 MHz is considered ultra high frequency (UHF) and 2.4 GHz is considered to be microwave. Each of these frequencies demonstrates differing performance characteristics in regards to read range, product interaction and tag collision. In selecting one frequency over the other, the industry has taken all these aspects into account. There are many uses for the different frequencies, but as a whole, the retail and CPG industry in the U.S. has moved towards UHF, or 915 MHz. “UHF (915 MHz in the US) has been focused on for the recent retail supply-chain mandates and investment due to its distance and cost attributes”^[13].

As a retail industry leader, Wal-Mart has taken on the role of a driver for RFID technology. They made this happen through issuance of a mandate for their suppliers. The mandate has been segmented into 2 phases. To date, the first phase, which was effected January 2005, stated that the top 100 suppliers to Wal-Mart must tag all cases and pallets shipped to Wal-Mart distribution centers and stores with UHF RFID tags, readable by the Wal-Mart equipment. For this mandate, items such as returnable containers, shrink wrapped bundles, bags, and other larger sized items are considered cases.^[14] The second phase states that the next 200 suppliers do the same by January of 2006. Neither phase of the mandate specifies how this is to be done, what manufacturer

to obtain equipment from, or where to place the tags. The mandate only says that Wal-Mart must be able to read the tags upon receiving the shipment. This mandate leaves the supplier with 2 options, comply with the mandate, or lose Wal-Mart as a customer. Compliance at this point is a very expensive proposition, with a lot of investment involved and very little identified return on this investment. This expense, however mighty, pales in comparison to the potential loss of Wal-Mart as a customer, for most companies. For this reason, many suppliers are implementing a 'slap and ship' policy for shipments to Wal-Mart. Slap and ship is when a tag is manually applied to a case or pallet, either at the manufacturing plant, or at a distribution center, on its way to Wal-Mart. In some cases an entire truckload is unloaded, depalletized, tagged, and reloaded as the final step before heading to Wal-Mart. This is a very bad situation for the supplier, as there is a large increase in costs associated with tags, equipment, labor for unloading and reloading the truck, and no increase in revenue. This is illustrated in a Chief Information Officers (CIO) journal article. "Many suppliers are applying the tag on pallets to be shipped to warehouses in the region where the Wal-Mart distribution center is located. Using the product that is destined to be shipped the next day (which is already palletized and stretch-wrapped), they are taking off the stretch-wrap, depalletizing, applying the tag, writing the tag, repalletizing, rewrapping and sending. And even then, suppliers are afraid the tags might not function on arrival because of mechanical problems."^[15] Simple compliance with the mandate using slap and ship will not show any return on investment (ROI) for a supplier, and aides only Wal-Mart in its' goal for a competitive advantage. In order for there to be a ROI, the suppliers must implement the technology further upstream in their own processing. The tire manufacturer Michelin is

one company that has already seen an ROI by tagging their product further up the manufacturing process. “But [Michelin] already is using RFID in connection with large, industrial tires, including those involving re-treads, where the chips are useful in tracking the product's life cycle”^[16].

There have been many additional mandates issued by Wal-Mart's competitors such as Target, Albertsons and Best Buy, further increasing the need for suppliers to find a way to make RFID work for them.

Target Stores has issued a mandate similar to Wal-Mart, in that they want all their suppliers using RFID. “Target, the fourth largest retailer in the United States, has told its top suppliers that they will be required to apply RFID tags on pallets and cases sent to “select” regional distribution facilities beginning late spring 2005. The company wants all suppliers to tag pallets and cases by the spring of 2007”^[17] Something that both Wal-Mart and Target mandates have in common is that they want the RFID to be used as a complement to barcodes, not as a replacement for barcodes.

Another large grocery retailer, Albertson's, has followed suit by issuing a mandate of their own. “Albertson's, the nation's second largest food and drug retailer, has launched its first RFID pilot and announced that it will require its top 100 suppliers to tag pallets and cartons by April 2005.”^[18] This mandate is similar to others in that it requires pallets and cases from suppliers be tagged, but is similarly vague in how this is to be accomplished.

A more recent mandate that follows similar guidelines is from Best Buy. “The Minneapolis-based consumer electronics retail chain will require its major suppliers to begin applying EPC-compliant tags to product cases and pallets by Jan. 2, 2006.”^[19] A

couple advantages that Best Buy has are that they have a later starting date, January 2006, and a lot of the cases shipped in are single items, so they will see more accurate item level tracking.

In order to gain ROI, suppliers affected by these mandates are attempting to implement RFID technology into their internal processing. In doing so they are encountering many issues^[20], some of which has to do with the nature of the technology. It is not a system that will react identically in every situation; in fact it will most likely have drastically different issues with each different implementation. “RFID is not plug-and-play, and it may never become that. ‘RFID is a complex recipe: it's equal parts physics, process changes, supply chain synchronization, and software integration’ states Deon Nel of Avatar Partners”.^[21] As the article states, many of the issues that implementers are facing have to do with physics of the technology, while others deal with the equipment, supply chain and software.

Another big area that is garnering a lot of attention is standardization. With the ratification of the Gen 2 standard, some of these issues are being resolved, but it is a slow process. Essentially the problem is that the first generation of tags and readers could not communicate with tags and readers produced by a different company. One can imagine the headaches this would cause, as Wal-Mart refuses to publicly endorse one manufacturer over another. The Gen 2 standard, and presumably the following generations, is designed to eliminate the problem of each of Wal-Mart's suppliers using tags from a different manufacturer, and thus forcing Wal-Mart to have that many different readers. This would be impossible for many reasons including cost and physical space limitations. Fortunately the Gen 2 standard, which was ratified December 16,

2004,^[22] is slowly gaining a foothold. It is a slow process because of a vicious cycle involving price and availability. Many companies are waiting to place orders until the prices come down, and manufacturers cannot make the prices come down until they are receiving bulk orders. Currently inlays are available for 7.9 cents and full self-adhesive tags are available for 12.9 cents for orders of 1 million or more.^[23, 24]

There has been a fair amount of research done on the physical limitations of the technology, with the goal being more efficient and accurate use. One area covered extensively is the tag orientation^[3]. The location of the RFID tag on a case of goods matters a great deal in obtaining reads of that case. This has to do with the product and packaging materials in the case and the location of the tag itself. An example of this from one of Wal-Mart's top suppliers stated, as follows, "Del Monte quickly realized the biggest problem it would face: where to place the tags. Cases of tuna are only a few inches tall — the height of a can — and the cans are packed closely together. Del Monte knew it needed 4-inch by 2-inch tags to fit on the cases, and the tags needed to be carefully placed for the best read."^[20] In this case, the metal can was causing the tag not to be read, but a slight adjustment of the tag location eliminated this problem. In each situation the location must be carefully assessed in order to obtain the best reads. Jeffery Tazelaar, researching tag orientations and product interactions, did a highly comprehensive study for a Master's thesis at Michigan State University. He utilized a pallet load of 48 corrugated cases, each tagged with a UHF Class 0 RFID tag. He compared five different tag locations and 5 different products, walking the pallet load through a simulated warehouse RFID portal. The hypotheses for his research were:

- “The orientation of the RFID tag on the package will have no effect on the readability of the transponders,
- The product contained in the package will not have an effect on the readability of the RFID transponders,
- Cases containing products made up of water will have lower read rates than those cases containing waterless products,
- All waterless products will have the same rate of readability.”

He found that the first 2 hypotheses were false, the third was true, and the fourth was also false.^[3]

Another Master’s thesis at Michigan State University looked at the difference between refrigerated beef loin and frozen beef loin. Individually packaged cuts of beef loin were tagged and subjected to either refrigerated or frozen environments. An attempt was made to read the tagged packages individually, and stacked atop one another. Beef loin, being a product with high water content, was found to have difficulties reading when the beef was refrigerated. When it was frozen however, the crystallized water molecules did not prevent the tags, even several deep in a stack, from being read.^[4] These studies all illustrate that the product can alter the tag readability, as does the tag orientation.

The durability of RFID tags is another issue to be considered, as most tags will be subjected to the harsh environment of a distribution system. A Master’s thesis was devoted to this topic at Michigan State University. A range of tests, implementing American Society for Testing of Materials (ASTM) and International Safe Transit Association (ISTA) standards were completed for UHF Class 0 RFID tags. Drop, shock,

vibration, compression and direct impact tests were all attempted. There was virtually no damage done to the Class 0 passive UHF tags, with the exception of when a direct impact was applied to the microchip. If the impact were not centered over the chip, no effect was recorded^[5]. These results may vary with differing tag constructs, however can be assumed true for other similar tags.

Another issue that a company must face is choosing a read point. There are a lot of options in this area, and each presents its own set of problems. Within a warehouse alone the read points can vary between racking systems, conveyor belts, hand held readers, around portals/doorways, stretch wrappers, or fork trucks/pallet jacks. In fact some RFID equipment manufacturers^[25] are selling equipment to be used in all these locations, as there will be a market for each. A manufacturing plant has some of these same options, as well as some unique to that specific plant. An example of a company using two of these read points is Wal-Mart. "Wal-Mart aims to read 100 percent of all tagged pallets coming through the dock doors at the DC and stores equipped with readers and 100 percent of all tagged cases on conveyors within the distribution center".^[26] Just because Wal-Mart is an industry driver in RFID does not mean that the way they do things works for everyone. Other companies have found other solutions to the implementing headaches they have come across. "Kleenex-maker Kimberly-Clark Corp. accidentally discovered a simple workaround... During normal assembly-line operations, all pallets are fully shrink-wrapped. The machinery that does this slowly spins the pallet around. The company discovered that an RFID scan taken during that rotation delivered much more accurate reads, Das said, apparently because it allowed the reader to "see" the tags from different angles and grab the best view".^[27] In talks with employees at

Kimberly-Clark, it has been determined that the machine discussed is actually a stretch wrapper, and this type of solution, one that fits into a companies current process, is ideal, however many companies may discover that they are not so lucky^[28].

Among the research being done across industries and at universities, there appears to be a noticeable gap in published literature. This gap is the read antennae configuration, consisting of the location of the antennae and the number of antennae used. Even in comprehensive books on RFID technology antennae are discussed only in terms of how they work or what different types there are^[29, 30]. A significant issue lies in the antennae configuration around whichever read point it is that has been chosen. This is an issue because results may vary with different configurations and significant cost reductions may be observed if fewer antennae can be used, by configuring them properly. There were no found published works showing that research has been done in this area, or to indicate that anyone has done anything beyond guesswork.

There are two aspects to antennae configuration studied in this research. The first is the number of read antennae utilized, and the second is the location of those antennae. If one can obtain equivalent reads from using less antennae and locating them properly, a significant amount of money might be saved. For example, in a warehousing or distribution center situation, where potentially hundreds of dock doors are to be equipped with read RFID antennae, this savings is especially significant considering the average antenna cost is around \$200 each^[31]. While there has been plenty of research that shows that product characteristics can alter a tag's readability, none has been done to see if this product will alter an antenna's performance, in different configurations. Another area

that has had some research performed is the difference that a tag from a different manufacturer makes. Individual companies are faced with an increasing choice as more and more tag manufacturers enter the market, and while they have undoubtedly assessed different tags based on price and performance, there is no published research on the tags interactions with differing antennae configurations.

Antennae selection for this research was based on a number of factors. Availability, and cost were assessed, but the more important aspect was functionality. Compatibility with the system used was a requirement and the polarization of the antennae was also evaluated. Antennae are polarized in one of two ways; linear or circular. This terminology refers to the way in which the radio waves are propagated. A linear antenna propagates the energy in a concentrated planar fashion. A circular antenna propagates the energy in a rotating circular pattern. Linear antennae are best utilized when reading tags from a long distance is required and the tag orientation is controlled in such a way that it aligns with the planar propagation of the radio waves. Circular antennae are best utilized for varying tag orientations and shorter read distances. This phenomenon can be observed in lab exercises for PKG 491: RFID and Packaging, a course taught at the Michigan State University School of Packaging^[32]. For this research, a short read distance was required and the tag orientations change as the pallet load spins, thus circular antennae were used throughout the testing.

CHAPTER 3 - METHODOLOGY

Equipment

The reader utilized throughout the testing was the Sensormatic Agile2 Reader, powered by ThingMagic (Boca Raton, FL). It was a Gen 2 reader, meaning it was able to read and send data from Electronic Product Code (EPC) Class 0, Class 0+, Class 1 and Gen 2 tags, to the computer for analysis using a crossover Ethernet cable. Gen 2 readers are different from first generation readers in that they are able to read tags from different manufacturers and of different classes at once. This capability made this testing possible. The Agile2 was an eight port reader, capable connecting to eight ultra high frequency (UHF) antennae, however for this research no more than four antennae were used at any given time.

The antennae used were SensorID™ OmniWave circular polarized antennae. The circular polarization antennae were used because they are less sensitive to tag orientation, and the read distance required for this testing was not large enough to require linear antennae. Differing combinations of 1-4 of these antennae were connected to the reader using 25' coaxial cables. The antennae were mounted in various locations around a wooden frame using small metal brackets and screws. Wood was the material chosen because it is relatively radiolucent compared to metal or polymer based structures. Constructed around a stretch wrapper (Synergy 3, Highlight Inc. Grand Rapids, MI), the frame consisted of 4 upright posts (84"), 2 top crossbars (92"), and 2 connecting bars (36")(Figure 1). For most configurations an antenna was screwed into the center of the

36" span. The reader rested upon one of the top crossbars such that all antennae cords could reach it.

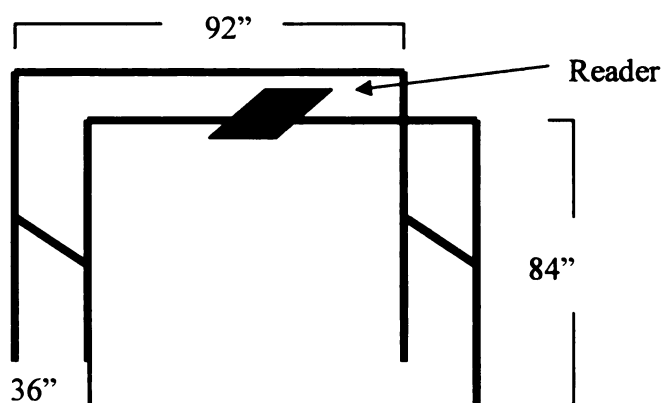


Figure 1

Wooden frame that antennae were mounted on. The frame was set up around the stretch wrapper turntable

Procedure

Forty-eight center special slotted containers (CSSCs), were assembled from standard 42-26-42 C-flute corrugated board and sealed at the glue flap using Surebonder® All Purpose Stik™ glue sticks, to create inside dimensions of 13" x 12" x 10". These case flaps were sealed with 2" clear, pressure-adhesive, packing tape and stacked in a 4 x 3 pallet pattern, 4 tiers high on a standard Grocery Manufacturers Association (GMA) 48" x 40" wooden pallet. This same pallet and pallet pattern were used throughout the testing with the only variables being product, tag type and antennae location.

The cases were securely tagged in the upper left hand corner with Alien squiggle tags (Alien Technologies, Morgan Hill, Ca), using scotch tape (Figure 2). These tags measure 4" X 1/2" and are EPC Class 1, meaning they have the capability of being programmed on site. The tags have 16 digits of information that can be programmed by the user. For this test the Alien tags were named 5555 5555 5555 0001, 5555 5555 5555 0002,....,5555 5555 5555 0048. Henceforth they will be referred to simply as tag 1, tag 2,....,tag 48.

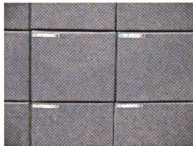


Figure 2
Alien Squiggle tags on cases

Cases with tag numbers 1-12 were positioned on the bottom tier of the pallet, 13-24 on the second tier, 25-36 on the third tier and 37-48 on the fourth or top tier. The placement of the tagged cases is shown in Figure 3.

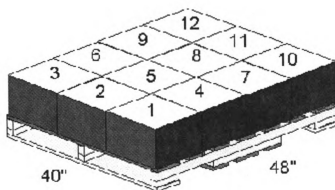
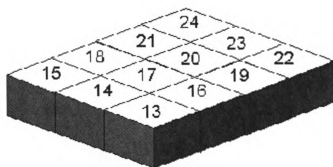
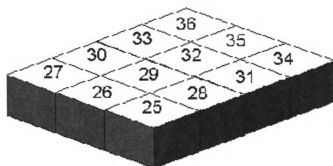
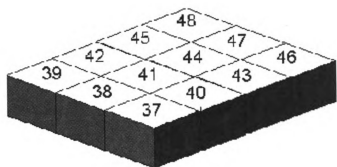


Figure 3
Tag position on pallet,
by tier

The pallet load was placed on the stretch wrapper turntable (Highlight Industries), with the wooden portal constructed around it (Figure 4), and set to a configuration where the machine would wrap the pallet with one full band around the bottom, and 2 full bands around the top. For these tests, however, the wrap was not attached to the pallet as the stretch wrap being used was found to have no impact on the results and thus would have been a waste of resources. Each trial consisted of 8.5 turns on the stretch wrapper lasting 50 seconds total, and the reader was manually started and stopped to synchronize with the start and stop of the stretch wrap machine. After each trial the tags that read were manually recorded into a Microsoft Excel document where a “1” indicated a read and a “0” indicated a no-read.

For each of the antennae configurations/tag types/product combinations, 25 trials were performed. Given nine antenna configurations and two tag types, the total number of trials per product was 450. Three different products were used, empty cases, to serve as a baseline, rice jars, and bottles of water. Two tag types were used, the Alien squiggle and the Symbol double di-pole.

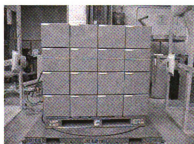


Figure 4
Pallet load on stretch wrapper

After 25 trials were completed, the antennae configuration was changed and the process was repeated. There were nine different antennae configurations used per each tag type and product. They are listed in Table 1.

Table 1. Configuration Identification

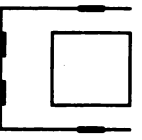
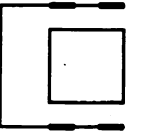
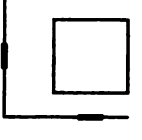
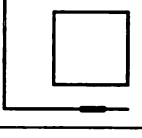
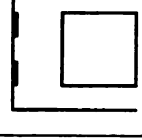
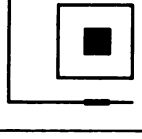
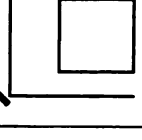
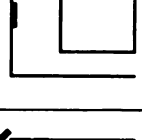
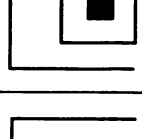
Configuration Number	1	2	3	4	5	6	7	8	9
Location Classification	Combo	Side	Combo	Side	Top	Side Top	Top	Top	Side
Number of Antennae	4	4	3	2	2	2	2	1	1
Side View Diagram									
Dimensions	Top antennae - 30.7" apart, 30" above pallet. Side antennae - 33" from floor.	24" and 48" from floor	Top antenna - midpoint of length, 30" above pallet. Side antennae - 33" from floor	33" from floor	30.67" apart, 30" above pallet	33" up from floor, on two adjacent sides	45 degree angles, 92" apart, 84" from floor	Top antenna - midpoint of length, 30" above pallet.	33" from floor

Table 2. Legend for Side View Diagram

Legend for Side View Diagram	I			
	Antenna Side View	Antenna Front View	Pallet Load	Wooden Frame

After the nine different antennae configurations were tested with 25 trials each, the Alien squiggle tags were replaced with Symbol double di-pole tags (Figure 5). These tags measure 6" X 4", and are EPC Class 0, (prewritten). For this reason the tags were individually read before application and the last three digits (both numbers and letters) of the data already in place were recorded and sorted alphanumerically. The 3-digit code was assigned a number (1-48) and applied to the cases in the same order as in the first test. When all 450 trials were completed, the tags were removed and the entire process was repeated using a new product.

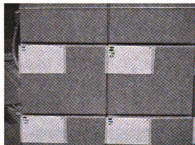


Figure 5
Symbol double di-pole tags on cases

The first set of trials was completed with empty cases, which have proven to be a good baseline for research as the corrugated alone has little to no effect on the readability of tags. The second product tested was bottles of water. Water was used because it is known that water has a significant effect on the readability of RFID tags. The bottles used were made of polyethylene (PET), contained 32 fl. oz. of tap water and sealed with twist caps made of polypropylene (PP). Each case held 12 of the 9.75" tall and 3.5" diameter water bottles. The bottles left no headspace in the cases which were again sealed with 2" clear pressure-adhesive packing tape (Figure 6).



Figure 6
Water bottles in cases

The third and final product for these tests consisted of rectangular PET jars of rice pilaf. This product was selected because it was a dry, dense product, to contrast with the water bottles, and thus was expected to have an impact on readability^[3]. Each case held 9 jars in a 3 x 3 pattern (6" tall, base of 3.75" x 3.5", 3.5" cap diameter), leaving a 4" headspace after being cased (Figure 7).



Figure 7
Rice jars in cases

Data from each test was collected and analyzed for statistically significant differences in certain areas. The comparisons of read rates were made were for case content, tag type, and antennae number and location(s). While different tags read differing amounts of times, if a tag was read at least once for a trial, it was considered a read and recorded accordingly. Samples of the data collection sheets are displayed in tables 3 and 4.

Table 3. Data Collection Sheet - Example 1

2 antennae: 2 side(33")
 Alien Tags
 Water Bottle Filled Cases
 Tag Number

[illegible]

Table 4. Data Collection Sheet - Example 2

2 antennae: 2 side(33")

Alien Tags

Rice Filled Cases

Tag Number

[illegible]

CHAPTER 4 – RESULTS

Case Content – Total Reads

The results listed below were collected for the 3 different case contents. The total number of reads consists of 9 antennae configurations, 2 tag types, 48 tagged cases and 25 trials performed for each antenna configuration and tag type. This gives a total of 21,600 possible reads for each case content.

1. Empty cases, for all antennae configurations and both tag types, had a total of 21,214 reads out of a possible 21,600 for a read rate of 98.21%.
2. Rice filled cases, for all antennae configurations and both tag types, had a total of 18,342 reads out of a possible 21,600 for a read rate of 84.92%.
3. Water bottle filled cases, for all antennae configurations and both tag types, had a total of 12,611 reads out of a possible 21,600 for a read rate of 58.39%.

These results show that tag readability is drastically dependent on case content, regardless of antennae configuration and tag type. The information above is illustrated in Figures 8, 9 and 10.

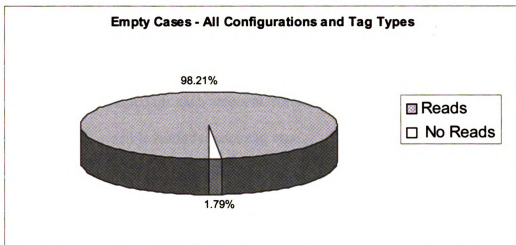


Figure 8. Percentage of Total Reads on Empty Cases

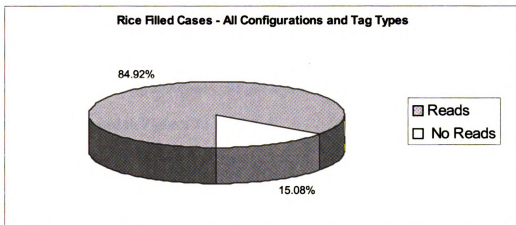


Figure 9. Percentage of Total Reads on Rice Filled Cases

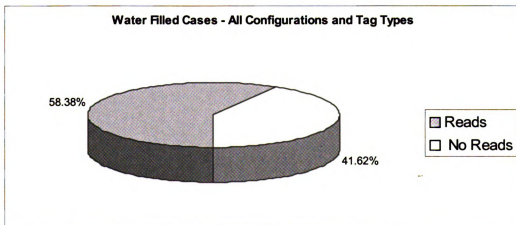


Figure 10. Percentage of Total Reads on Water Filled Cases

Tag Type – Total Reads

The results listed below were collected for the 2 different tag types. The total number of reads consists of 9 antenna configurations, 3 case contents, 48 tagged cases and 25 trials performed for each antennae configuration and case content. This gives a total of 32,400 possible reads for each tag type.

1. Alien Squiggle tags, for all antennae configurations and case contents, had a total of 25,786 out of a possible 32,400 for a read rate of 79.59%.
2. Symbol Double Di-pole tags, for all antennae configurations and case contents, had a total of 26,381 out of a possible 32,400 for a read rate of 81.42%.

These results show that the readability of the different tag types is not statistically different when altering antennae configurations and case contents. The information above is illustrated in Figures 11 and 12.

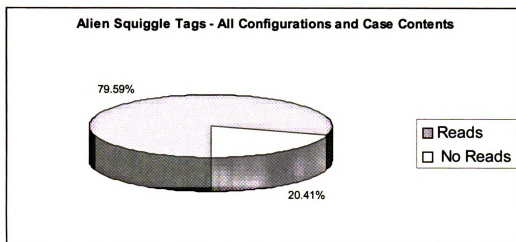


Figure 11. Percentage of Total Reads on Alien Squiggle Tagged Cases

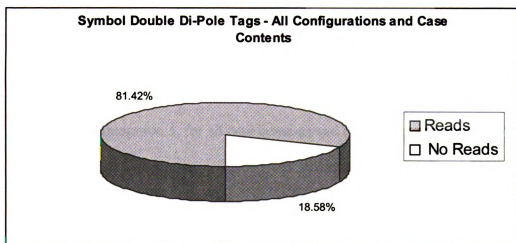


Figure 12. Percentage of Total Reads on Symbol Double Di-Pole Tagged Cases

Antennae Configuration – Total Reads

The results listed below were collected for the 9 different antennae configurations.

The total number of reads consists of 3 different case contents, 2 different tag types, 48 tagged cases and 25 trials performed for each case content and tag type. This gives a total of 7,200 possible reads for each antennae configuration.

1. Configuration 1, for all case contents and both tag types, had a total of 6,556 reads out of a possible 7,200 for a read rate of 91.06%.
2. Configuration 2, for all case contents and both tag types, had a total of 6,623 reads out of a possible 7,200 for a read rate of 91.99%.
3. Configuration 3, for all case contents and both tag types, had a total of 6,680 reads out of a possible 7,200 for a read rate of 92.78%.
4. Configuration 4, for all case contents and both tag types, had a total of 6,064 reads out of a possible 7,200 for a read rate of 84.22%.
5. Configuration 5, for all case contents and both tag types, had a total of 5,416 reads out of a possible 7,200 for a read rate of 75.22%.
6. Configuration 6, for all case contents and both tag types, had a total of 6,028 reads out of a possible 7,200 for a read rate of 83.72%.
7. Configuration 7, for all case contents and both tag types, had a total of 4,680 reads out of a possible 7,200 for a read rate of 65.00%.
8. Configuration 8, for all case contents and both tag types, had a total of 4,681 reads out of a possible 7,200 for a read rate of 65.01%.
9. Configuration 9, for all case contents and both tag types, had a total of 5,439 reads out of a possible 7,200 for a read rate of 75.54%.

These results show that readability is changed when the antennae configuration is changed, across all case contents and tag types. The information above is illustrated in Figures 13-21.

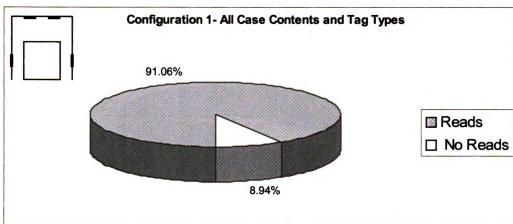


Figure 13. Percentage of Reads for Configuration 1

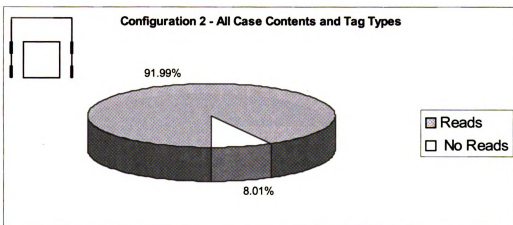


Figure 14. Percentage of Reads for Configuration 2

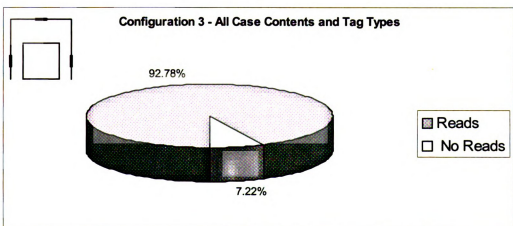


Figure 15. Percentage of Reads for Configuration 3

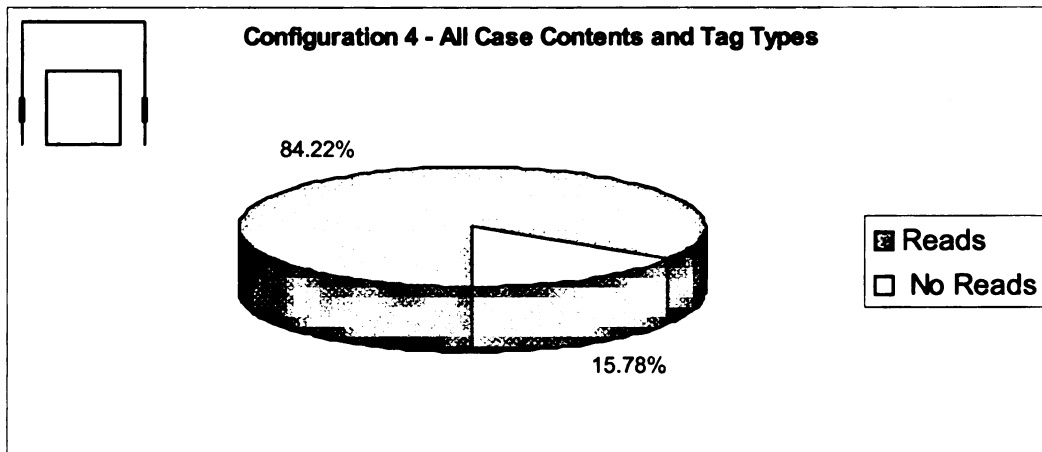


Figure 16. Percentage of Reads for Configuration 4

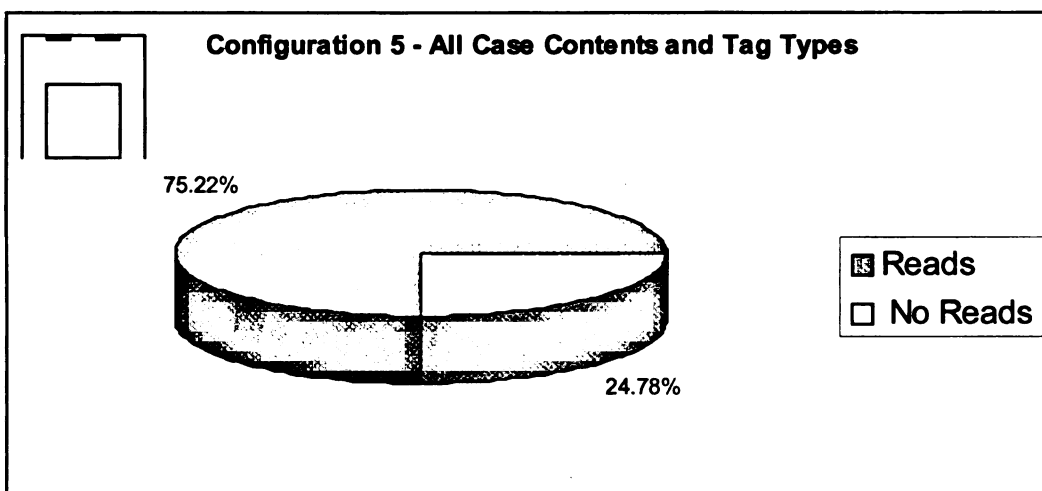


Figure 17. Percentage of Reads for Configuration 5

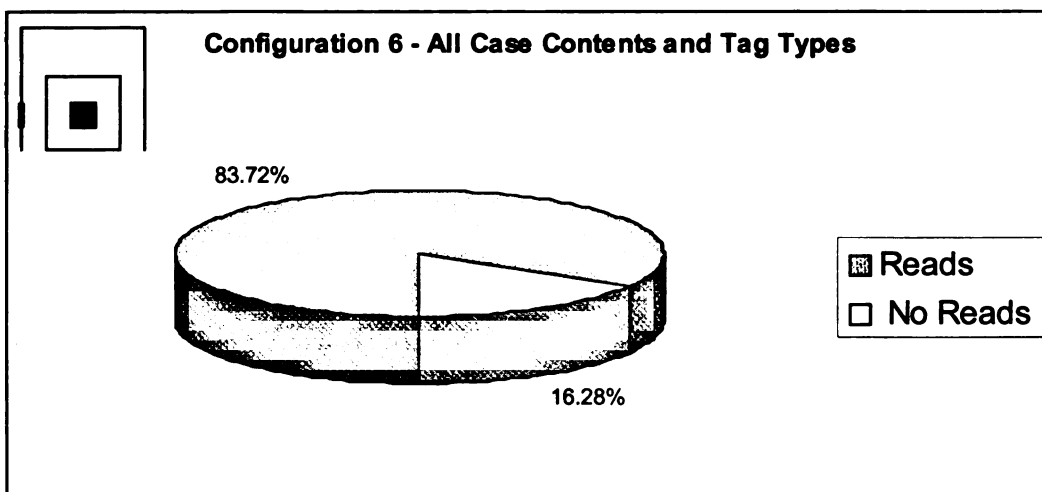


Figure 18. Percentage of Reads for Configuration 6

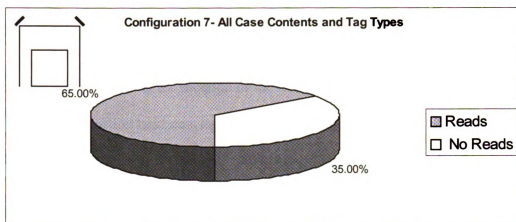


Figure 19. Percentage of Reads for Configuration 7

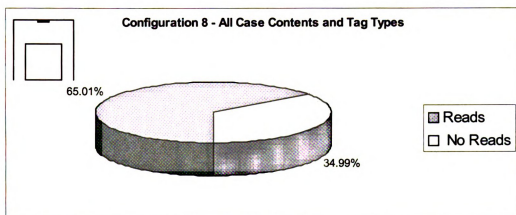


Figure 20. Percentage of Reads for Configuration 8

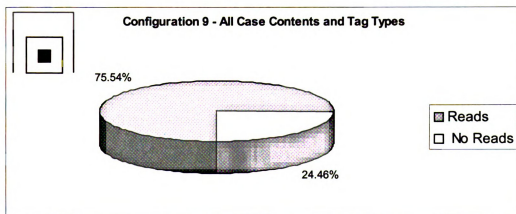


Figure 21. Percentage of Reads for Configuration 9

There are two aspects of antennae configuration that are responsible for the differences seen above, the location of the antennae, and the number of antennae used. The location portion has been segmented into 3 groups for analysis; Top, Side, and Combo. The Top segment consists solely of configurations in which the antennae are above the pallet load reading down, the Side segment consists solely of configurations in which the antennae are on the side of the wooden portal and the Combo segment consists of those configurations in which antennae are both above the pallet load and on the side. There are 3 configurations in the Top group, 4 configurations in the Side group and 2 configurations in the Combo group.

Antennae Configuration – Location of Antennae

The results listed below have been grouped into segments based on the location of the antennae. All three segments include 3 case contents, 2 tag types, 48 tagged cases and 25 trials. The Top segment consists of 3 configurations for a total of 21,600 possible reads, the Side segment consists of 4 configurations for a total of 28,800 possible reads, and the Combo segment consists of 2 configurations for a total of 14,400 possible reads.

1. Top antennae, for all case contents and both tag types, had a total of 14,777 out of a possible 21,600 reads for a read rate of 68.41%.
2. Side antennae, for all case contents and both tag types, had a total of 24,154 out of a possible 28,800 reads for a read rate of 83.87%.

3. Combo antennae, for all case contents and both tag types, had a total of 13,236 out of a possible 14,400 reads for a read rate of 91.92%.

These results show that the readability was significantly affected by the location of the antennae. This information is illustrated in figures 22, 23, and 24.

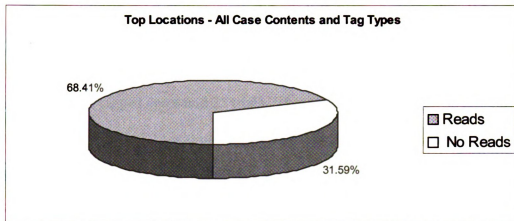


Figure 22. Percentage of Reads for Top Antennae Configurations

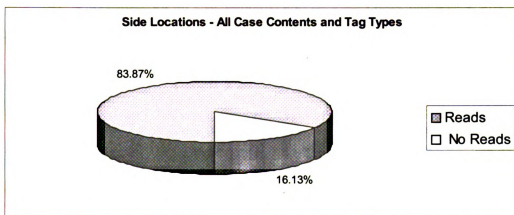


Figure 23. Percentage of Reads for Side Antennae Configurations

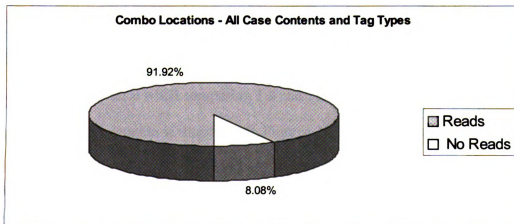


Figure 24. Percentage of Reads for Combo Antennae Configurations

Antennae Configuration – Number of Antennae

The results have also been segmented into number of antennae groups, 4 antennae, 3 antennae, 2 antennae and 1 antenna. The results listed below have been grouped into segments based on these groups. All four segments include 3 case contents, 2 tag types, 48 tagged cases and 25 trials. There were 2 configurations utilizing 4 antennae, for a total of 14,400 possible reads, 1 configuration utilizing 3 antennae, for a total of 7,200 possible reads, 4 configurations utilizing 2 antennae, for a total of 28,800 possible reads, and 2 configurations utilizing 1 antenna, for a total of 14,400 possible reads.

1. 4 antennae, for all case contents and both tag types, had a total of 13,179 out of a possible 14,400 reads for a read rate of 91.52%.
2. 3 antennae, for all case contents and both tag types, had a total of 6,680 out of a possible 7,200 reads for a read rate of 92.78%.
3. 2 antennae, for all case contents and both tag types, had a total of 22,188 out of a possible 28,800 reads for a read rate of 77.04%.
4. 1 antenna, for all case contents and both tag types, had a total of 10,120 out of a possible 14,400 reads for a read rate of 70.28%.

These results show that there is not a significant difference between 3 or 4 antennae, and that there is also not a significant difference between 1 or 2 antennae. However there is a significant difference when comparing 3\4 and 1\2 antennae.

This information is illustrated in Figures 25, 26, 27, and 28.

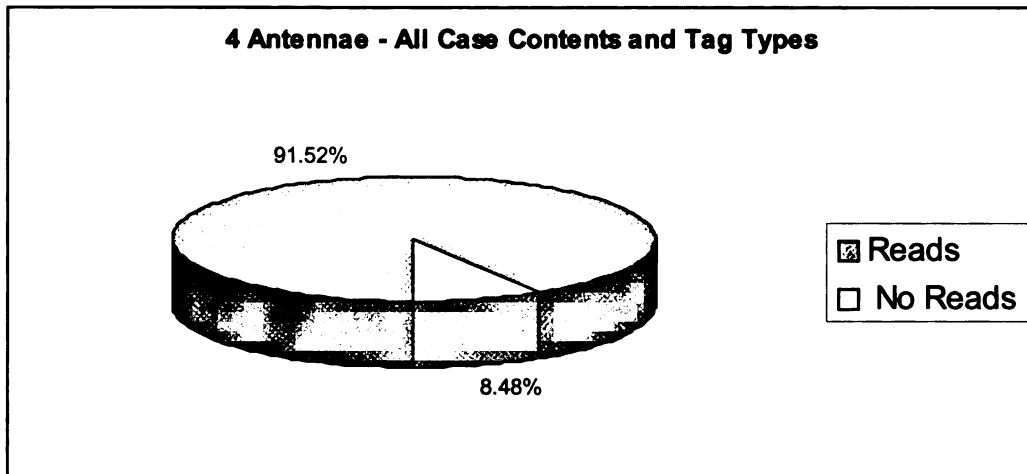


Figure 25. Percentage of Reads for Configurations with 4 Antennae

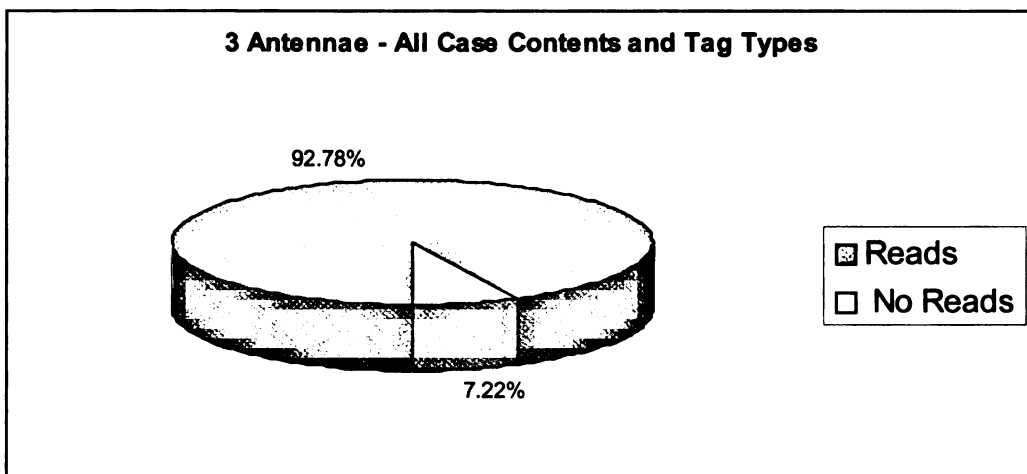


Figure 26. Percentage of Reads for Configurations with 3 Antennae

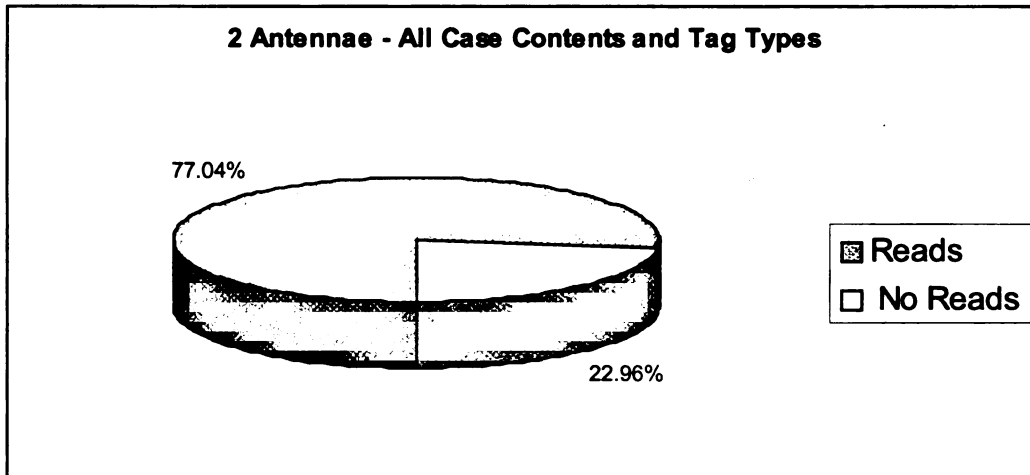


Figure 27. Percentage of Reads for Configurations with 2 Antennae

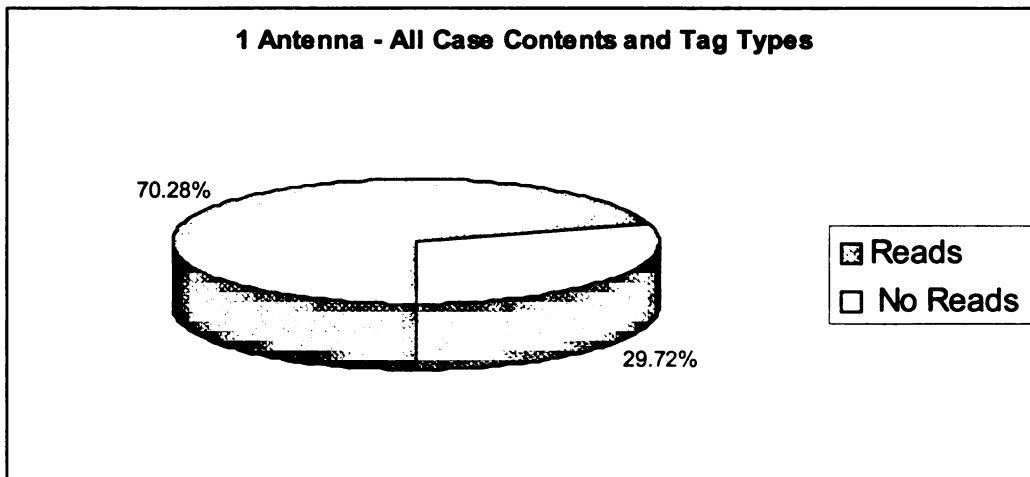


Figure 28. Percentage of Reads for Configurations with 1 Antenna

There were variations within the configurations that utilized two antennae. The results ranged from 65.00% reads to 84.22% reads and because the number of antennae was constant it can be confirmed that the location of the antennae was responsible for this difference. The variation in results can be seen in the table below.

Table 5. Variation in configurations with 2 antennae

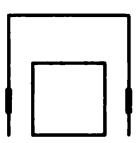
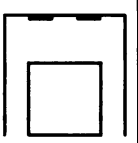
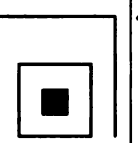
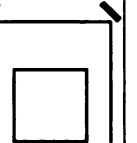
Diagram				
Configuration #	4	5	6	7
Total %	84.22%	75.56%	65.00%	75.56%

Table 6. Results for Empty Cases

Configuration #	Configuration	Empty Alien		Empty Symbol	
		Total Reads	%	Total Reads	%
1	4 Antennae:2 Side 2 Top	1200	100.00%	1200	100.00%
2	4 Antennae: 2 On Each Side	1200	100.00%	1200	100.00%
3	3 Antennae: 1 Top, 1On Each Side	1200	100.00%	1200	100.00%
4	2 Antennae: 1 On Each Side	1200	100.00%	1200	100.00%
5	2 Antennae: On Top	1200	100.00%	1200	100.00%
6	2 Antenna: Adjacent Sides	1200	100.00%	1200	100.00%
7	2 Antennae: On Top @ 45 Degrees	1197	99.75%	1146	95.50%
8	1 Antenna: On Top	1072	89.33%	999	83.25%
9	1 Antenna: On A Side	1200	100.00%	1200	100.00%
	Totals	10669	98.79%	10545	97.64%

Table 7. Results for Rice Filled Cases

Configuration #	Configuration	Rice Alien		Rice Symbol	
		Total Reads	%	Total Reads	%
1	4 Antennae:2 Side 2 Top	1182	98.50%	1187	98.92%
2	4 Antennae: 2 On Each Side	1197	99.75%	1186	98.83%
3	3 Antennae: 1 Top, 1On Each Side	1200	100.00%	1165	97.08%
4	2 Antennae: 1 On Each Side	1153	96.08%	1073	89.42%
5	2 Antennae: On Top	796	66.33%	1067	88.92%
6	2 Antenna: Adjacent Sides	1169	97.42%	1046	87.17%
7	2 Antennae: On Top @ 45 Degrees	671	55.92%	820	68.33%
8	1 Antenna On Top	707	58.92%	1000	83.33%
9	1 Antenna On A Side	935	77.92%	788	65.67%
	Totals	9010	83.43%	9332	86.41%

Table 8. Results for Water Filled Cases

Configuration #	Configuration	Water Alien		Water Symbol	
		Total Reads	%	Total Reads	%
1	4 Antennae:2 Side 2 Top	887	73.92%	900	75.00%
2	4 Antennae: 2 On Each Side	832	69.33%	1008	84.00%
3	3 Antennae: 1 Top, 1On Each Side	864	72.00%	1051	87.58%
4	2 Antennae: 1 On Each Side	627	52.25%	811	67.58%
5	2 Antennae: On Top	630	52.50%	523	43.58%
6	2 Antenna: Adjacent Sides	665	55.42%	748	62.33%
7	2 Antennae: On Top @ 45 Degrees	498	41.50%	348	29.00%
8	1 Antenna On Top	503	41.92%	400	33.33%
9	1 Antenna On A Side	601	50.08%	715	59.58%
	Totals	6107	56.55%	6504	60.22%

CHAPTER 5 – CONCLUSIONS

The results of the testing described in previous chapter show that product (case content) and antennae configuration have a significant impact on the readability of RFID tags in a pallet load being read on a stretch wrapper. The results also show that the type of tag, in this situation, has little effect at all. The hypotheses outlined at the start of this research were evaluated and determined to be true or false. The outcomes of this evaluation are listed below.

Hypothesis 1. The case contents will have a similar effect on the readability of RFID tags at the stretch wrapper as they did at the portal.

This hypothesis was found to be true. Empty cases had no effect on the readability of tags, rice filled jars decreased the readability, and water bottled filled cases significantly decreased the readability.

Table 9. Results for Case Content

Case Content	Empty	Rice	Water
Total Read %	98.21%	84.92%	58.39%

Hypothesis 2. The tag type will not have an effect on the readability of RFID tags.

This hypothesis was found to be true. There was no significant difference in the readability of Alien squiggle tags versus Symbol Double Di-Pole tags across all case contents and antennae configurations.

Table 10. Results for Tag Type

Tag Type	Alien	Symbol
Total Read %	79.59%	81.42%

Hypothesis 3. The number of antenna utilized will not affect the readability of RFID tags.

This hypothesis was found to be false. While there was not a significant difference in comparing 3 and 4 antennae, or 1 and 2 antennae, the groups were significantly different, showing that there is a dramatic increase in reads when adding the 3rd or 4th antenna.

Table 11. Results for Number of Antennae

	Number of Antennae			
	1 Antenna	2 Antennae	3 Antennae	4 Antennae
Empty	93.15%	99.41%	100.00%	100.00%
Rice	71.47%	81.20%	98.54%	99.00%
Water	46.23%	50.52%	79.79%	75.57%
Total	70.28%	77.04%	92.78%	91.52%

Hypothesis 4. The location of the antenna utilized will not affect the readability of RFID tags.

This hypothesis was found to be false. Antennae that were above the pallet load, facing down had a lower read rate than antennae that were on the side of the pallet load, and a significantly lower read rate than configurations that had a combination of both top and side antennae.

Table 12. Results for Location of Antennae

	Location of Antennae		
	Top	Side	Combo
Empty	94.64%	100.00%	100.00%
Rice	70.30%	89.04%	98.63%
Water	40.31%	62.58%	77.13%
Total	68.41%	83.87%	91.92%

The effect of package content was quite clear for this situation. Empty cases served as the baseline, and yielded by far the best reads with only 2 of the 9 configurations (numbers 7 and 8) had any misreads at all. Rice filled cases were the next best, and while none of the configurations yielded 100% reads, 5 of the 9 (numbers 1,2,3,4, and 6) were over 90%. Water filled cases were by far the worst, with none of the configurations over 80%, and some as low as 35%. This progression from empty cases to dry product to water filled cases shows the same relationship to readability as was found in the Master's Thesis work by Jeff Tazelaar^[3]. A major difference however was found in the water results, due to the test method. In Tazelaar's research the pallet load was walked through an RFID equipped portal, and in this research the pallet load was spun on a stretch wrapper. This new test method yielded much higher results for the water cases. The variable for the Tazelaar testing was tag orientation, and the highest read rate that was obtained was 67% and the rest of the results were much lower, with 2 virtually reading 0%. Contrasted with the stretch wrapping method, where the 6 of the antennae configurations yielded read rates of over 50% and 35% was the lowest result observed. The reason for this is twofold. First, the tags spend an extended period of time in the read field as the stretch wrapper runs its program, allowing more tags to energize and release their information. Secondly the rotation of the load allows for multiple tag orientations, which also aid in the readability.

As previously mentioned, the tag type for this research did not have a significant effect on readability. While there were some differences between the tag manufacturers for certain case content/antennae configuration combinations, the results were proven to be statistically insignificant.

The antennae configuration was found to have an impact on readability. Both components of the configuration, number and location of antennae, played a role in this. As shown in tables 11 and 12, the configurations which only had antennae above the pallet load, reading down, performed the worst, configurations that only had antennae on the side performed next best, and configurations that utilized antennae in both of these locations performed the best. As far as the number of antennae is concerned, some interesting results were observed. There was no significant difference in switching from 1 to 2 antennae, and there was also no significant difference in switching from 3 to 4 antennae. There was however a large statistical difference between the 2 groups (1 and 2 vs. 3 and 4). This is important to know because if you are getting the reads necessary with 2 antennae, it may be possible to drop down to 1. Also if you are not getting the required reads with 2 antennae, it can be observed that adding a third will significantly increase your readability.

Now the question becomes at what point is the percentage of reads that are being obtained acceptable for use in industry. As shown by these tests, the results are nowhere near 100%, even with steps being taken to optimize the situation. The preliminary thought on RFID was that in order for it to be used on a widespread basis, the results needed to be flawless. The nature of the technology prevents this from being a possibility, so implementers are altering their stance. Now it appears that 100% reads are not necessary, as long as each item is found to be present. This means that the use of a backup plan is necessary, or at least some redundancy in the system. For instance, if a tag is read at one point along the distribution chain, and then again further along, it is not necessary for the tag to be read at all points in between. This is an example of a

redundant system. An example of a backup system would be in the use of RFID as a toll collection on a highway. As a car passes the toll booth, a tag is read and the fee is deducted from a predetermined account number. If the car is traveling too fast, or it is raining out or for some other reason the tag does fails to read, a snapshot of the car's license plate is taken and a bill is mailed to the person the car is registered to. In this case 100% reads are not required, as long as 100% of the fees are still collected in one manner or another.

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