Radio Frequency Identification

EECS 189: Senior Design Project

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Introduction to RFID

Radio Frequency Identification, or RFID is a technology which stores data on a small chip and is able to transmit and receive data remotely. It can be used like barcodes, but with much more capability and potential because it can store more data and does not require line-of-sight. Active RFID tags, which are powered by batteries, are commonly used in devices such as FastTrak for paying tolls without stopping. Passive RFID tags, which are remotely powered by energy absorbed from radio waves, are used to manage supply chains in the US military and are becoming more common in warehouses, libraries, and some retail stores. If the cost and size of passive RFIDs are reduced and reliability increased enough, they could potentially be used in lieu of barcodes in almost all retail stores, replace credit cards and passports, enable better tracking of shipments, and be used in places that barcodes could never be feasible, like being embedded into clothing. RFID has a huge commercial potential if the prices are right and the technology becomes small enough.

Motivation and Objectives

The problem with passive RFID tags is their cost, range, size and unreliable read rates. Current tags, such as the Alien Gen 2, only have a reliable read range of approximately 12", cost around $.25 each in high volume, and are 3"x 1" and very thin. In order to increase RFID's usability in the commercial world, Professor G.P. Li proposed that we design an RFID antenna with increased range and a smaller size. A tag that was much smaller could be embedded in more products like clothing, and tags with a longer range could make package tracking more efficient and reliable. We decided to accomplish this by designing two different versions of our tag to improve two different problems –

increase range and decrease size by researching various aspects of antenna design. Specifically, we proposed to research the effects of size and geometry on read range and reliability. Our baseline was the Printronix Alien Gen 2 RFID tag shown in Figure 1.

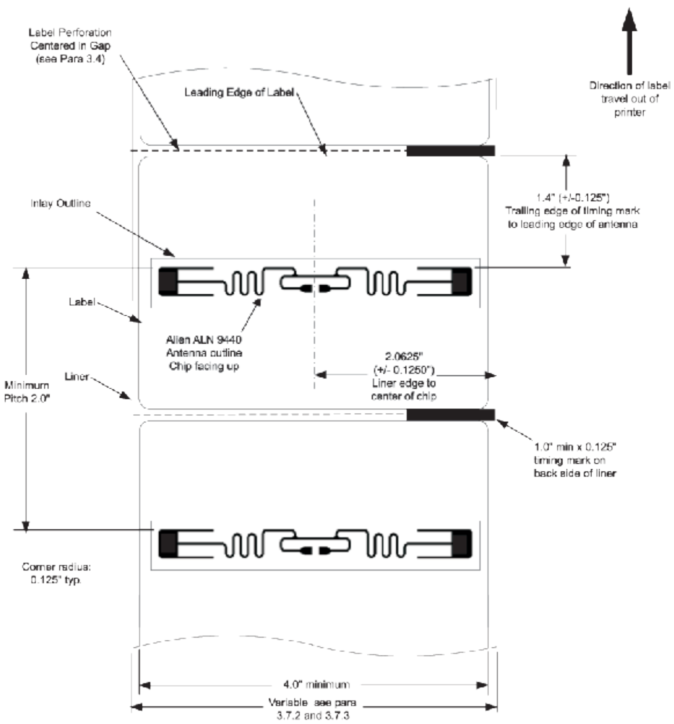

Figure 1: Alien Gen 2 RFID tag from Printronix

Our goal was to improve upon this design in two ways – one to make a smaller tag with nearly comparable performance, and the other was to improve the performance but maintain the size. We decided to manufacture many different tags and compare them against each other as well as against the commercial Alien Gen 2 tag. We decided to start by investigating the effects of number of antenna turns, geometric shape of antenna, and thickness of traces.

Background and Research

While learning how to manufacture our own antennas using lithography, we also began our research on RFID technology and different theories of antenna design.

To design effective RFID tag, an understanding of its operating principles must be achieved. Based on experimentation as well as various online sources, two hypotheses of the tag operating principles were postulated. Both hypotheses agreed on the following two points: (1) that the design of the antenna directly affected the performance and (2) the antenna served a dual purpose, to harvest incoming RF power, which is used to power-up the RFID chip and serve as an antenna for transmitting signals. The hypotheses differed on the design principles resulting in an antenna that is efficient in both harvesting and transferring RF power to the chip.

Hypothesis 1

The RFID tag's antenna is an induced coil forming a mutual inductor or transformer between the tag and the reader.

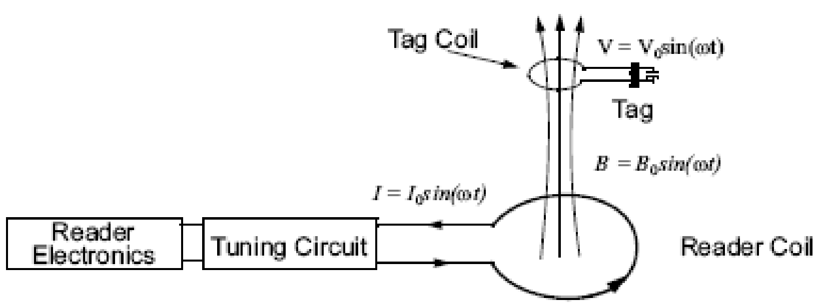

Figure 2: Inductive Antenna

The RFID reader generates a magnetic field using its own inductor coil. The magnetic field is generated following Ampere's Law, sending a current through a conductor which generates a magnetic field. In the case of the RFID Reader, an alternating current is sent though the reader coil to generate a magnetic field of varying intensity. The intensity of the magnetic field for an infinitely long conductor given below for the purpose demonstrating Ampere's Law combined with an AC current.

$B = \frac{\mu_0 I}{2\pi r}(Weber / m^2)$ $\qquad I = I_0 \sin(\omega t)$

$B = B_0 \sin(\omega t)$

The magnetic field is sent out from the reader over the air where it will eventually reach an RFID Tag. Since the tag has a finite surface area, only fraction of the total amount of magnetic field reaches the tag, this is called magnetic flux. The magnetic flux at the tag is also changing as the magnetic field from the reader is changing. The tag antenna utilizes Faraday's Law, by using the change magnetic flux to induce a voltage.

$$V = -\frac{d\Phi_B}{dt}$$

The induced voltage is then rectified, converted to DC, and used to power the RFID chip. However, the antenna coil must induce a large enough voltage to power-up the RFID chip. The amount of induced voltage can be affected by many factors, distance, conductor losses, magnetic field intensity, and number coil turns. The effect of these many factors is demonstrated with the following equation derived based on the Reader Coil / Tag Coil diagram given above.

$V = 2\pi f N S Q B_0 \cos\theta$ where,

f = Reader's operating frequency

N = number of coil turns

S = coil surface area

B = magnetic field strength

Based on the theories established regarding the operating principles of the antenna coil, to improve range we should design tags to maximize the magnetic flux.

Hypothesis 2

The RFID tag's performance is dependant on how well the impedance of the tag antenna matches the RFID chip impedance for maximum power transfer.

Hypothesis 2 was postulated after designs based on Hypothesis 1 failed to produce conclusive results. Antenna tags with more inductive and magnetic flux maximization performed worse. After consulting with Professor Li, we discovered that the efficiency of mutual inductors and transformers decayed as the operating frequency increased. Since our tags operated at 915 MHz (UHF), the frequency is far too high for transformer principles to apply. Furthermore, transformers typically use magnetic flux material, whereas in our case our flux material is air. Based on the fact that the mutual inductors and transformers simply do not operate effectively in at UHF, we concluded that Hypothesis 1 was fundamentally flawed.

In the UHF range, the wave length of the signal becomes comparable to the dimensions of the tag's antenna trace lengths. Transmission line effects need to be taken into account. Various lengths of the transmission line will produce different reflection coefficients, where percentages of the signal will be reflected or absorbed. The refection coefficient of the tag and its antenna is directly controlled by the impedance of the antenna and the RFID chip. When the RFID antenna's impedance is the complex conjugate match to the RFID chip's impedance, the reflection coefficient drops to zero, and all of the signal power is transferred to the chip. The impedance of the RFID Chip used in our experiments are approximately $(10 + j150)\ \Omega$, mostly capacitive. To match this impedance the antenna's on our RFID Tags should be approximately $(10 - j150)\ \Omega$, mostly inductive.

The RFID Chip also operates under the principal of impedance matching. The chip alternates between a matched and mismatched impedance to transmit and receive RF signals.

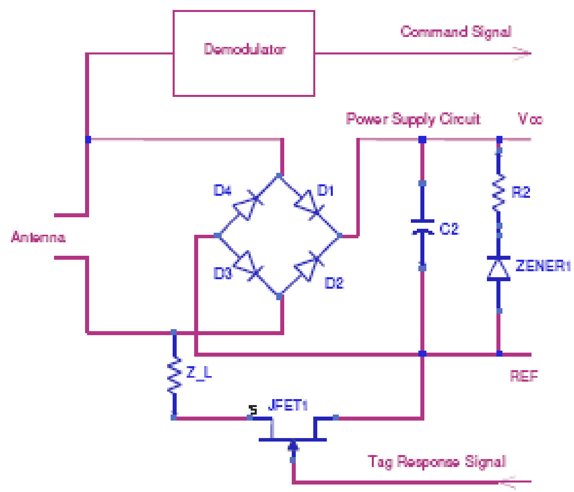

Figure 3: Powering an RFID Chip

Initially when a signal is received the chip is a matched load effectively absorbing all of the incoming RF power. The absorbed RF Power is rectified, converted to DC and used to power the rest of the chip. When the chip transmits a signal, the chip's effective impedance is changed to a mismatch, where the reflection coefficient is 1. This effectively reflects the incoming RF power back to the reader. The constant alternating between matched and mismatched load is the basis of how the RFID tag communicates to the reader. We can see that antenna must match the impedance the RFID chip is expecting.

Sources of Theory

Most of our theories were derived from IEEE, Ph. D. Thesis and Master Thesis papers found on the World Wide Web. Hypothesis 1 was derived by a paper written by Youbok Lee, Ph. D. at Microchip Technology Inc. Understanding Hypothesis 1 also required a basic understanding Electromagnetic theory taught in lower division Classical Physics classes and Franco De Flaviis's Electromagnetics course (EECS 180). Hypothesis 2 was developed after analyzing the inconclusive results of the RFID tags. After consulting with Processor G. P. Li, we were able to surmise that Hypothesis 1 was fundamentally flawed. Using knowledge recently gained from Franco De Flaviis's MMIC Design course (EECS 182), we understood the significance of impedance matching. After reviewing several IEEE publications, a master thesis, and part of a Ph. D thesis we postulated Hypothesis 2. Grasping the concepts and building our hypotheses would not have been possible without the knowledge gained in those courses, the advisement of Professor Li, and the publications we have read.

This research and literature was essential to our designs and our understanding of RFID tags and antennas. We realized that this type of research using published literature and the knowledge of others such as our advisor is always a necessary part of any design project.

Economic and Ethical Issues

With the introduction of the technology of RFID tags there are many potential applications for its use. But because of certain issues that come from RFID technology, there are also some ethical issues involved. In the worlds economy RFID tags can help increase the productivity of the shipping industry. RFID's can be used to replace or used with barcodes so that shipping companies can keep better track of there products. RFID's can also be used for product tracking in stores like Wal-Mart. Each item can be tagged with a simple RFID chip so that the company can keep track of all the items in the store which would also help prevent any theft. Lastly RFID chips can be used to increase security like in passports. If you passport was tagged with an RFID chip, the passport would contain lots more information about the person which would help decrease the chances of there being any type of identity fraud.

The ethical problem with RFID tags are that even though companies can keep better track of there products, other companies can also help themselves to that information. This is because RFID's antennas emit their signal in all directions so that anyone can receive and analyze the signal. Also current RFID tags have no real significant security measure so that if someone wanted to steal information from someone all they would have to do would be to get an RFID reader and then they would be able to get all the data on the chip. But with the advancement of RFID technology, hopefully by the time the technology becomes mainstream, these issues will be solved.

Visiting Printronix

After performing much of our initial research and forming our first hypothesis, we visited Printronix, a company that makes printers for RFID tags. While there, we learned about some of their RFID tags and the problems they encounter while reading and writing tags at high speeds and in close proximity to other tags. One of the interesting facts we learned was that as an RFID printing company, they were not interested in the performance of the RFID tags, but were only interested in improving the manufacturability and printability of the tags. This meant they had an entirely different perspective of RFID tags, and focused on aspects that we had never considered in our original proposal. Although we learned a lot about manufacturing RFID tags and printing them at high speeds, we did not gain much information on improving range and size of antennas.

Steps, Methods, and Techniques

Collaboration and Documentation

After determining our goals and requirements, we immediately put our project onto a website, FTP server and online forum so that each of us could independently perform our research and tasks, and also collaborate and share our findings. This also allowed us to share software, files, research papers and action items from each meeting. Setting up this kind of online collaboration was essential to the efficiency and effectiveness of our project. We were able to constantly communicate between all group members while sharing important files and other information, and also keep everything recorded and organized. We were able to look back from the beginning of the project through the end, and see all action items and goals that we met and what we failed to meet.

Manufacturing

The next step in our project was to learn how to manufacture our own antennas. We researched a number of possible methods of manufacturing small circuits, including sending our design to a company such as PCB Express, drawing our own antenna using solder or silver Epoxy, and using various techniques of lithography. After analyzing the quality and cost of each method, we narrowed our options down to using a company such as PCB Express and using lithography. Using a company would cost around $100 per tag to produce, restrict us to the company's software, and require several days to manufacture and ship; but would also yield high quality antennas with nearly 100% reliability. Learning lithography would cost less than 1 dollar per tag, enable us to use any software we wanted, and take a few hours to manufacture; but would require us to buy many extra materials, learn and experiment with the lithography process, and would not yield perfect antennas every time. After weighing the costs, benefits, and time, we decided to use lithography to make our own tags instead of paying a company such as PCB Express to make the tags. This allowed us to make nearly unlimited tags for very low cost, which allowed us to try many different antenna designs. Although this method was not as reliable as using a company, we thought that we could yield circuits with that would meet our requirements. However, we also had to consider the safety of using the acids and chemicals, so we were careful to always use safety goggles, work in open areas, use only glassware, and have baking soda nearby in case of any spills. We also disposed of all etching solutions by mixing a 5:1 solution of water and solution and adding baking soda to neutralize the acid.

We performed a more exact analysis of our material costs by searching prices online, and came up with a budget shown in Table 1.

Table 1: Budget Estimates

10x Copper Clad Boards	$35.00
Staples High Gloss Photopaper	$15.00
Silver Conductive Epoxy	$20.00
Corded Iron	$15.00
Acetone	$1.50
5x Hydrogen Peroxide	$10.00
Measuring Cup	$4.00
2 Gallons Muriatic Acid	$7.50
Glass 9in Plate	$5.00
Air Pump	$5.00
Total:	**$118.00**

In addition to budgeting our costs, we also decided to devote 4 hours per week of time to learning the lithography process, although we spent far more hours in the beginning. The time spent learning lithography was in addition to the 4 hours per week we had devoted to research and design, plus the 1 hour meeting with our advisor each week.

For our lithography process, we purchased copper clad boards, high-gloss photo paper, an iron, Muriatic acid, hydrogen peroxide, an air pump, silver epoxy, a glass measuring cup, and a glass pan. We started by printing an image of the pattern of the antenna onto the high-gloss photo paper using a laser printer. We then ironed the paper against the copper clad board, which transferred the toner from the paper onto the board, and then removed the excess paper. We mixed the hydrogen peroxide and Muriatic acid in a 2:1 solution and poured it into the glass pan, and placed the copper board into the solution. We also added the air pump to agitate the solution and speed up the process. After about 30 minutes, we removed the copper board, rinsed it off, and scrubbed off the toner. During the process, all exposed copper that wasn't covered by the toner was etched off the board, leaving only the printed pattern. After etching the antenna onto the board, we mounted the commercial RFID chip from Printronix onto the antenna using silver epoxy.

As shown in Figure 4 below, it took many trials and several failed attempts before we were able to build functional antennas. As we manufactured more antennas, we improved our lithography process and were able to consistently make reliable and high quality antennas.

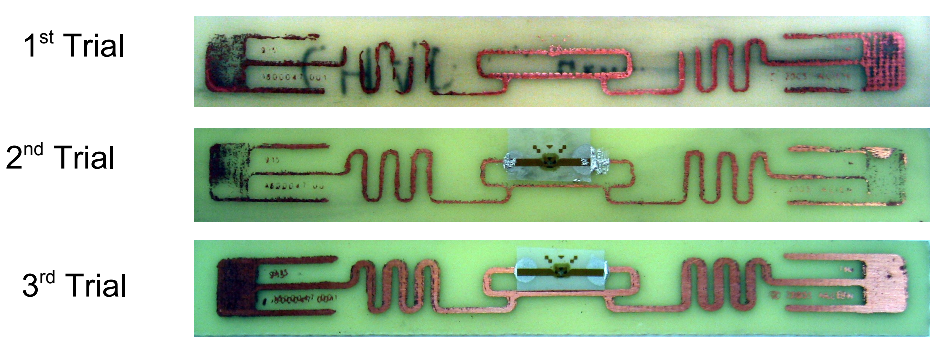

Figure 4: Lithography Quality Progression

Designing Tags Under Hypothesis 1

Under our Hypothesis 1 theory, we designed several tags to optimize inductance by varying antenna geometry and number of turns. We made each tag's 3" x 3" antenna design using MSW Logo and Adobe Photoshop. As shown in Figure 5, we made a circle, octagon, and square antenna with 1, 10, and 25 turns.

Figure 5: Hypothesis 1 Testing Part 1

After manufacturing these designs, we also tried making tags with thicker traces to reduce Ohmic losses and improve resistance, and also reduce the size of the tags to 1.5”x1.5”. We designed the antennas shown in Figure 6 using MSW Logo and Adobe Photoshop.

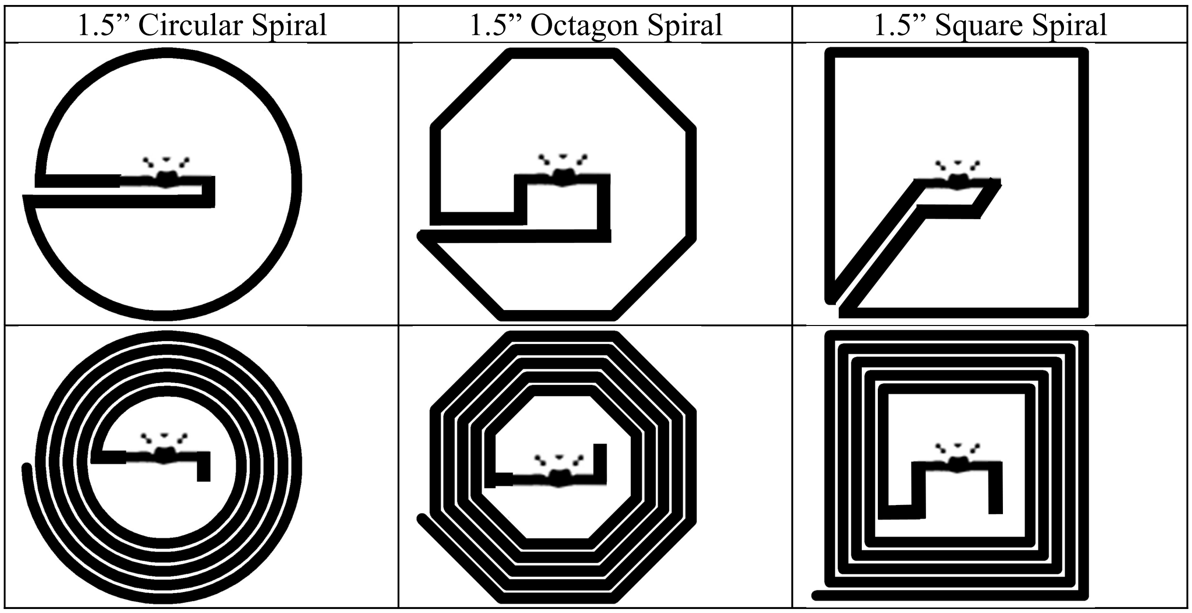

Figure 6: Hypothesis 1 Testing Part 2

Designing Tags Under Hypothesis 2

Designing RFID antennas for precise impedance matching is an incredibly complex process. There is no simple way to determine the impedance of copper traces at a given frequency by hand. Instead, antenna designs are drawn on an EM CAD program and simulated. With general knowledge and experience of how to create inductive and capacitance effects, and after running many simulations, designers can tune their designs to match desired impedance. For this project, our group used Ansoft Designer to draw and simulate our RFID tags. The student version of Ansoft Designer does not allow the simulations of designs longer than 1cm, and the full commercial version required was far beyond the scope of our budget. Once the tags are manufactured, an impedance analyzer must be used to determine the real world impedance of the tag's antenna. Our group did manage to gain access to a network analyzer; however the impedance analyzer component of the unit was missing and no where to be found. With an EM CAD program and an impedance analyzer, designers can potentially build a fined tuned RFID tag capable of reaching ranges up to thirty-feet.

In order to control the impedance of our antenna, we decided to try a Meander antenna, as shown in Figure 7. With this antenna, the strip of copper at the bottom is used to control the capacitance, and the meandering traces above control the inductance. In order to determine the proper lengths, the capacitive strip of copper at the bottom and inductive strip above is trimmed shorter to tune the tag for optimum length during testing.

Figure 7: Meander Antenna under Hypothesis 2

Our next attempt to optimize impedance was to design a patch antenna, as shown in Figure 8. The large block of solid copper is the patch antenna, and a stub-matching network is used to achieve impedance matching. Stub-matching is a short circuit or open circuit placed an exact distance from the chip on a transmission line to mimic the effects of a capacitor or inductor. The amount of mimicked capacitance and inductance depends on the distance the short circuit is placed from the antenna. Since we did not have a commercial copy of Ansoft Designer, the only method was to manufacture several tags of varying stub lengths and test each to determine the best.

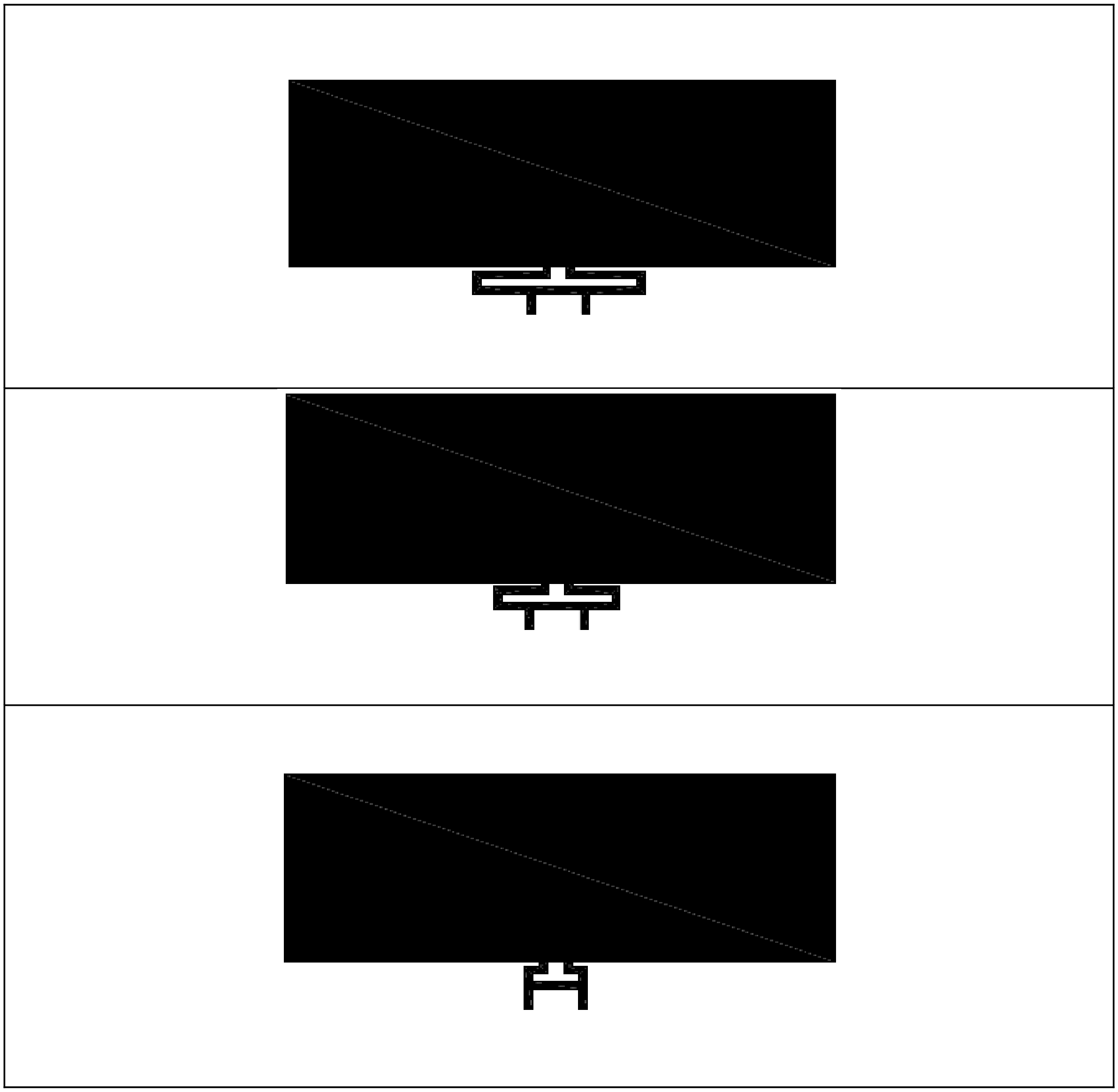

Figure 8: Patch Antenna under Hypothesis 2

Alternative Designs and Solutions

Throughout the process of designing and constructing our tags we encountered many different ideas and solutions to our problems. One of our goals for designing our tag was to create a tag that gave off the same signal in all directions. We tried to design a tag by designing a three dimensional tag in the shape of a pyramid. This idea did not come to fruition due the fact that we realized that with our supplies and PCBs on hand, we would be unable to manufacture a 3-dimensional tag without creating so much loss that the antenna itself wouldn't work. We also tried designing a fractal tag which would theoretically work as well as a normal tag but at a smaller size. We designed and built a fractal tag, but it did not meet the performance of other simpler solutions while testing. One of our problems while we were designing and building our tags was that we lacked the proper equipment to analyze them. We were able to find a solution by finding an impedance analyzer so that we could measure the impedance of the antenna and try to conjugate match our antenna with the chip of the tag. But we found out the parts for the analyzer were missing so that we ended not using it. Another solution we found was to find software that would enable us to design and analyze an antenna all on the computer. We were able to get our hands on the student copy of Ansoft Designer which was supposed to enable us to design and analyze any tag on the computer. But found out the student edition prevented us from designing the tags that we needed. Even though we were able to come up with many designs and found many solutions, none of these designs and solutions could help us in our path to designing a tag with our specifications.

Best Solution

After researching many alternative solutions to designing an RFID tag with maximum range and minimum size, we decided that a 3-dimensional tag would be nearly impossible to manufacture for the design project and too costly to be viable as a commercial solution. Other materials were too expensive for our project and we were not convinced they would yield any better performance. Therefore, we decided to take a simplistic approach and use standard copper clad boards as the basis of our antenna and silver epoxy to attach the RFID chip. We decided to begin with simple geometric shapes and varying number of turns to observe the effects of different antenna properties. We used simple software such as MS Logo to create the geometric shapes and print them to be used for our lithography process.

Testing and Results

We then tested the performance of our replica against the commercial tag, with almost identical results, which meant our lithography process was comparable to commercial tag's quality. We continued testing by creating antennas of simple geometric shapes, i.e. square, octagon, circle, etc. and using different numbers of turn to observe the effects on performance. After manufacturing and testing over a dozen different tags, we concluded that a large octagonal antenna with 10 turns could outperform a commercial tag, but was much larger and more expensive. We also researched the effects of antenna impedance on performance, and decided to test various thicknesses of traces, and concluded that trace thickness and impedance has a very large impact on read range. We have been continuing to research other factors in RFID read range in various RFID books and online sources, and have concluded that impedance has the largest impact on read range. We have decided to finish out our research project by further investigating the effects of impedance by manufacturing various impedance controlled antennas including a meandering and fractal antenna.

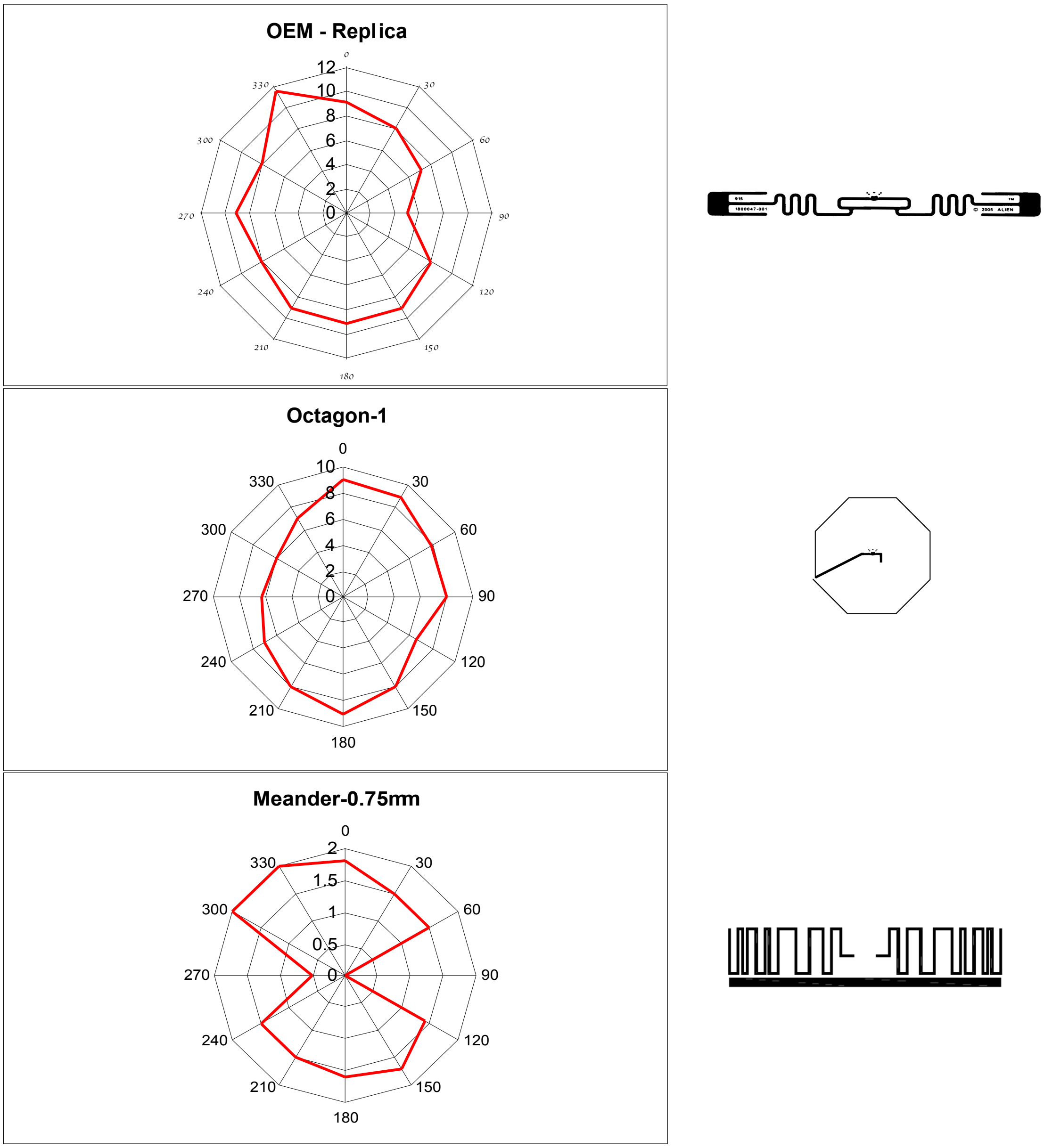

Figure 9: Read Angles

Table 2: Hypothesis 1 Testing Results

Tag Design	Max Range
OEM	10.5”
Replica	9.5”
1-Turn Square	6.5”
1-Turn Octagon	11.5”
10-Turn Octagon	2”

10-Turn Square	4.5”
10-Turn Circle (Broken)	2”
25-Turn Octagon	0”
25-Turn Circle	0”
25-Turn Square	0”
1-Turn Small Square	1”
1-Turn Small Octagon	1”
1-Turn Small Circle	1”
5-Turn Small Octagon	0”

Table 3: Hypothesis 2 Testing Results

Tag Design	Max Range
OEM	10.5”
Replica	9.5”
Patch 3	0”
Meander - 1.0mm	7”
Meander - 0.75mm	2”
Fractal	0”

Conclusion

Throughout the project we have encountered many problems and have come up with numerous solutions. We were able take a problem and analyze it so that we could find a solution for it. Through the process of designing, building, and testing our tags, we did a lot of research into RFID and antenna technology so that we would be able to accomplish our goals. We were able to learn a lot about the theory of how antennas work from books, internet, and even some of our classes. From what we learned we were able to slowly figure out how to design an antenna with our goals. But throughout the project we had numerous issues like finding a method in building our antennas without going over budget and in a timely fashion. We were able to accomplish this by using PCBs and etching the antenna designs onto them. This gave us the opportunity to create as many tags as we wanted practically instantly without spending very much money. Another problem we had was having the right equipment to create, test, and analyze our RFID tags. We solved these issues to a certain degree by borrowing our faculty mentor's RFID reader so that we could test the range of our tags. We also were able to get our hands on certain Ansoft software like Ansoft Designer and Ansoft HFSS which helped us analyze our tags which helped explain to us why one would work better than another. But due lack of equipment and lack of time we were only able to design, build, and test a certain number of tags with little success in accomplishing our goal. In hindsight there are certain routes that we believe we should not have taken. We think that because we spent so much time on learning about how antenna technology worked, we should have spent a little more time just building and testing the tags which may have helped us figure out how to accomplish our goals quicker. We also believe that we should have looked harder for software that exists because near the end of the project we found out by chance that there existed software that would have enabled us to design and analyze an antenna all on a computer. If we had found out about this at the beginning of the project we could have saved lots of time and probably been able to come up with a design that would have accomplished our goals. But at the end of the project we were unable to fully accomplish our goal of creating an antenna that had farther range capabilities than a conventional antenna. But at the end of the project we were unable to fully accomplish our goal of creating an antenna that had farther range capabilities and a smaller size than a conventional antenna. Even though we were unable to accomplish our goal we think that because we were able to learn so much throughout the project, if we had a few more weeks we could have come out with an antenna that would definitely have farther range than conventional tags.

Appendix A: Software

1. Ansoft Designer
2. MSW Logo
3. Adobe Photoshop
4. Ansoft HFSS

Appendix B: References

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