2006-07-15

# Incorporating Wireless Power Transfer in an LED Lighting Application

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# INCORPORATING WIRELESS POWER TRANSFER

# IN AN LED LIGHTING APPLICATION

by

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A thesis submitted to the faculty of

Brigham Young University

In partial fulfillment of the requirements for the degree of

Master of Science

School of Technology

Brigham Young University

August 2006

BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

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This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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| Date | Barry Lunt |
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BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read the thesis of Jonathan S. Shipley in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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# ABSTRACT

## INCORPORATING WIRELESS POWER TRANSFER
## IN AN LED LIGHTING APPLICATION



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There are various situations in which electrical energy is desired but cannot by conveniently supplied. Since the days of Hienrich Hertz and Nikola Tesla, scientists have tried to solve this problem using different methods of wireless power transfer. Today, wireless power transfer has only been commercially demonstrated at small distances through use of induction. This thesis demonstrated the transfer of wireless power at relatively large distances through radio frequencies in the development of a prototype for a commercial product – a wireless household lamp.

ACKNOWLEDGMENTS

I would first like to acknowledge and thank the people close to me who have supported me throughout my education. I am grateful for my wife, Jessica, and my son, Beckham, who have been a giant strength and support to me in my life and in my studies. I love them dearly. I am grateful for the guidance of my Father in Heaven; specific prayers where answered in this thesis when what seemed like insurmountable obstacles were seen. I am thankful for parents who valued education and helped each of their six kids get ahead in life.

I would also like to acknowledge and thank the faculty advisors who made this work possible. I cannot say enough about Dr. Brent Strong. I believe there are few (if any) others who would have chaired this project. His belief and support towards his students is exemplary. I am grateful for Dr. Barry Lunt's help; he spent many hours patiently answering my questions and troubleshooting with me. His help and instruction was invaluable and sincerely appreciated. I am also thankful for Dr. Charles Harrell's willingness to serve on the committee.

Lastly, I would like to thank all those who come to me with innovative ideas urging me to develop them; specifically to my wife's aunt, Shelley Helm, who came to me with the idea to develop a battery-powered lamp.

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# 1 Introduction

There are various situations in which a permanent source of electrical energy is desired but cannot be conveniently supplied. Ishiyama (2003) documented this need in mobile applications such as notebook personal computers, personal digital assistants (PDAs), and radio frequency identification (RFID) tags. Hirai (1999) conveyed it in flexible manufacturing systems; desiring that machines be wirelessly powered to allow product variation with few constraints on power supply. Additionally, it is assumed that there are numerous commercial product applications that could benefit from a wireless power transfer.

This thesis focused on a commercial product need – the need to supply wireless power to household lamps. This need is considered a latent need of many homeowners because it is not widely recognized. It is estimated that in 2000, consumers spent $759.6 million on table and floor lamps (Encyclopedia of American Industries, 2006). In many instances, these table and floor lamps were placed in remote locations within the house that do not facilitate the use of power cords. For example, a lamp may be placed in the middle of a room making it inconvenient to power by cord. For the most part homeowners leave such lamps without power, providing only aesthetic benefits. These lamps are ideal candidates for wireless power. This thesis demonstrates the use of wireless power in a prototype for a commercial product that allows remote lamps to provide both functional (light) and aesthetic (décor) benefits.

## 1.1 Statement of the Problem

Wireless power transfer is a daunting task because few people have ever been able to perform it efficiently at distances longer than about six feet and then only with a very low amount of power. Even fewer people (none at the time of this thesis) have been able to implement long-distance wireless power transfer in commercial applications. Induction has been used as a form of wireless transfer for distances of less than a couple inches; however, this technology is not a feasible method of transferring power across a room.

Wireless power transfer through radio frequencies has also previously been explored. Heikkinen and Kivikoski (2004) measured an output voltage of 1.3 volts (V) when 1.58 watts (W) was transferred two meters using radio frequencies. No example of wireless power transfer beyond these parameters was found.

There are many applications that would benefit from the ability to transfer power wirelessly (even at low wattage) such as the charging of laptop personal computers and cell phones; the appropriate technology must be developed to satisfy these applications.

## 1.2 Purpose of the Study

This thesis proposes a wireless power transfer system that is targeted at delivering enough power to a battery at a distance of 30 feet to be able to power a 4.7 watt (W) light bulb for six hours. A distance of 30 feet was used as a benchmark because a distance of 30 feet would satisfy the needs of most all homeowners; most lamps are placed within at least 30 feet of an outlet. A shorter distance would be less ideal, but would still be acceptable for the needs of many homeowners. 4.7 W was used as the target for the amount of energy needed at the receiving end because of the light bulb selection that will be documented later in the thesis. A duration of six hours was used to allow the battery to be charged for 18 hours to accumulate enough power to allow six hours of operation.

The purpose of this study was three fold. The first objective was to analyze the marketplace to establish the uniqueness of the proposed product. The second objective was to design a wireless power transfer system that would theoretically power a light bulb for six hours. The third objective was to actually build the system and test it to establish its functionality.

### 1.3 Significance of the Study

There is a demand for cordless lamps. Figure 1-1 shows a living room with a lamp that is located in a remote location; the lamp is far from a wall and likely far from an outlet. Many homeowners have lamps in locations such as the one shown in Figure 1-1 and have a need to power these lamps without extending a power cord across the floor. An article published by Newsday.com (2005), states: “We talk on cordless phones, we clean with cordless vacuums, but our homes are crisscrossed with extension cords to accommodate our lighting needs. We have outdoor lamps that can withstand a tropical downpour, so why can’t someone invent a cordless lamp?” The successful development of the technology proposed in this thesis would fill a significant need in the marketplace.

**Figure 1-1 Family Room with Remote Lamp (Pottery Barn 2006)**

Wireless data transfer via the Ethernet protocol was developed in 1988 and widely commercialized in 1999 (Economist, 2004) and it is already prevalent throughout the world; it is found in many homes throughout the world and in most college campuses. Analysts predict that 100 million people will be using Wi-Fi by 2006 (Economist, 2004). It is not unreal to think that a developed wireless power transfer technology would have much the same potential in home and business applications as wireless data transfer experienced.

There are numerous applications, such as cell phones, laptop personal computers, and home theatre equipment, in which wireless power transfer would be desirable. The opportunity to leverage this knowledge into other areas is huge. This study documented the design of a wireless power transfer system for a specific product which will satisfy a significant need in the marketplace. This design could easily serve as a model that can be leveraged into other wireless applications.

## 1.4 Hypotheses

The following were the hypotheses tested in this thesis.

### 1.4.1 Hypothesis 1

The proposed electronic product is unique.

### 1.4.2 Hypothesis 2

The proposed electronic product can in theory be produced.

### 1.4.3 Hypothesis 3

Upon building the proposed product, power can be transferred wirelessly at a practical distance typical of that found between a lamp and an outlet. The target distance used in this thesis was 30 feet although a shorter distance would likely be acceptable.

### 1.4.4 Hypothesis 4

Using the proposed product, 1.175 watts of power (the amount needed to power the chosen light-emitting diode [LED] light for six hours) can constantly be received at a practical distance typical of that found between a lamp and an outlet. Again, the target distance used in this thesis was 30 feet although a shorter distance would likely be acceptable.

## 1.5 Delimitations

For the purpose of this study, the following conditions are identified as variables and were not statistically evaluated as significant contributors as applied to the final analysis:

1. Fluctuations in power supplies
2. Differences in non-controllable variation in measuring techniques from measurement to measurement
3. Air temperature, barometric pressure, and humidity at the time of transmission
4. The safety of the system beyond the components' Federal Communications Commission (FCC) registration
5. The efficiency of the battery, lamp, or small electrical components

## 1.6 Thesis Outline

The remainder of this thesis is organized as follows:

Chapter 2, *Background and Review of Literature*, analyzes the history of wireless power transfer. This chapter considers historical references to wireless power transfer as well as an analysis of the contemporary works dealing with the subject. It also considers issues and concerns related to wireless power transfer.

Chapter 3, *Design of the Proposed System*, shows the tradeoffs and decisions that were made in order to build the system. Each component of the system is discussed weighing out the pros and cons of all the possible solutions for that one component. After the components are chosen, the system as a whole is documented.

Chapter 4, *Building the System,* shows how the system was actually built.

Chapter 5, *Testing the System,* shows the testing that was performed in order to verify that the system was working properly.

Chapter 6, *Results,* shows how the system performed in the various wireless power transmission trials that were performed.

Chapter 7, *Conclusions and Recommendations,* tests the hypotheses, draws conclusions from the results, and recommends future areas for research.

# 2 Background and Review of Literature

## 2.1 Introduction

Wireless power transfer has been attempted many times throughout the last century. The concept began with the experiments of Heinrich Hertz and Nikola Tesla around the 1890s and has continued until this day. Although Tesla was confident in his hypothesis to transfer power, nobody has been able to ratify it. In today's world, wireless power transfer is largely exhibited through induction. Although functional, wireless power transfer through induction is constrained to very small distances; the transfer efficiencies get increasingly worse as the distance between transmitter and receiver increases. This chapter provides a literature review of the history of wireless power transfer throughout the last century. All of the methods that have been used to achieve wireless power transfer will be reviewed along with the advantages and disadvantages of each method. The chapter will conclude with a small discussion on issues with wireless power transfer.

## 2.2 Early History of Wireless Power Transfer

The early history of wireless power transfer involves two main figures: Heinrich Hertz and Nikola Tesla.

### 2.2.1 Heinrich Hertz

Heinrich Hertz was born in Hamburg, Germany on February 22, 1857. Hertz was gifted not only in school but also as a mechanic, sculptor, draftsman, linguist, and athlete (Susskind 1988). Hertz studied at numerous universities, most prominently studying at the University of Berlin under Hermann Helmholtz (Susskind, 1988). Hertz proved that electricity can be transmitted in electromagnetic waves. In 1889 Hertz received an inquiry from a German engineer, Heinrich Huber: "could not Hertzian [radio] waves be used to transmit electric power and telephone signals (Susskind, 1988)?" Hertz responded with skepticism, but ultimately created an experiment to generate high-frequency power and detect it at the receiving end (Brown, 1984). Hertz laid the foundation for wireless power and communication transfer. Hertz died January 1, 1894 at the age of 36.

### 2.2.2 Nikola Tesla

Nikola Tesla was born on the stroke of midnight July 9, 1856 in what now is Yugoslavia. Tesla had a special gift of being able to imagine things so well that they seemed real. This allowed him to build mental rather than physical prototypes that led to successful finished designs. The downside to this was that Tesla took very poor notes; he only wrote down those things that he deemed absolutely necessary. Tesla was far beyond his time in his experimentations. It wasn't until 1970 that Robert Golka became the first to replicate the Tesla coil. Other experiments of Tesla have yet to be replicated. (Vuckovic, 1990)

Tesla worked briefly with Edison, but quit on a dispute over $50,000. Edison had promised Tesla $50,000 to solve a problem, but later reneged saying that Telsa didn’t “understand our American humor.” Later, Tesla met George Westinghouse, Jr. who funded Tesla’s idea to develop an alternating current motor. Following this development, a feud developed between Edison’s direct current and Tesla’s alternating current. (Vuckovic, 1990)

In 1899, Tesla went to Colorado Springs to build a laboratory and try out some new ideas. One of these ideas was the wireless transmission of power. “In this experiment he was able to light 200 lamps, 26 miles away from his lab. This experiment has yet to be duplicated today.” (Vuckovic, 1990)

Tesla’s theory of the wireless transmission of power was a little different than today’s vision; it was centered on his consideration of the earth as a giant conductor. Tesla transferred power directly through the earth’s surface (Vuckovic, 1990). Tesla held a firm belief that wireless power transfer was feasible, yet, after considerable expenditures of time and money, was unable to conclusively demonstrate its viability. Many blame this inability on insufficient funding (Van Voorhies, 1991). Tesla died January 7, 1943.

In “The Promises and Prospects of Worldwide Wireless Power Transfer: An Overview,” Kurt Van Voorhies (1991) documents Tesla’s wireless power transfer efforts by saying, “the key challenge to feasible worldwide wireless power distribution is whether a means can be found for efficiently coupling power into and out of the cavity formed by the earth.”

## 2.3 Contemporary Mediums for Wireless Power Transfer

There are four types of mediums for power transfer that are explored in this thesis: radio waves/microwaves, induction, lasers, and ultrasonic waves.

### 2.3.1 Radio Wave/Microwave Wireless Power Transfer

Power transmission by radio waves dates back to the early work of Heinrich Hertz (Brown 1984). Hertz experimented largely with power transfer through radio waves while Tesla's work was based on much longer wavelengths (Brown, 1984). For about fifty years after Hertz and Tesla, there were not many people who experimented with wireless power transfer because people realized that efficient point-to-point wireless transfer of energy depended upon concentrating electromagnetic energy into a narrow beam. The only practical way to do this was by using electromagnetic energy that was very short in wavelength and devices were not available to supply energy in these wavelengths (Brown, 1984). Although these devices were developed during World War II, it would be more than a decade later before serious interest in microwave power transfer would begin (Brown, 1984).

In 1958, the funding of many sponsors, including Raytheon, the Air Force, and National Aeronautics and Space Administration (NASA), spurred research on the development of wireless power transfer in the solar-powered satellite area (Brown, 1984). By 1980, most of the sponsors had dropped out and wireless power transfer research was largely limited to NASA (McSpadden, 2002).

Wireless power transfer through radio waves is a three-step process: (1) direct current (DC) or alternating current (AC) electrical power is converted into radio frequency (RF) power, (2) the RF power is transmitted through space to some distant point, and (3) the power is collected and converted back into DC power at the receiving point (Brown, 1984). There are many choices of converters for stage 1; numerous devices will convert electrical energy to RF power. The choices of converters for stage

3 are not as abundant; this part is largely dominated by semiconductor rectennas (Dickinson, 2003).

The advantage of using radio waves for wireless power transfer is that the technology is fairly mature; as mentioned before, wireless power transfer through radio waves dates back to Heinrich Hertz in the 18$^{th}$ century. The key drawbacks are beam safety, frequency allocation, and affordability (Dickinson, 1996). All of these issues will be talked about later in the chapter.

### 2.3.2 Inductive Power Transfer

Inductive power transfer systems are defined as systems where energy is transferred from a primary winding to a secondary winding using an alternating magnetic field (Stielau, 2000). The first developed inductive links were introduced in the 1960s, focusing mainly on artificial heart systems (Vandevoorde, 2001). Today, there are many commercial products that use inductive power transfer; some of these include the Sonicare toothbrush (Dench, 1999), artificial cardiac pacemakers (Vandevoorde, 2001), trolleys (Anon, 1984), and computer mice (A4 Technologies, 2005).

The structure of an inductive power transfer system is very simple (see Figure 2-1). The basic structure consists of a primary AC source, a primary winding, a secondary winding, and the load output. Because the link between the primary and secondary winding is driven by electromagnetism, inductive power transfer can only be accomplished at short distances. In 2001, Vandevoorde celebrated an inductive link that transferred 20 W of power over a distance of 1 centimeter (cm) with an overall efficiency of 80%.

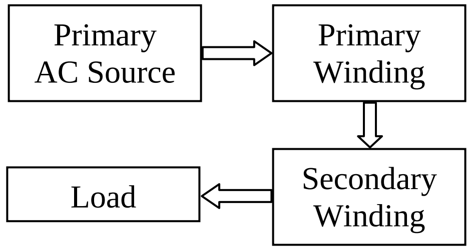


**Figure 2-1 Components of an Inductive Power Transfer System (Stielau 2000)**

The advantage of inductive wireless power transfer is that it is a low cost and highly efficient method of transferring power. The design of an induction link is fairly straight forward and surprisingly efficient at small distances. The main drawbacks to inductive wireless power transfer include the following: the amount of power transferred is limited to the size of the coil geometries and (2) the distance between coils must be very small, such as distances smaller than 2 cm (Vandevoorde, 2001).

### 2.3.3 Laser Wireless Power Transfer

In 2003, Dickinson stated that “laser wireless power transfer systems for electric power transfer are newcomers.” The International Space Information Service (ISIS) reported a breakthrough in laser power transfer in their “Highlights in Space Technology and Applications for 2000” paper. They stated that “power transmission by lasers [was developed] as a viable alternative to microwaves.”

Laser transmission of power is performed by first converting DC power into electromagnetic waves using a laser. These waves are transferred wirelessly by the laser and then are received and converted back to DC power. (Dickson, 2003)

Historically, the main problems with laser power transfer were low efficiencies (as low as 10% – 20% for the entire system) and safety concerns (ISIS, 2000). Recently, solid-state lasers in the frequency range of 1-1.4 microns have been developed. These lasers conform to the current regulatory limits on eye (retina) and skin exposure; they also seem to better as far as efficiencies go (around 30%) (ISIS, 2000). Once fully developed, these lasers may be a viable option to transfer power wirelessly.

### 2.3.4 Ultrasonic Wireless Power Transfer

In addition to laser wireless power transfer, a new-concept wireless power transmission system that uses an ultrasonic air transducers has been developed (Ishiyama, 2003).

In ultrasonic wireless power transmission a transmitter, which is composed of a pulse generator, an amplifier, and a horn, transfers the power through the air. A receiver composed of a receiving transducer, a rectifier, and a capacitor, then receives the power and applies it to a circuit. (Ishiyama, 2003)

These systems have promise, but have not been demonstrated over large distances. With time, ultrasonic wireless power transfer will be more promising in low power consuming applications. In fact, Ishiyama (2003) was able to power an alarm clock that consumed about 0.3 mW at a distance of about a foot. This distance, however, is no where near the 30 foot distance that is targeted in the proposed application.

## 2.4 Radio Wave Wireless Power Transfer Issues

This section is dedicated to the discussion of wireless power transfer issues that are common to transferring power in electromagnetic or ultrasonic applications. Induction is not considered because induction transfers energy through magnetic flux rather than wavelength allocation. There are four issues in transferring power through electromagnetic or ultrasonic waves: (1) beam safety, (2) frequency allocation or wavelength, (3) affordability, and (4) beam right-of-way. The evolution of wireless power transfer system engineering studies has revealed that these issues have staying power (Dickinson, 1996).

### 2.4.1 Beam Safety

When people first hear of wireless power transfer, their first reaction is often to express concern about the potential or perceived harmful effects that may occur. Although low frequency beamed power systems are generally one-thirtieth the intensity of sunlight, anything connected to the word radiation is suspect (Dickinson, 1996). "Particularly onerous is the fact that we cannot see RF power beams" (Dickinson, 1996).

In order to separate users from any risk of safety problems, a wireless power transfer system must remain below FCC regulations. In addition to abiding by the FCC regulations, a WPT system should allow the user to turn the system on or off manually. An alternative fail-safe approach that is commonly used is to use a beam intrusion detection system that shuts off the beam in the absence of the detection signal (Dickinson, 2003).

### 2.4.2 Frequency Allocation or Wavelength

The issue of frequency allocation or wavelength is always a problem for WPT systems. This is because attenuation, due to scattering of radio waves by dust particles, raindrops, cloud droplets, ice crystals, sleet, hail stones, and snow, of the radio waves occurs. Because of this, frequencies below 3 gigahertz (GHz) are a must (Dickinson, 1996). Beams of this frequency are much harder to focus than those of longer wavelengths. Therefore, a cost-performance trade-off is almost always made in designing wireless power transfer systems. This situation is further complicated by the many different RF signals that are already occupied by radio, broadcasting, and satellite (Dickinson, 1996). An appropriate frequency allocation must be decided upon for each application.

### 2.4.3 Affordability

Dickson (2003) stated, "in connection with the end-to-end beam power transfer efficiency, certified to be greater than 54%, these results should dispel doubts about the technical feasibility of wireless power transfer. Thus wireless power transfer is a proven technology. Its only current drawback is that it is expensive." Wireless power transfer involves many components that are oftentimes expensive. One driver of the cost is that the wireless power transfer systems use different forms of power converters at the two ends of the system. It will not be commercially feasible to develop unless the system can be produced at an affordable price.

## 2.5 Conclusion

Wireless power transfer technologies have been developing since the 1890s. Today, feasible methods of transferring power wirelessly include transfer through radio frequencies, induction, laser, and ultrasonic waves. Of the alternatives listed, wireless power transfer through radio frequencies is the most mature transfer method. Induction is also fairly mature, but it is severely limited by the small distance between coils that is required. There are safety, implementation and affordability issues in regards to wireless power transfer, and these will likely be improved as the technology further matures.

# 3 Design of the Proposed System

### 3.1 Constraints Imposed on the System

The notion of powering a lamp wirelessly brings with it many challenging implications. First, there are a number of constraints imposed on such a system by rules and regulations set by the FCC. These regulations limited the scope of this thesis, making it infeasible to transfer sufficient power (anywhere from 5 to 60 W) directly to a lamp. Because of this, a storage device was used in the system to accumulate the transferred power.

In addition to the FCC regulations, others constraints were placed on the system. The system was expected to transfer and store energy 24 hours of the day. During 6 of these 24 hours, the system was expected to power a light bulb. This constraint was decided upon because it was assumed that most lamps are not used for more than six hours a day; thus, six hours of use would satisfy the needs of the average homeowner and would serve as a good benchmark.

### 3.2 Analysis of Similar Products

The first hypothesis stated that the “proposed electronic product is unique.” In order to test this hypothesis, an analysis of similar products in the market was conducted. The analysis was focused in two areas: (1) other lamp products, and (2) other wireless power transfer devices. The scope of this analysis was delimited to commercially marketed products.

### 3.2.1 Analysis of Similar Lamp Products

It is estimated that in 2000, consumers spent $759.6 million on table and floor lamps (Encyclopedia of American Industries, 2004). There are a few companies that currently sell cordless lamps. All of these lamps work off a battery and do not recharge by themselves. Neoz, an Australian company, markets cordless lamps that "provide 10 times the light that a candle does." Neoz seems to be the dominant player in this market; they have been producing cordless lamps that have halogen bulbs since 1995. Horchow, a catalog sales company headquartered in Dallas, also currently sells rechargeable lamps.

In addition to these cordless table lamp manufacturers, there are various other companies that sell cordless lights that are not categorized as table lamps. For example, there are many cordless picture lights, headlamps, hand-held lanterns, and yard lamps.

Solar yard lamps are actually very similar in concept to the product proposed and developed in this thesis. Solar yard lamps convert light energy into dc power. This power is then accumulated in a battery which in turn powers an LED. This product is very prevalent in the marketplace.

**Figure 3-1 Solar Yard Lamps (Silicon Solar Inc)**

An analysis of the current lamp market did not yield any products that were directly correlated to the product proposed in this work. There appears to be no company in the current market that is selling wireless lamps that do not require the user to manually recharge the battery.

### 3.2.2 Analysis of Similar Wireless Power Transfer Systems

Commercially, there are few companies employing wireless power transfer. In contrast, many products employ wireless data transfer including wireless internet devices, walkie-talkies, ham radios, marine radios, and klystrons. Devices such as magnetrons radiate radio frequencies without any intentions to recapture the signal.

It appears as though the few companies that do employ wireless power transfer use induction rather than power transfer through radio frequencies. As aforementioned, Sonicare, a product of Royal Philips Electronics, produces a toothbrush that recharges through induction. Another company, A4Tech, uses induction to power a wireless-batteryless mouse for a computer. Panasonic uses induction to recharge some of their electric razor products.  A few companies such as Splashpower and MobileWise are also currently offering a pad that recharges any previously enabled device set on it (such as a cell phone or a camera).

**Figure 3-2 A SplashPad by Splashpower**

No commercial product was found that transfers power wirelessly by use of radio waves.  As previously stated, many researchers are proposing the use of radio waves to be employed to transfer power from solar power satellites to the earth (Soubel, 2004).  A student group from the University of Connecticut also transferred power wirelessly through radio waves using a five foot long wave guide (Silva).

### 3.3 Design of the Wireless Lamp System

The system proposed in this thesis was divided into three parts: (1) the wireless power transfer system, (2) the storage assembly, and (3) the lamp assembly.  Each of these parts posed challenges in their own respect.  The following is a discussion of the three parts.

### 3.3.1 The Wireless Power Transfer System

The wireless power transfer system consisted of three parts: (1) a transmitter, (2) transmitting and receiving antennas, and (3) a rectenna.

#### 3.3.1.1 The Transmitter

The wireless power transfer system needed the ability to transfer sufficient power from a wall outlet to a remote location. In order to get sufficient power from a wall outlet to a remote location, the energy needed to be directed towards the receiving end as opposed to broadcasting the energy in all directions. The latter method is not very efficient when the receiving location is known because most of the energy is sent in the wrong direction.

The amount of power that was transmitted was considered sufficient if it met Hypothesis 4 which states that "1.175 watts of power can constantly be received." This amount of required power was derived using the following equation:

$$(4.7W * 6h) \div 24h = 1.175W \qquad \textbf{(3-1)}$$

4.7 W of power is used in this equation because the LED that was ultimately decided upon for use in the system required 4.7 W of power in order to function. Six hours is used because this is the amount of time the light is expected to function. 24 hours is the amount of time that the wireless power transfer system will be transmitting energy to the lamp.

In order to constantly receive 1.175 W of power at the receiving end, much more power must be transmitted at the transmitting end. This is due to path losses and efficiency losses while rectifying the received power from RF to DC power; these losses diminish the amount that is actually received as compared to the amount that is transmitted.

In summary, the transmitter must meet the following requirements:

1. Transmit sufficient power – enough to receive 1.175 W at the receiving end after all efficiency losses.
2. Transmit in a unidirectional pattern.

Many devices were evaluated in search of a transmitter that met these requirements. Table 3-1 shows a comparison of the different transmitting devices that were evaluated for use in the system.

**Table 3-1 Available Transmitting Devices**

| Device | Maximum Output Found (W) | Most Common Frequency | Directional Antennas Available? |
|---|---|---|---|
| CB Radio | 4 W | 26 MHz | No |
| Ham Radio | 15 W | 29 MHz | No |
| Marine Radio | 25 W | 156 MHz | No |
| FRS/GRMS Radio | 5 W | 465 MHz | No |
| Trunking Radio | 15 W | 800 MHz | Yes |
| Wireless Access Point | 200 mW | 2.4 GHz | Yes |
| Wireless Bridge | 2W | 2.4 GHz | Yes |
| Audio/Video Transmitter | 2 W | 2.4 GHz | Yes |

After evaluating the devices listed in Table 3-1, it was apparent that a trunking radio best met the requirements for a transmitter. A trunking radio is a system that distributes frequencies for two-way radio use according to traffic levels so that two-way radios do not depend on a dedicated radio frequency. The trunking radio that was chosen for this experiment was made by RELM Uniden (SMS825TSA). It transmitted on the 800 megahertz (MHz) frequency band and had a rated output power capacity of 15 W.

#### 3.3.1.2 The Antennas

As stated in the previous section, a unidirectional antenna was preferred over an omni-directional antenna because unidirectional antennas direct all of the power towards the receiving end while omni-directional antennas broadcast the power in all directions. At the time this thesis was written, it appeared that Laird Technologies, a company headquartered in St. Louis, made the only unidirectional antenna commercially available that was designed to be used on the 800 MHz band (ID850-SF00). This antenna was selected to be used in the system both at the transmitting end and the receiving end. The receiving antenna was considered part of the rectenna.

#### 3.3.1.3 The Rectenna

The rectenna was the only part of the system that was not commercially available for purchase. There were a few rectenna designs documented in peer reviewed articles. One of these, made by McSpadden (1998), defines a rectenna as consisting of the parts shown in Figure 3-3.

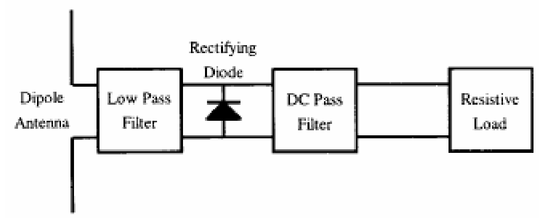


**Figure 3-3 McSpadden's (1998) Rectenna Design**

McSpadden used a dipole antenna in his rectenna. As mentioned previously, directional panel antennas are used in the system documented in this thesis. The main component of the rectifying circuit of the rectenna is the rectifying diode. A Schottky rectifying diode made by Diodes, Inc. (1N5818) was used in this system. This diode was chosen because previous works had used Schottky diodes in their rectenna designs and this particular Schottky diode was rated at a 30 V reverse (blocking) voltage which was assumed to be sufficient. The low pass filter and DC pass filter are included to improve the efficiencies of the rectenna.

### 3.3.2 The Storage Assembly

In order for a lamp to be functional, it needs to receive power. As was discussed previously, due to the limits imposed by the FCC on wireless transfer, the total energy needed to power a lamp could not be transferred from the outlet to the lamp assembly in real time; a storage device was needed to accumulate sufficient energy to power the lamp for six hours. Light bulbs that fit in normal lamp fixture (whether they are incandescent or fluorescent), typically need 120 volts of alternating current (AC) to work. It was unrealistic to store and supply DC power at 120 V. There are some marine light bulbs (both of the incandescent and fluorescent types) which run off DC power at 12 V, however these still typically draw a high amount of current. It was desired to keep the amount of power needed to a minimum for two reasons: (1) so the size and price of the storage assembly could be kept to a minimum and (2) so that the amount of energy that would need to be transferred through the wireless system could be kept at a minimum.

There are two types of energy storage devices: batteries and capacitors. In addition to the goals already stated, the storage device needed to be rechargeable; it would go through many cycles of charge and discharge. There were four different types of rechargeable batteries: (1) nickel-cadmium, (2) nickel-medal hydride, (3) lead-acid, and (4) lithium ion. In addition to these options, an ultracapacitor could be used.

#### 3.3.2.1 Nickel-Cadmium Batteries

The nickel-cadmium (NiCd) battery is commonly used in portable electronics and toys due to their beneficial weight/energy ratio as compared to lead-acid batteries. NiCd batteries, due to their low series resistance, also have the ability to provide high surge currents allowing them to be used in applications such as portable power tools. The disadvantage to NiCd batteries is that they suffer from a memory effect if not completely discharged once in a while.

#### 3.3.2.2 Nickel-Metal Hydride Batteries

Nickel-Metal Hydride (NiMH) batteries are similar to NiCd, but are less toxic, offer higher capacities, and are less affected by a memory effect. They are, however, slightly more expensive than NiCd batteries and they have a higher self-discharge rate. Hybrid vehicles, such as the Toyota Prius, use NiMH batteries. Usually NiCd batteries are used in high-drain applications (due to their low internal resistance) and NiMH batteries are used in more moderate-drain applications such as flashlights and digital cameras.

#### 3.3.2.3 Lead-Acid Batteries

Lead-acid batteries were invented in 1859 by French physicist Gaston Planté and are today the most commonly used rechargeable battery. The advantage of lead-acid batteries is that they are inexpensive. The disadvantage is that they have a low energy-to-volume ratio. These batteries are used when size and weight are not important considerations. (U.S. Department of Energy, 1995)

#### 3.3.2.4 Lithium Ion Batteries

Lithium Ion batteries (Li-Ion) are commonly used in consumer electronics. The advantages of Li-Ion batteries are that they have a high energy-to-weight ratio, no memory effect, and a slow self-discharge. The disadvantages are cost and capacity loss (typical Li-Ion batteries loose about 20% capacity per year beginning from the time it was manufactured).

#### 3.3.2.5 Ultracapacitors

The first ultracapacitor was developed in 1957 by General Electrics. Ultracapacitors have the following advantages relative to batteries: high rates of charge and discharge, light weight, little degradation over cycles. The disadvantage is that they are not easy to use for two reasons: (1) to effectively store and recover energy requires sophisticated electronic control, and switching equipment and (2) the voltage varies with the energy stored.

3.3.2.6 Storage Technology Selection

Table 3-2 gives a summary of the advantages and disadvantages of each storage technology that was considered for use in this system.

**Table 3-2 Summary of the Storage Technology Available**

| | **Advantage** | **Disadvantage** |
|---|---|---|
| **NiCd** | Beneficial energy-to-weight<br>Low resistance | Suffer from memory effect |
| **NiMH** | Similar to NiCd<br>Higher capacities<br>Less affected by memory effect | Expensive<br>High discharge rate |
| **Lead-Acid** | Inexpensive | Low energy-to-weight |
| **Li-Ion** | High energy-to-weight<br>No memory effect<br>Slow discharge | Cost<br>Capacity loss over time |
| **Ultracapacitor** | High rate of charge/discharge<br>Light weight<br>Little degradation over cycles | Complex<br>Voltage varies with energy stored |

There were two criteria used to evaluate the best storage device to be used in the system: size of the device and the absence of a memory effect. The size of the device is important because it will directly affect the size of the system as a whole. It is assumed that the consumer will not want a large device sitting next to their lamp. The absence of a memory effect is important because the battery will rarely completely discharge (as energy will be transferred to it 24 hours a day or until the battery is completely charged).

Given this criteria, a lithium ion battery was chosen to store the energy transferred within the system. The energy density of lithium ion is typically three times that of the standard nickel-cadmium found in today's nickel-metal-hydride batteries. To supply the 11.1 V (actually 10.8 V) that is needed to power the LED light it takes only three cells with a lithium-ion battery rather than the nine cells that it would take with nickel-metal-hydride batteries. In addition, lithium ion batteries have no memory effect.

Because the LED previously selected runs off 11.3 V, the lithium ion battery selection was limited to 11.1 V batteries. The LED also needs 4.7 watts to run. The following equation was used to derive the necessary watt-hours required to run the LED for 6 hours:

$$4.7W * 6h = xWh \qquad \textbf{(3-2)}$$

Using this equation, 28.2 watt-hours (Wh) is needed to power the LED for six hours. This allows us to use the following equation to derive the necessary amp-hour (Ah) rating of the battery that should be used:

$$30Wh = xAh * 11.1V \qquad \textbf{(3-3)}$$

Using this equation, the battery must be able to provide 2541 milli-amp-hours (mAh). This, however, is not entirely true because the battery is being charged during the 6 hours of operation making the required milli-amp-hours a little lower than 2541 mAh. A Powerizer 11.1 V 2500 mAh Polymer Li-Ion battery (PL-0550100-3S-WR) was chosen for use in the proposed system.

### 3.3.3 Lamp Assembly

The lamp assembly consisted of the light bulb and the lamp itself. The amount of energy that needed to be transferred (in the wireless assembly) and stored (in the battery assembly) was largely dependant on the type of light bulb that was selected. There are many different choices of light bulbs. Those that were considered in this thesis were incandescent, fluorescent, and light-emitting diode (LED) bulbs. In order to decrease the size and cost of the battery it was decided to use light bulbs that worked on 12 V rather than 120 V.

Each type of bulb has its advantages and limitations. Incandescent bulbs are largely the standard in modern homes. The disadvantage to incandescent bulbs is they draw a lot of power and are very inefficient. A typical 12 V incandescent bulb draws 50 watts of power and loses a lot of energy in dissipated heat. Fluorescent bulbs are slightly more efficient than incandescent bulbs, but they still draw a lot of power – around 13 watts. Because of this, LED lights were considered. LED lights were available that use small amounts of power. These lights had two drawbacks: (1) they were expensive and (2) they were not as efficient as fluorescent bulbs. Fluorescent bulbs deliver about 60 lumens/watt (lm/W) while it appears that the best LEDs that are commercially available at the time of this thesis deliver from 25 – 35 lm/W (incandescent bulbs deliver about 15 lm/W). At the time of this thesis, Cree, a company headquartered in Durham, NC, claimed to have developed an LED that produced 131 lm/W in their lab (Cree 2006), but this LED had yet to be released commercially.

Despite their limitations, LED lights were viewed as the best alternative lighting source to use in the wireless system. Although they are currently expensive, it is assumed that the price of LED lights will decrease over time and they will become more efficient. It was estimated that LED lights have the potential to deliver 200 lm/W (OIDA, 2001). If this efficiency is achieved or approached, LED lights will surpass the efficiencies of fluorescent bulbs. An LED that consumes 5 W will produce as many lumens as an incandescent bulb that consumes 60 W. Given this information, the wireless system presented in this thesis will need to deliver 5 W of power for 6 hours (30 watt/hours).

The most efficient commercially available LED light was chosen for use in this thesis. This LED was made by Lamina Ceramics (BL-22D0-0130) and delivers 108 lumens (lm) on 4.7 W of power. The LED was hooked up to a normal incandescent light bulb screw thread assembly, which allowed the LED to screw into any household light and make contact with the positive and negative power contacts.

The design of the lamp itself merits some examination. There were two basic options for the lamp: (1) the lamp could be included in the design of the wireless system or (2) the lamp could be excluded from the design of the wireless system. The advantage in including the lamp in the design of the wireless system is that the lamp could be specifically designed for the components of the system. For example it could be designed to house the wireless receiver and the antenna. The disadvantage is that the consumer would have to be persuaded to buy a completely new lamp. The advantage in excluding the lamp from the design of the system is that the end product would allow any lamp to be used. The light, the energy storage device, and wireless system could be designed around a conventional lamp which would allow consumers to purchase the device to use with any lamp. The disadvantages of this type of system are many:

- the light would have to be constrained to fit into a conventional light fixture;
- the wireless and battery systems would have to plug into the lamp and sit external to it; and
- there would be a possibility that the consumer could plug the lamp into a wall outlet (supplying 120 V AC) rather than into the device (which supplies 12 V DC) which could cause serious problems.

For the purposes of experimentation, a generic lamp was chosen to house the LED light. The final decision of whether to include the lamp in the design of the wireless system can be postponed until after experimentation is completed. It is assumed that the nature of the lamp (whether it is external or internal to the system) will not affect the results of experimentation.

### 3.4 Summary of the Design

This chapter defined the design of the proposed wireless lamp system. The design consists of a transmitter, a transmitting antenna, a rectenna (a receiving antenna and a rectifying circuit), a Li-Ion battery and the lamp assembly. A light-emitting diode is used as the light source in the lamp assembly. Figure 3-4 is a graphical representation of the described system.

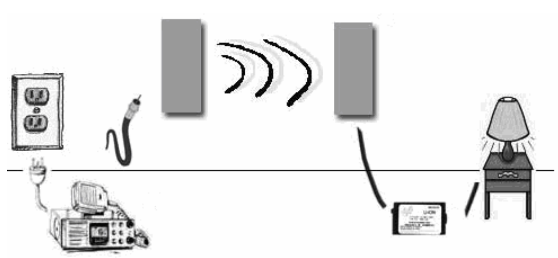

**Figure 3-4 Wireless Lamp Design Summary**

# 4 Building the System

After the system was designed and all the necessary parts were purchased, the system was built. At times, slight variations to the original design needed to be employed. This chapter documents the entire build of the system.

## 4.1 The Wireless Power Transfer System

The wireless power transfer system consisted of the trunking radio, the transmitting antenna and the rectenna.

### 4.1.1 The Trunking Radio

The trunking radio ran off power at 12 V DC, so a power source had to be used to step the voltage down from 120 V to 12 V, and rectify it from AC to DC. Additionally, the radio had to be forced to transmit constantly. A radio can be forced to transmit by shorting the push to talk (PTT) circuit with the ground. This was accomplished by using a microphone connector and soldering the PTT pin with the ground pin.

### 4.1.2 The Transmitting Antenna

The trunking radio attaches to the transmitting antenna using a radio frequency adapter; the radio has a type N output and the antenna has an SMA input. The appropriate adapter was used. The trunking radio together with the transmitting antenna can be seen in Figure 4-1.

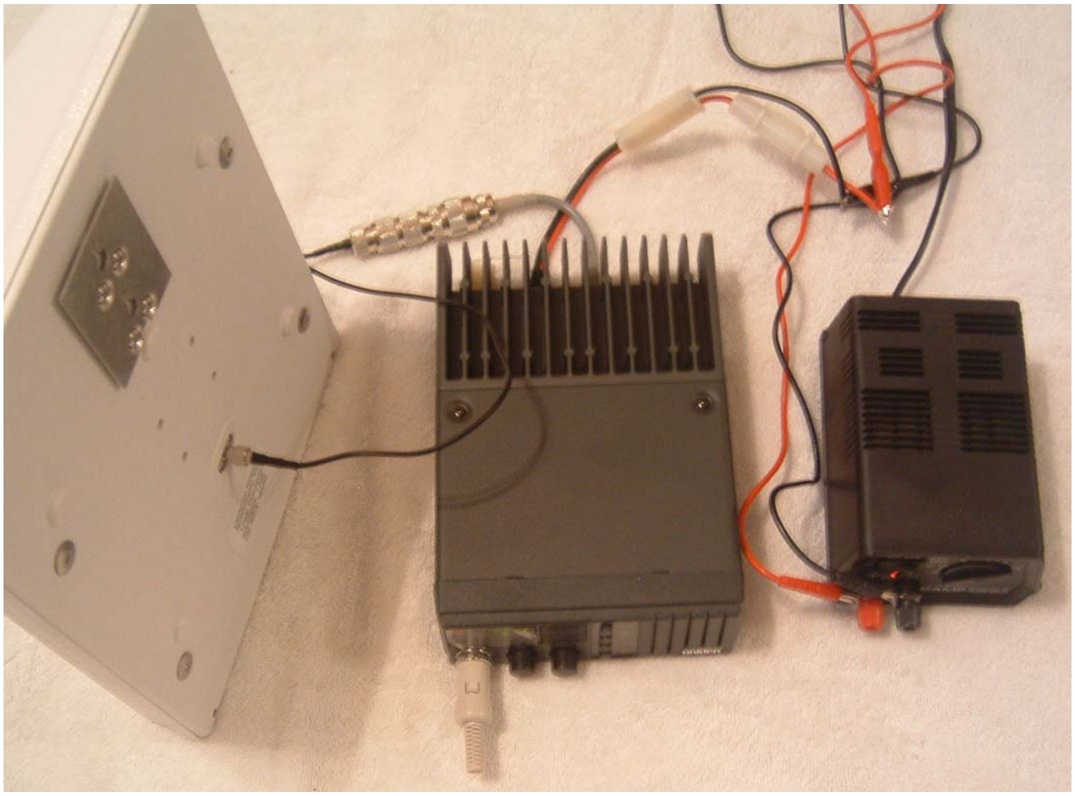

**Figure 4-1 The Transmitting Antenna, Trunking Radio, and Power Source**

### 4.1.3 The Rectenna

The first part of the rectenna was the receiving antenna. The same antenna as the transmitting antenna was used for the receiving antenna. As mentioned previously, the antenna has an SMA RF output. An SMA to BNC adapter was used and the BNC adapter was hooked directly into the rectifier. The rectifier was first built on a protoboard.

As the low pass and DC filters' purpose were to improve the efficiencies of the rectenna, they were initially excluded from the system in order to simplify the design. The initial simplified rectifying circuit schematic is shown in Figure 4-2.

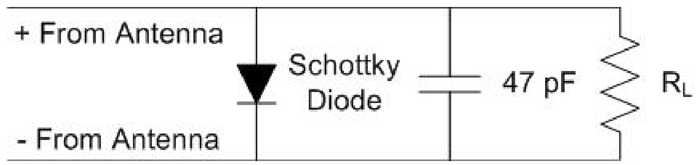


**Figure 4-2 Initial Rectifying Circuit Schematic**

The original rectenna design, as a whole, is shown in Figure 4-3.

**Figure 4-3 Original Rectenna Design**

## 4.2 The Battery Assembly

The rectenna fed DC power to the battery. The battery was charged on power at 12 V DC. Because the rectenna would likely not output a constant 12 V, it would be necessary to regulate the power (if the output were more than 12 V) or boost the power (if the output were less than 12 V). Upon the initial build of the system, it was uncertain as to how much voltage the rectenna would output. Because of this, the design to charge the battery was left untouched until the initial results were established.

## 4.3 The Lamp Assembly

The lamp assembly consisted of the LED, the screw thread, and the lamp. The LED required a heat sink to dissipate the heat generated when operating. The LED was attached to the heat sink using a heat sink compound (silicone) and four screws. Wires were then soldered to the positive and negative connections of the LED which were connected to a light screw thread assembly. The resulting light assembly is shown in Figure 4-4.

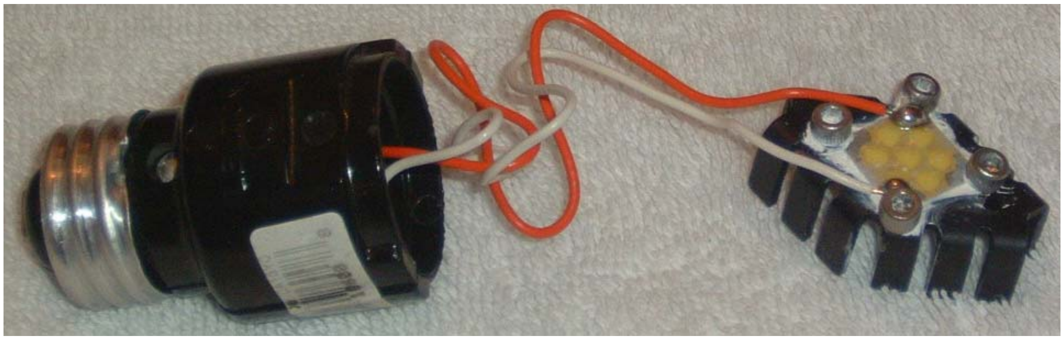

**Figure 4-4 Light Assembly**

With the LED attached to a screw thread, the light assembly could be used with any household lamp.  As was decided earlier, a common table lamp was used to test the system against the hypotheses.

# 5 Testing the System

After the system was built, it was sanity tested for things such as continuity and basic functionality. This section documents all the validation that was performed.

## 5.1 The Wireless Power Transfer System

Two tests were performed on the wireless power transfer system: one to test basic continuity and another to test the output power of the transmitter. A basic continuity check was performed on each applicable part to make sure that every connection and adapter was properly attached.

To verify the output power of the transmitter, the amperage was measured while toggling the transmitter on and off. While the transmitter was off, it was pulling 0.39 amps (A) at 11.9 W. Using the power formula, the wattage can be derived:

$$0.39A \times 11.9V = 4.64W \tag{5-1}$$

While the transmitter was on, an amperage of 2.63 A was measured at 8.78 V. Again, using the power formula, the wattage was derived:

$$2.63A \times 8.78V = 23.09W \tag{5-2}$$

This is a difference of 18.45 W. This shows that 18.45 W goes into the transmitter in the transmit state. This passes the sanity test that the transmitter could be transmitting 15 W as it is rated.

## 5.2 The Storage Assembly

After charging the battery using the supplied charger, the output voltage of the battery was measured to verify that it was around 11.1 V. The test revealed a voltage difference of 12.42 V. This was within the acceptable range to power the LED light.

The assembly was then tested to see if the battery would charge on a 12 V DC charge provided by a power source. With the power source off, the battery recorded an input amperage of -0.07 A. With the power source on at 12 V, the battery recorded an input amperage of 3.24 A. It appears as though the battery is taking a charge with 12 V from a power source.

## 5.3 The Lamp Assembly

The light assembly (the LED with the screw thread attached) was tested to see if it would light while applying 12 V of power. In order to do this, the continuity of the lamp had to be measured to establish which plug prong was positive and which was negative. Once continuity was established, the light could be tested. Figure 5-1 shows the results of this test.

**Figure 5-1 Light Assembly Test**

The light assembly was then tested by applying the positive and negative leads from the charged battery (rather than the power source). This test also went well; the LED lit up as it had before.

# 6 Results

The result considered as a key metric of the system was the output voltage of the rectenna. This is the key metric because if the voltage is sufficient, the battery is likely to receive the power needed (if the respective current is sufficient). Many trials were executed in an attempt to get acceptable results. Changes to the rectenna were made between each trial while the rest of the system was held constant. This chapter documents these trials as well as the changes that were made between each trial.

## 6.1 Schottky Diode Trials

As mentioned in the design and build of the system, Schottky diodes were originally used in the rectifier. Many trials were attempted using Schottky diodes. This section documents the results of these trials.

### 6.1.1 Schottky Diode - Trial #1

In this trial the rectenna was built on a protoboard according to the schematic shown in Figure 6-1.

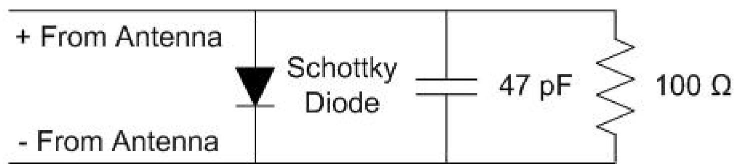


**Figure 6-1 Trial #1 Schematic**

The antennas were abutted to each other in order to measure the maximum voltage possible (this is the case with successive trials unless otherwise specified). The voltage was measured across the resistor. The output voltage in this trial was measured at 0.01 mV.

### 6.1.2 Schottky Diode - Trial #2

In this trial two Schottky diodes were used according to the schematic shown in Figure 6-2.

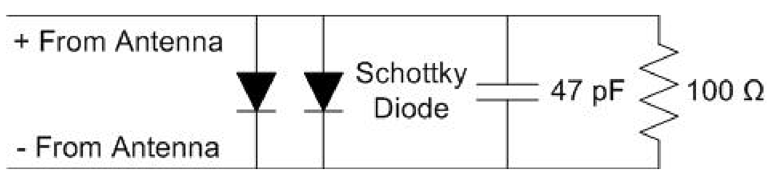


**Figure 6-2 Trial #2 Schematic**

The output voltage in this trial was also measured at 0.01 mV.

### 6.1.3 Schottky Diode - Trial #3

In this trial, the resistor was eliminated. The rectenna was built on a protoboard according to the schematic shown in Figure 6-3.

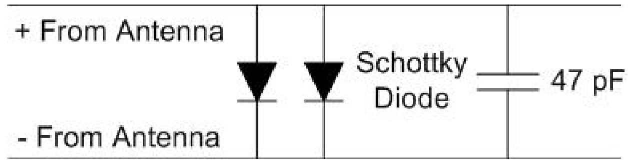


**Figure 6-3 Trial #3 Schematic**

The voltage was measured across the positive and negative leads (after the capacitor). The output voltage measure in this trial was 7.85 mV.

#### 6.1.4 Schottky Diode - Trial #4

In this trial, a bigger capacitor was used. The rectenna was built on a protoboard according to the schematic shown in Figure 6-4.

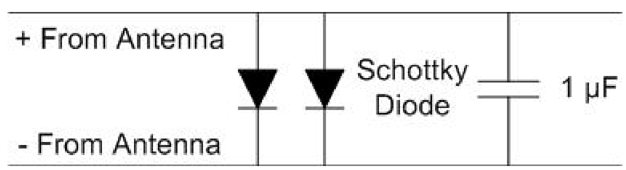


**Figure 6-4 Trial #4 Schematic**

The output voltage in this trial was 3.12 mV.

#### 6.1.5 Schottky Diode - Trial #5

In this trial, the capacitor was removed from the system all together. The rectenna was built on a protoboard according to the schematic shown in Figure 6-5.

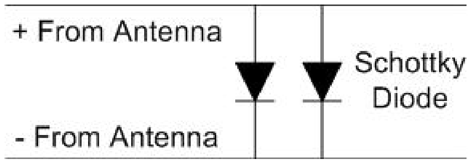


**Figure 6-5 Trial #5 Schematic**

The output voltage in this trial was 9.0 mV.

### 6.1.6 Schottky Diode - Trial #6

In this trial, the same schematic that was shown in Trial #3 was used but the circuit was built on an actual circuit board. A picture of the built rectenna can be seen in Figure 6-6.

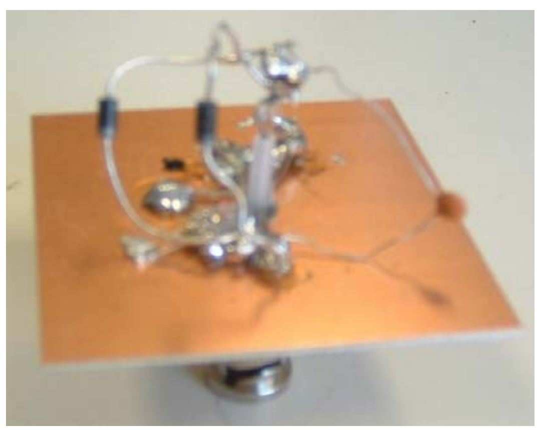

**Figure 6-6 Trial #6 Picture**

With the antennas abutted, the output voltage was measured at 23.2 mV. A graph showing the voltage drop as the antennas are moved apart is shown in Figure 6-7.

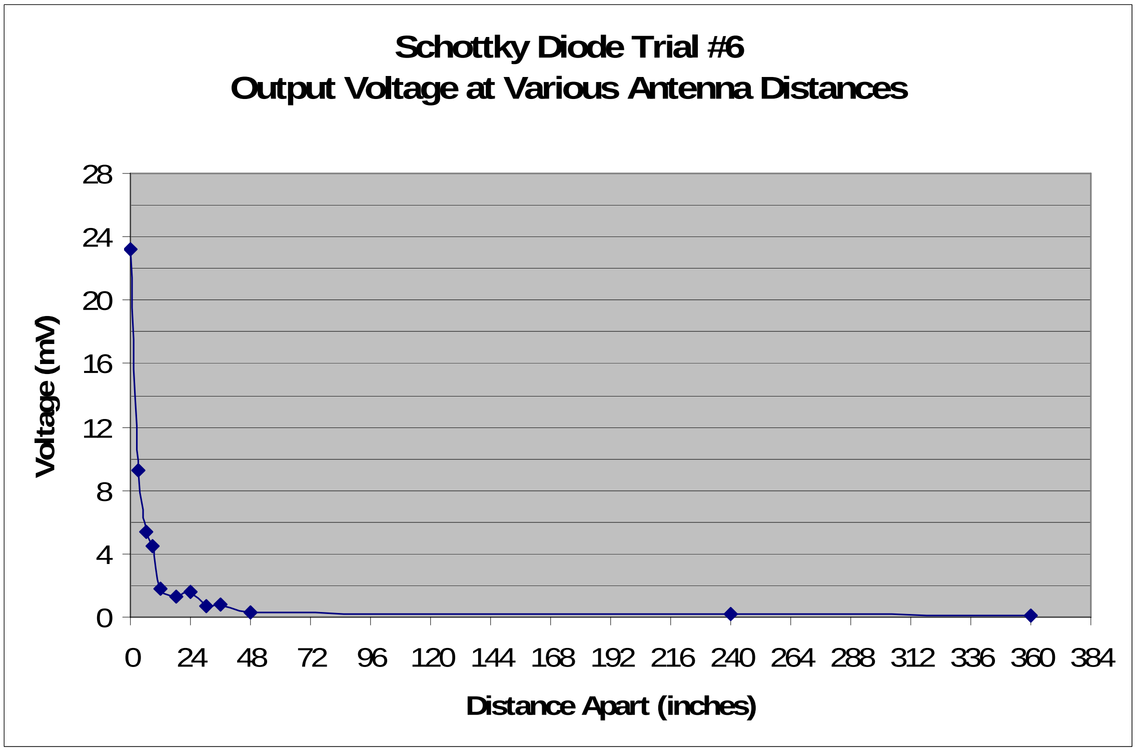


**Figure 6-7 Trial #6 Output Voltage**

### 6.1.7 Schottky Diode - Trial #7

In this trial, the capacitor was eliminated from the system (similar to the schematic shown in Trial #5) and the circuit was built on a circuit board. The initial output voltage (with the antennas abutted) in this trial was 37.1 mV. The drop in voltage due to distance is shown in Figure 6-8.

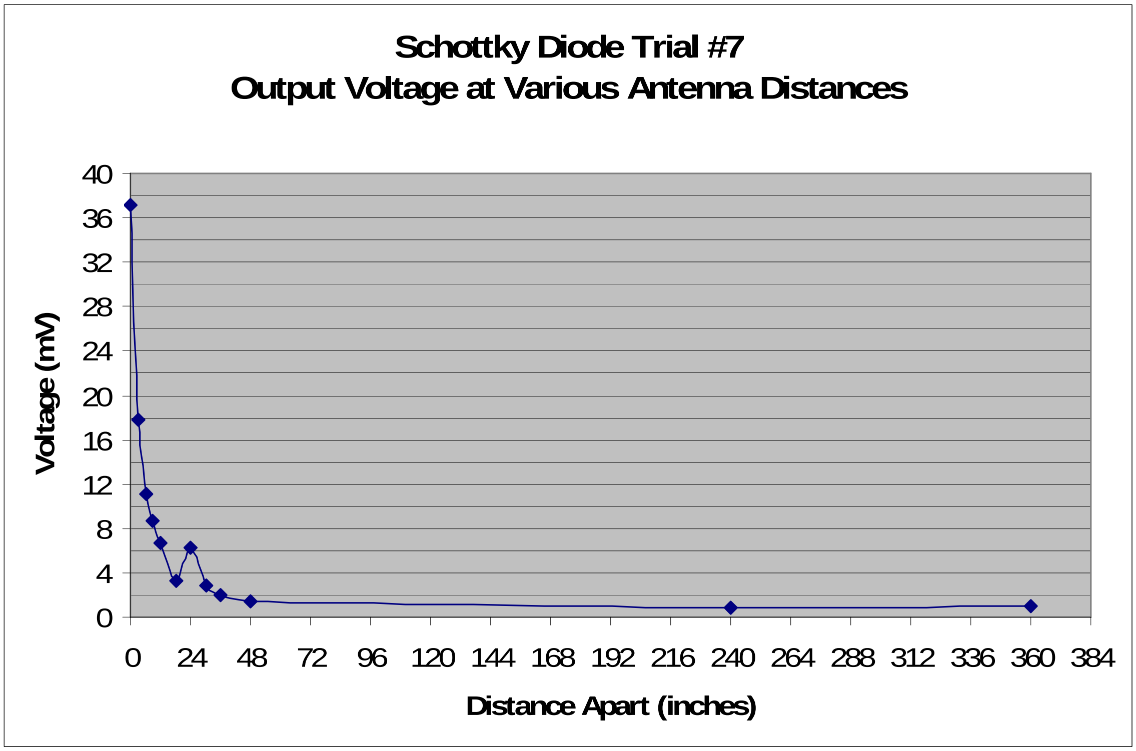


**Figure 6-8 Trial #7 Output Voltage**

### 6.1.8 Schottky Diode - Trial #8

In this trail one of the Schottky diodes was eliminated from the system according to the schematic shown in Figure 6-9.

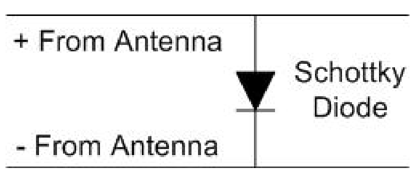


**Figure 6-9 Trial #8 Schematic**

The initial output voltage in this trial was 55 mV. A graph of the voltage recorded dependant on the distance between antennas is shown in

Figure 6-10.

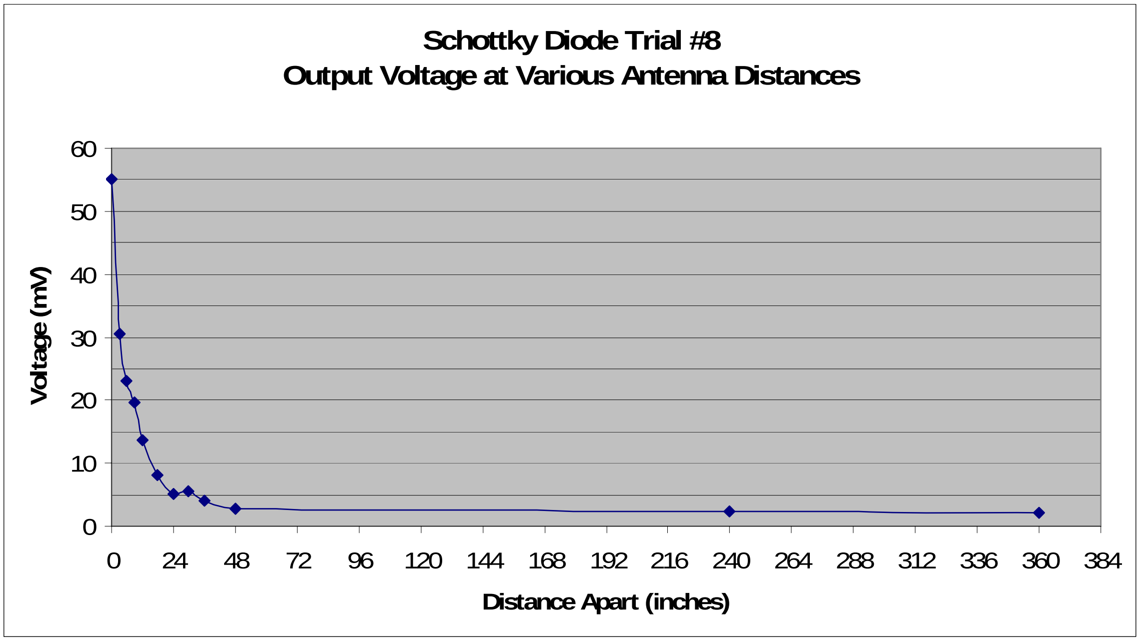


**Figure 6-10 Trial #8 Output Voltage**

### 6.2 General Rectifier Diode Trials

By way of experimentation, different types of diodes were used in the rectenna. This section documents the trials that were performed using general rectifier diodes. The specific diode that was used was made by NTE electronics (NTE116).

#### 6.2.1 General Rectifier Diode - Trial #9

In this trial, the same schematic that was used in Trial #8 (Figure 6-9) was used with the general rectifier diode. The result was an output voltage of 300 mV (much better than the Schottky diodes previously used). In defense of Schottky diodes, a Schottky diode (NTE578) was later used with similar results.

#### 6.2.2 General Rectifier Diode - Trial #10

In this trial a full wave rectifier was employed. The schematic of the rectenna is shown in Figure 6-11.

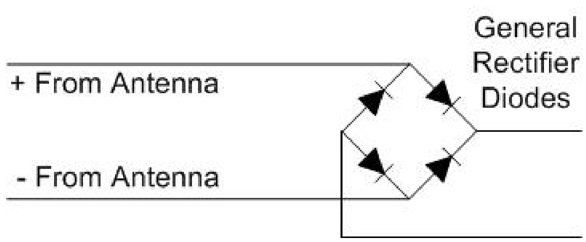


**Figure 6-11 General Rectifier Diode Trial #10 Schematic**

The output voltage in this trial was 1 V with the antennas abutted.

### 6.3 Switching Diode Trials

Out of further experimentation, switching diodes, or high speed diodes, were used in the rectenna. The switching diode that was used was manufactured for Radio Shack (1N914). This section documents the results of the experimentations using switching diodes.

#### 6.3.1 Switching Diode - Trial #11

In this trial, a single switching diode was used employing the same schematic that was used in Trial #8 and Trial #9 (Figure 6-9) with the diode changed. The result was an output voltage of 24 V with the antennas abutted.

### 6.3.2 Switching Diode - Trial #12

In this trial, a full wave rectifier (see the schematic shown in Figure 6-11) was used using the switching diodes. A picture of the rectenna circuit used in this trial can be seen in Figure 6-12.

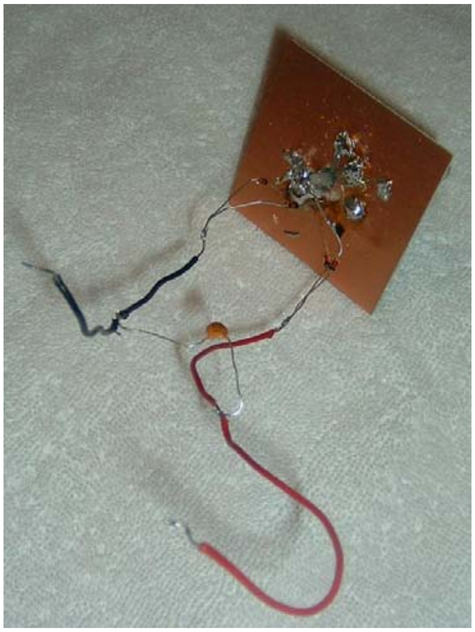

**Figure 6-12 Trial #12 Rectenna Picture**

An output voltage that fluctuated from 83 V to 106 V was measured in this trial (with the antennas next to each other).

Figure 6-13 shows the output voltage that was measured at different distances between the antennas.

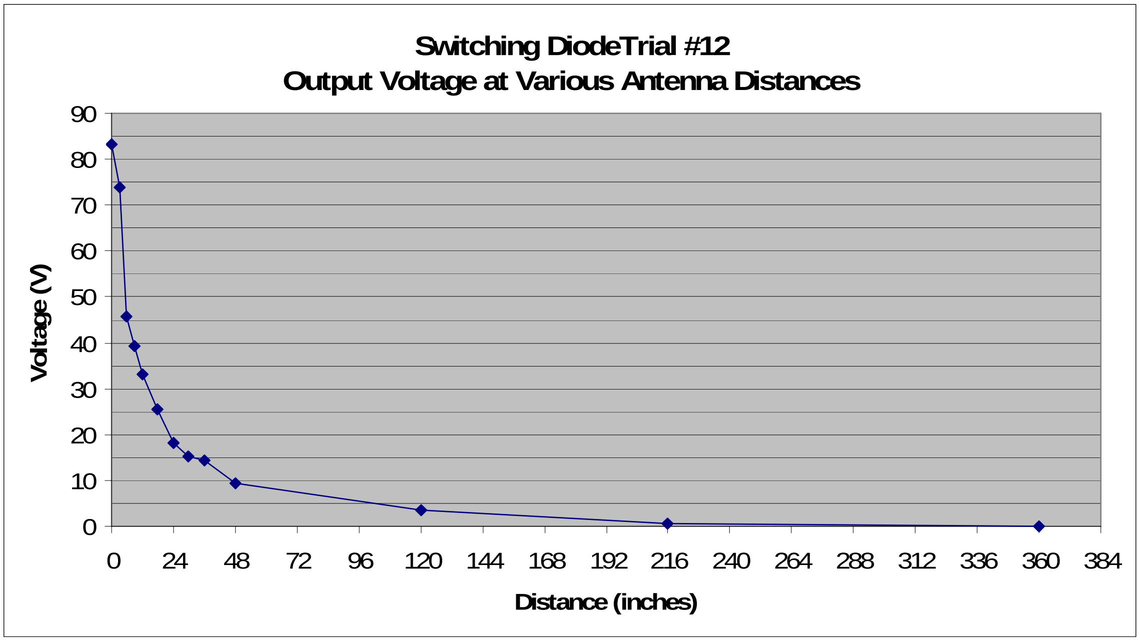


**Figure 6-13 Trial #12 Output Voltage**

## 6.4 Refinement of the System: DC to DC Conversion

It was discovered, in Trial #12, that the output voltage of the rectenna exceeded 12 V when the distance between the antennas was less than about 42 inches. When the distance increased beyond this point, the voltage was below 12 V. This created a situation were the voltage needed to be regulated or boosted depending on how far the antennas were from each other.

### 6.4.1 Voltage Regulation

To focus efforts on getting a working prototype at some distance, an attempt was made to first regulate the voltage and test the system within the acceptable range for the regulator. The voltage regulator that was used was made by NTE electronics

(NTE966). It accepted input voltages of 13.8 V to 35 V with a constant output of 12 V (this corresponded to distances between 12 to 42 inches).

Upon testing the system with the voltage regulator attached, an unusually low voltage was recorded; at a distance of 36 inches between antennas, an output voltage of 2.4 V was measured (a recording of 15 V as an input to the regulator was expected at this distance).

Based on this unusually low result, it was suspected that the output voltage was dependant on the load that was applied. To test this theory, several discrete resistors were applied to the output of the rectenna and the resulting voltage was measured. Figure 6-14 shows the results of these measurements.

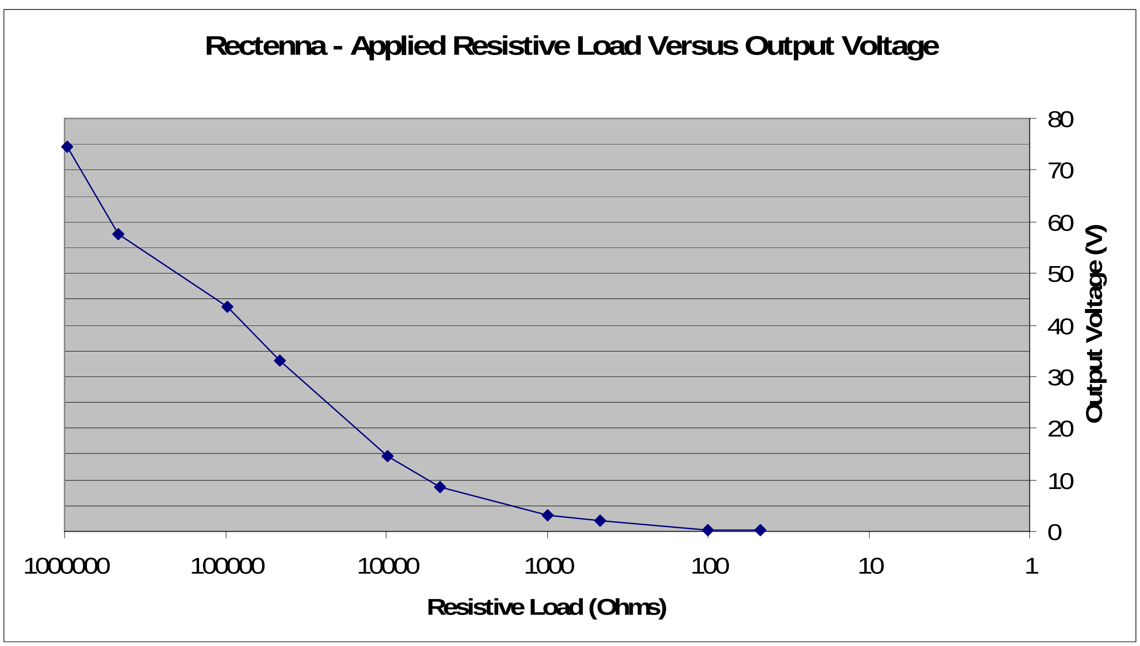


**Figure 6-14 Output Voltage with Varying Resistive Loads**

The theory that the output voltage is dependant on the applied load seems to be correct. This implies that the voltage will always drop with an applied load. With this realization, a DC regulator would not work because the voltage would always drop below 12 V with the regulator applied. Given this information, a boost DC to DC converter was attempted.

### 6.4.2 Voltage Boost

A voltage booster manufactured by Intersil (EL7515) was used to try to boost the voltage outputted by the rectenna to 12 V. Intersil specifies a circuit that can be used to boost a low-voltage variable input (1.8 V – 9 V) to a constant 12 V. The circuit is shown in Figure 6-15.

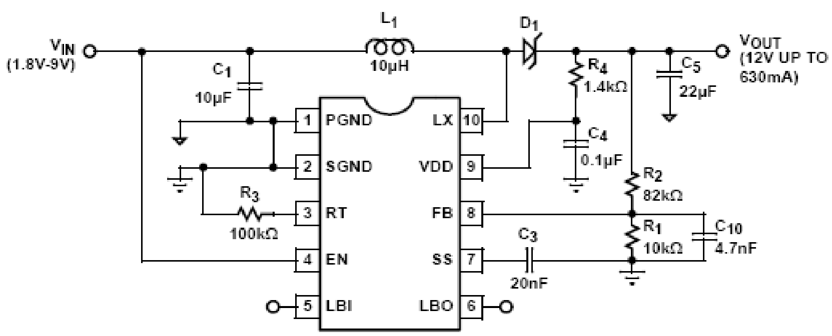


**Figure 6-15 Voltage Boost Circuit (Intersil 2005)**

The pinout description for the chip is explained in Figure 6-16.

***Pin Descriptions***

| PIN NUMBER | PIN NAME | PIN FUNCTION |
|---|---|---|
| 1 | PGND | Power ground; connected to the source of internal N-channel power MOSFET |
| 2 | SGND | Signal ground; ground reference for all the control circuitry; needs to have only a single connection to PGND |
| 3 | RT | Timing resistor to adjust the oscillation frequency of the converter |
| 4 | EN | Chip enable; connects to logic HI (>1.6V) for chip to function |
| 5 | LBI | Low battery input; connects to a sensing voltage, or left open if function is not used |
| 6 | LBO | Low battery detection output; connected to the open drain of a MOSFET; able to sink 1mA current |
| 7 | SS | Soft-start; connects to a capacitor to control the start-up of the converter |
| 8 | FB | Voltage feedback input; needs to connect to resistor divider to decide $V_O$ |
| 9 | VDD | Control circuit positive supply |
| 10 | LX | Inductor drive pin; connected to the drain of internal N-channel power MOSFET |

**Figure 6-16 Pinout Description for the EL7515 (Intersil 2005)**

A picture of the voltage boost circuit can be seen in Figure 6-17.

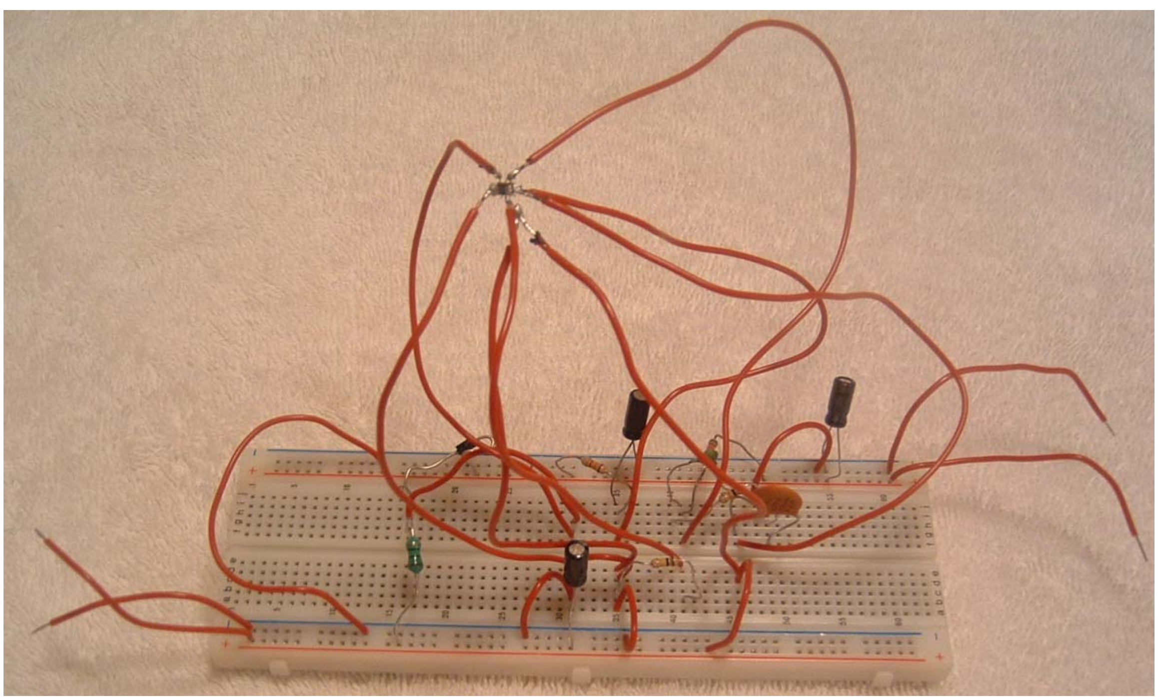

**Figure 6-17 Picture of the Voltage Boost Circuit**

The boost circuit was tested using a power supply with a variable output. When 6 V were applied to the boost circuit, 10.98 V were detected on the output. When 7.5 V were applied, 12.24 V were detected on the output.

Despite these results, with the voltage boost circuit attached to the rectenna, a voltage around 1 V was recorded at distances between 0 and 36 inches. The voltage boost circuit was apparently not effective when applied to the output voltage of the rectenna.

### 6.5 Final Results

To test that the system was actually producing voltage that could be applied towards something, a simple 2.1 V LED was attached to the rectenna. With the system transmitting and the LED attached to the antenna, the LED would light up at distances up to 37 inches. Figure 6-18 shows a picture of the lit up LED.

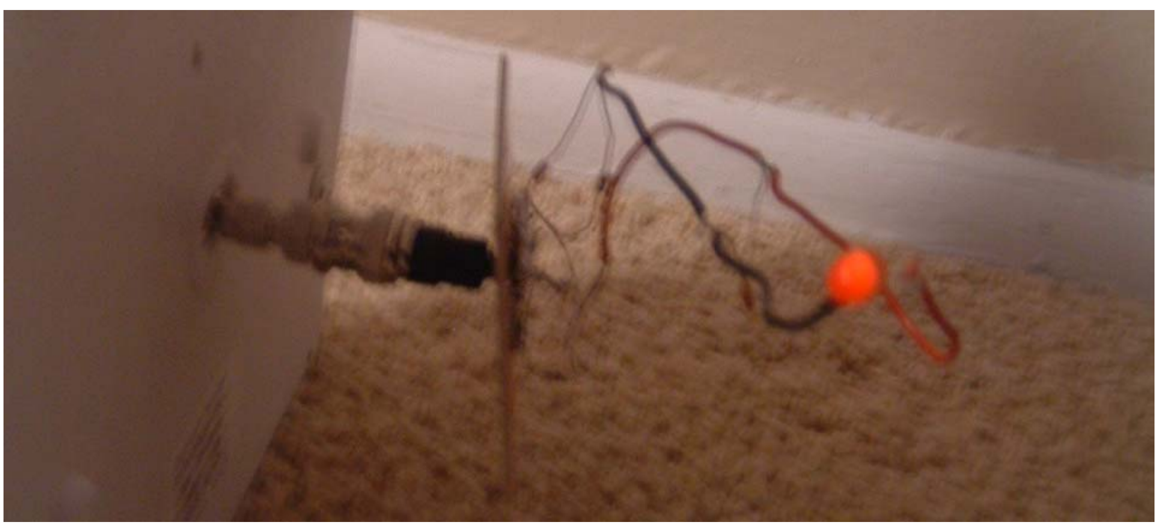

**Figure 6-18 Final Results - 2.1 V LED Lit Up**

With the knowledge that the 2.1 V LED would light up when directly applied to the output voltage of the rectenna, it was decided to test the 11.3 V Lamina LED that was originally chosen for use in the system. To do this, the battery was eliminated from the system. Figure 6-19 shows the result of this experiment.


**Figure 6-19 Final Results - The 11.3 V Lamina LED Lit Up**

As shown in Figure 6-19, the 11.3 V Lamina LED lit up when directly connected to the output voltage of the rectenna. The LED began to light up dimly at about 21 inches and progressively got brighter as the antennas were moved together.

With the antennas together, the LED did not reach its full brightness. The picture shown in Figure 6-19 was taken when the antennas were nearly together.

# 7 Conclusions and Recommendations

This chapter documents the conclusions and recommendations that were drawn from the results that were shown in the previous chapter. In this chapter each of the hypotheses is tested, general conclusions are drawn, and recommendations for future research are established.

## 7.1 Testing the Hypotheses

Each of the hypotheses that were proposed in the first chapter was tested to establish its validity.

### 7.1.1 Hypothesis 1

Hypothesis 1 stated that "the proposed electronic product is unique." In the analysis of similar lamp and wireless power transfer products that was conducted in chapter 3, no similar product to the one that is proposed in this thesis was found. It appears that this hypothesis is valid. The product developed in this thesis was unique and seems to satisfy a need in the marketplace.

### 7.1.2 Hypothesis 2

Hypothesis 2 stated that "the proposed electronic product can in theory be produced." The review of literature presented in chapter 2 and the design of the product laid out in chapter 3 showed that it seems like the proposed product could likely be produced. Hypothesis 2 seems to hold true. The system should have worked by design, but ultimately the output voltage could not be successfully stored in the battery. With some further research and experimentation in the area of voltage regulation, the system should work as designed.

### 7.1.3 Hypothesis 3

Hypothesis 3 stated that "upon building the proposed product, power can be transferred wirelessly at a practical distance typical of that found between a lamp and an outlet." The target distance used was 30 feet although a shorter distance would likely be acceptable. This hypothesis seems to be valid. In trial #12 of the results section, 72 mV was measured at a distance of 30 feet. It is a significant development that power was successfully transferred and rectified at a relatively large distance.

It is also significant to note that at a distance of 4 feet, nearly 10 V was measured. This is a significant contribution to the experiments of wireless power transfer. No documented work was found that transferred this amount of voltage at any distance.

### 7.1.4 Hypothesis 4

Hypothesis 4 stated that "using the proposed product, 1.175 watts of power can constantly be received at a practical distance typical of that found between a lamp and an outlet." The target distance used in this thesis was 30 feet although a shorter distance would likely be acceptable. This hypothesis could not be proved completely. As previously noted, the most voltage that could be detected at 30 feet was 72 mV. It would require a current of 16.2 A at 72 mV to produce 1.175 W. Given the problems with holding voltage with a load applied to the system, it seems highly improbable that this amount of current was supplied by the rectenna at a distance of 30 feet. Despite not having transferred the target amount of power at 30 feet, a significant amount of power was transferred at shorter distances that would likely be acceptable for the proposed product as well as other products that might benefit from similar technology.

### 7.2 General Conclusions

In the end, a 2.1 V LED was directly lit up by transferring power wirelessly at a distance of 37 inches. An 11.3 V LED was also dimly lit using the same system transferring power wirelessly at a distance of 21 inches. Power was successfully transferred and rectified at significant distances in this thesis. The product, that at the beginning of this thesis was just an idea, became a working prototype by the end of the thesis. Now that there is a working prototype of the system, it awaits further optimization.

The prototype was successful in transferring a significant amount of power wirelessly. The system as a whole is operational and functional. As the individual component technology evolves, the improved components can be substituted or added to the system without affecting its functionality. This is important because many of the components are rapidly evolving and progressing. For example, improvements in LED efficiencies will only enhance the functionality of the product as a whole. This work lays the foundation for wireless power transfer technology to be implemented in commercial products. Laptop personal computers, cell phones, and other products will likely one day receive power wirelessly.

### 7.3 Recommended Research Areas

There are a number of points throughout the system in which improvements would bring tremendous results. The following is a list of recommended research areas for this product:

- **Voltage Regulation Research and Development.** This area of research is the most immediate need for the system. Once the output voltage from the rectenna can be regulated to a consistent 12 V, the output power can be stored and accumulated to fully power the lamp.
- **Rectenna Research and Development.** Improvements in rectenna design and efficiency would make this product work even more effectively at larger distances. In this thesis, the efficiency of the rectenna was improved from initial output voltages in the single digit milli-volt range to large voltages. It is suspected that further research in this area would bring even better results than those experienced in this thesis. If rectenna efficiencies were sufficient, the system could likely be changed to transfer power point to multi-point rather than point to point. This would open up a whole new market for wireless power transfer; devices such as cell phones and laptops could be charged regardless of their location.
- **Antenna Research and Development.** The antennas that were used in this thesis were relatively large. If efficient directional antennas could be developed that were compact, it would allow this product to be marketed in a household environment.

- **Transmitter Research and Development.** Echoing the antenna problem, the transmitter used was large and contained many components that were not necessary for this system (some components, such as the speaker, were even disabled). A compact transmitter that could plug directly into the wall (in order to bypass using a power source) would bring a lot of value to the product.
- **LED Research and Development.** As mentioned in chapter 3, LEDs are currently less efficient than fluorescent lights. The efficiencies must increase so that a 5 W LED can compete with a 60 W incandescent bulb. Already, Cree (Cree 2006) has developed an LED with efficiencies of 131 lm/W. As developments like this are commercialized, LEDs will become more acceptable in the marketplace as a primary lighting source.

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