­­­IEEE Citation Style

Gemstone Program

Draft Proposal

Time-Reversed Energy Sourced through Localized Antennae (TESLA)

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*I pledge on my honor that I have not given or received any unauthorized assistance on this assignment.*

February 20, 2014

# Abstract:

Existing methods for wireless power transfer have significant drawbacks such as range limitations, safety issues, and orientation requirements. TESLA plans to investigate a novel signal focusing technique known as time reversal to circumvent these issues. Firstly, TESLA will investigate the possibility of transmitting non-negligible electrical power with this technique. Secondly, TESLA will explore the efficiency of the method and how it varies with the distance between receiver and transmitter. These data will be compared to existing wireless power transmission systems. Lastly, by adding a velocity component to the receiver, TESLA plans to simultaneously prove independence of orientation and explore the relationship between efficiency and motion of the receiver. Subjects for future research may include long-term biological effects or generalizability to multiple receivers.

# 1 Introduction

For over a century, civilization has become accustomed to simply plugging into a wall socket in order to power its devices. But what if the outlet could be taken out of the picture? What if these devices could operate beyond the confines of cord and cable? At present, this concept has more basis in science fiction; however, this fiction is quickly becoming reality. Although the concept of wireless electricity has existed since its proposal by Nikola Tesla in 1891, it was left largely uninvestigated throughout the twentieth century [1]. In the past decade, significant strides have been made in this field, but the age of wireless power has only just begun, and there remain methods of transmitting this power to electronic devices still unexplored.

## 1.1 Introduction to Wireless Power

The ability to wirelessly transport energy from one point to another has the potential to attract many unique investors and customers. Such a technology is convenient; it saves space by eliminating the need for unwieldy chargers or elusive wall outlets. Businesses that offer Wi-Fi connectivity may be interested in this technology as another service to both retain and grow their customer bases. A convenient method of recharging devices will discourage the use of non-reusable batteries and present environmental benefits. Residential consumers would certainly be interested in a convenient way to charge their cell phones, laptops, and other small devices. Automobile companies such as Toyota, Infiniti, and Volvo have demonstrated interest in wireless power technology, so users can charge their electric or hybrid cars more conveniently. There are also surely technologies, which will develop as a consequence of wireless power transfer (WPT), that have not yet been fathomed.

One specific example in which wireless power could be particularly beneficial is an airport terminal, where individuals may wait for hours until their flight takes off. Many of these travelers will have a need to charge laptops, cellphones, and other electronic devices for both personal and work reasons. However, the layout of an airport terminal means that most people will be unable to reach a plug with their limited charging cords. Often, this creates a high amount of stress and unrest among travelers in the airport, particularly where individuals need their devices to get work done. This example can be extended anywhere there are more people who desire power for their devices, and the use of outlets is inconvenient. The college library is another paradigm in which hundreds of people are confined to a space where outlet access may be an issue.

These are not the only locations where individuals plug in their devices regularly. Wireless power technology could in fact have its most widespread impact in a domestic setting. The Federal Energy Regulatory Commission (FERC) notes that there are 80,000 GWh used per week on average across the entire United States [2]. Assuming even just 5% of this power goes to powering laptops, cell phones, and tablets, this leaves 4,000 GWh of power per week that go to these devices. The topic of convenient power transmission clearly transcends just an airport or library. With so many people plugged into the grid, it is apparent that new methods of energy transfer would benefit millions of people in a multitude of situations. From domestic users to students and travelers, it is clear that millions of people will benefit from improved delivery of power.

## 1.2 TESLA’s Project and Hypotheses

Team TESLA plans to examine a theoretical technique that has the potential to drastically improve the range of a WPT system and eliminate the issue of alignment. This technique, known as electromagnetic time reversal, has already been proven to be a successful method of information transfer [3][4], but its application to WPT has not yet been investigated. Time reversal (TR) is a method of locating the position of a transmitter by utilizing the reflection and interference of waveforms in a complex environment. This indicates that it should be an ideal method for WPT, as rooms and buildings contain complex surfaces, and TR can determine the location of the device’s battery without knowing any information about the environment itself.

The questions that TESLA intends to investigate are as follows: With what electrical efficiency and over which distances can power be transferred wirelessly using the method of time reversal? What impact does the environment have on these values? Finally, how is this efficiency affected by the motion of the receiver?

TESLA’s first hypothesis posits that significant amounts of power can be transmitted using TR. TESLA is defining a specific benchmark for this number to be at least one watt; it has already been proven that TR can transmit small packets of electricity in the form of data signals [3]. As such, it is believed that the same technique can be used for larger quantities of power because the amplitude of an electromagnetic wave does not impact factors such as frequency, wavelength, and dispersion. By leaving these factors untouched, TESLA believes that TR WPT can be scaled up using different circuitry setups. This conjecture is important to test, as the following hypotheses rely upon it.

The team’s second hypothesis proposes that TR methods will be on par with or more efficient – defined here as the ratio between the power received by the load and the power transmitted – than other WPT techniques. In traditional methods of WPT, signals are broadcasted in all directions, which results in significant energy losses. In a TR WPT system however, the energy will be focused on a single point. Although there will be some amount of loss due to absorption by the environment, it should be significantly less than the amount of loss from radiating power in all directions. Generally, TESLA believes that this method will optimize range and efficiency without compromising safety.

Finally, TESLA hypothesizes that the efficiency of the TR-based WPT will not decrease significantly if the receiver is moving in an arbitrary fashion relative to the transmitter. It is logical that, since electromagnetic waves traverse at the speed of light, any distance traveled by the receiver during the process will be so miniscule that it can be ignored [5]. During statistical analysis of collected data, TESLA seeks to reject the null hypothesis that TR is only a viable method for transmitting data, not power, and that the transmission will break down if the receiver is in motion.

## 1.3 Conceptual Overview

Time reversal (TR) is a signal processing technique used in order to focus waves on a given location. Consider a room with two antennas. At a basic level, if the first sends a signal out into the room, then this signal will take a unique path bouncing off the walls of the room until it reaches the second antenna. If this second antenna records the signal, and plays it in reverse, then the signal will follow the opposite path back and converge upon the first antenna. This concept can be applied to both physical waves, such as sound waves, as well as electromagnetic (EM) waves in order to send a focused signal to and from a specific location. However, it is important to note that time reversed waves can only converge on the original point if the environment they move through remains undisturbed [5]. As long as the environment is unperturbed, the complexity of the surroundings actually contributes to a more distinct scattering path for the waves and, subsequently, a clearer return signal [6]. TR will be discussed more formally in Chapter 3: Methodology.

Given the high demand for power and the interest in its wireless delivery, TESLA intends to research the novel application of TR to electromagnetic waves for WPT. Next, TESLA will explore the background related to its research question in the literature review section and then overview its approach to implement WPT in the methodology section.

# 2 Literature Review

The wireless transfer of electrical power has captured imaginations since Nikola Tesla demonstrated it in 1891 [7]. The benefits of a practical WPT system are myriad, as has been delineated above. It is important that the reader first understand what progress has been made towards these benefits, so that they may see where TESLA’s project breaks new ground. Consequently, TESLA will open this section with a description of the field of wireless power as it currently stands: the team examines three of the most commonly used techniques. The bulk of the relevant literature is, however, in the method of time reversal itself. This literature is given a thorough treatment, concluding with a look at where the existing knowledge base is weakest and what TESLA plans to do to expand it.

## 2.1 The State-of-the-Art in Wireless Power

Past attempts to solve the problem of practical WPT have been dominated by magnetic induction, microwave beaming, and (more recently) highly resonant magnetic coupling. Of these, magnetic induction is perhaps the most well-known; it is commonly used in electric toothbrushes, shavers and charging mats. When current is passed through a metallic coil, a magnetic field is created in the environment around it in accordance with Faraday’s Law [8]. If another coil is positioned within this field such that the magnetic flow lines pass through it, the field induces a current in the second coil. The induced current can then be used directly or stored by the rest of the circuit [8]. This type of power transfer is simple to implement, but is constrained by its limited range and its need for precise coil alignment. To maximize the induced current, the magnetic field must be as strong as possible. Unfortunately, the strength of such fields decreases with the inverse of their distance from the source. Further, if the second coil is even slightly misaligned from parallel to the magnetic flow lines, little to no current is induced in the wire [9]. In practical application, the range is limited to only about a few centimeters and the angle difference away from being parallel can only be a few degrees [10]. Both of these features make this method a good choice for when the device to be charged can be positioned in direct contact with the charging device, as with electric toothbrushes and certain cell phones. However, this is not always desirable – constraining the device in place was one of the problems with traditional plugs that WPT systems seek to avoid. Magnetic induction, then, while useful and simple, is only good for specialized applications where its lack of range is acceptable. The technique cannot be feasibly generalized to longer ranges due to its sharp decreases in efficiency with only minor changes in orientation and range.

However, there are solutions available to overcome induction’s shortcomings in range. The longest-range WPT technique currently available is microwave beaming. Microwave beaming involves the use of microwave-frequency lasers, called masers, to fire microwave beams from transmitter to receiver [11]. These beams are collected and converted back into usable electricity through the use of rectifying antennas [12]. Theoretically, it is extremely efficient due to the self-propagating properties of electromagnetic waves: in a vacuum, the microwave beam could travel indefinitely. In air, some energy is lost to dispersion, but the practical ranges of the technique are still on the order of hundreds of miles instead of centimeters. Unfortunately, there are serious drawbacks to using microwave beaming as a feasible means of WPT. The first is that it requires incredible precision: if the beam misses its intended target in the slightest, all of its energy is simply lost to the environment. When considering the ranges at which microwave beaming is considered, even a small miscalculation in transmission angle could result in the beam missing its target by miles. Another concern is that the microwave beam will be completely neutralized if there is anything between the transmitter and receiver. Again, when considering the environment that microwave beaming is used for, this means that minor environmental factors can significantly disrupt the beam and reduce efficiency. Furthermore, the use of high amplitude microwaves can pose a threat to biological tissue and organisms should they miss their target. Thus, microwave beaming only has applications in well-controlled or isolated environments such as labs. It requires extreme precision with little interference. Worse, microwave beaming poses threats to biological tissue if done improperly.

Until recently, there was no good intermediate choice between the two methods described above. This is no longer the case. The Boston-based company WiTricity has developed “highly resonant” magnetic coupling that offers a more broadly applicable version of magnetic induction. In this method, the transmitter and receiver circuits are both tuned to the same resonant frequency, a concept akin to tuning two instruments to the same pitch. This creates a much larger voltage in the receiver than in the traditional induction case when the two antennas are not coupled. This new method of WPT looks to be promising, with a documented 50% efficiency at two meters, and around 10% efficiency at four meters [13][14]. This method has also been used to charge multiple devices without sacrificing overall efficiency [13]. The power entering the transmitter generates a magnetic field, which radiates broadly enough that it can encompass multiple receivers. Alternately, this property can be used to increase range by using a relay device that has a strong mutual inductance, allowing the magnetic field to be re-created around the relay with minimal loss [10]. Achieving such large gains over traditional induction is not easy. The novel technique in WiTricity’s method is to actively adjust the resonance and impedance of their networks so that transmission remains optimal [13]. Impedance matching minimizes the amount of wave reflection inside the transmitter and receiver circuits, making sure that all of the energy is actually passed to the load component. This process requires a constant, proprietary feedback loop of information in order to optimize the receiver for any given distance from the transmitter.

Though the method is complicated, WiTricity has achieved impressive results. A WiTricity demonstration at a TED Talk illustrated powering relatively small devices - a phone and a television– at a distance of about three or four feet [15]. WiTricity has partnered with several car companies, including Delphi and Audi, and has demonstrated that electric vehicles can be charged using this method. This indicates that resonant coupling can transmit power from mW to kW, significantly more than was practical with traditional induction [13]. While this looks very promising in the coming years for commercial applications, the method is not without its drawbacks: it is likely to be prohibitively expensive for residential use and range is still reasonably limited to only a few feet. Thus, there is still no safe wireless charging method which can efficiently transmit energy over a distance greater than four meters.

## 2.3 A Brief History of Time Reversal

Team TESLA’s project hopes to overcome some of these limitations through a novel method: the use of electromagnetic time reversal (TR), the process of which was briefly described above. TR is already a proven technique in signal processing. Though its exposure is limited even within the acoustic research community, there is a wealth of available literature regarding TR in certain specialized areas. The development of and historical applications of the technique provide insight as to where TESLA’s project will expand this literature.

Time reversal as a technique was first developed in the 1990s. Some of the earliest and most influential work was by teams of scientists led by Mathias Fink and Claire Prada of the University of Paris, who used the technique as an iterative focusing method [16]. An array of transducers would fire a sonic pulse into some propagation medium and listen for the echo. The recording of that echo was reversed in its time domain and transmitted back into the medium. In the resulting echo, the strongest reflector, or “scatterer”, appears more prominently. Prada and her team submitted this “DORT” method (a French acronym) as a process for finding cracks or faults in structural members [16]. More importantly, Prada et al. went on to prove that the method could always resolve the brightest scatterer if given enough iterations, that it worked better in a heterogeneous medium than a homogenous one, and that it was both experimentally and mathematically possible to resolve multiple targets at once [17]. These discoveries generated significant interest in the audio research community.

Others in the field of acoustics went on to refine the DORT method as an imaging technique, such as D. H. Chamber’s 2007 examination of acoustic TR for target detection and characterization. Chamber’s treatment also included an overview of the field of electromagnetic TR that was beginning to blossom [18]. Chambers ensured the math behind the technique was well understood. In 2010, Nguyen and Gan developed a way to extract much more information from an anisotropic (directionally distinct) scatterer, including its rough shape, density, and radius. In doing so, they developed a faster mathematical approach to locating their scatterers that relied on several good approximations instead of one exhaustive computation [19]. Also in 2010, Barbieri and Meo made a large contribution to the field by bringing together the DORT method, which works in linear environments, and another similar method for working in nonlinear environments. This allowed them to resolve and distinguish between linear scatterers such as holes and nonlinear scatterers such as cracks [20]. As far as TESLA could determine, this was the most recent publication concerning TR in its original use as an imaging technique.

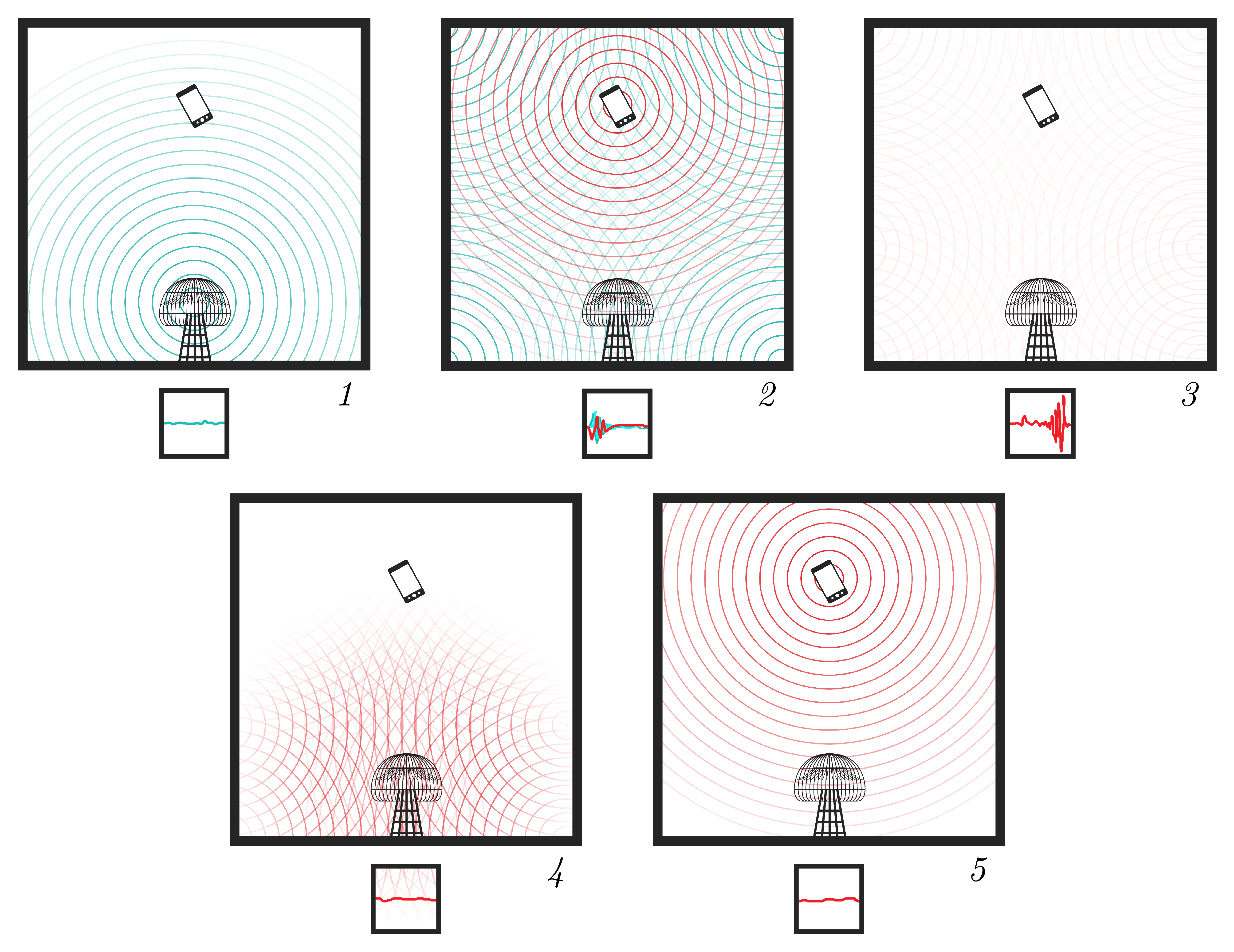
Imaging is not the only application for a focusing method, however, and others adapted the existing body of TR research to new problems. Interestingly, the reciprocity of the wave function that Fink and Prada relied on to develop the technique holds for all waves it can be used to model – this means that the time reversal operation works much the same way with electromagnetic waves as it does with sound [18]. This was being explored as early as 1999, but was largely concerned with the same imaging problems occupying those in acoustics until at least 2007 [18]. However, that gradually began to change. In 2011, a team including graduate students from the University of Maryland argued that time reversal was an ideal paradigm for clean wireless communication [15]. In the same way that a sound wave could be made to collapse on a scatterer, they showed that an information packet could be made to collapse on a receiver. The team submitted this as a “green” or eco-friendly communication method, because information could be tightly concentrated at a single point rather than beamed wastefully in all directions [15]. Later, this same property was examined for its security benefits instead of its environmental ones. In February of 2013, a team of researchers at the University of Maryland, including Matthew Frazier and Steven Anlage, published a study discussing TR as a method to selectively send information in a chaotic wave environment [3] [21]. Essentially, the team was able to create an exclusive communication link to a certain object, without needing to know its location, and without interfering with nearby objects. In their experiment, they were able to transmit data (in the form of images) exclusively to either a linear or nonlinear port, while the other port received only nonsense.

Besides the practical applications, in the process, Frazier and his team used nonlinear elements to extend TR in new and exciting ways. Recall in traditional TR many iterations are required to “home in” on the target. The addition of a significantly nonlinear element changes things. When a wave strikes the element, harmonic frequencies are produced at integer multiples of the original frequency. These harmonics can be quickly located in the echo’s frequency domain and filtered to select them exclusively. The important distinction is that since the harmonics originated directly from the target, all subsequent broadcasts of the TR signal will collapse there exactly without the need for iteration [3]. Frazier and the others put forth several exciting directions to pursue with this concept: the aforementioned secure communication channels, hyperthermic treatment of tumors, and a long range WPT system that eschews the traditional high power beams. It is this last area that TESLA intends to explore.

# 3 Methodology

Little research on WPT via TR is present in the current literature. TESLA’s research methodology seeks to fill this gap by answering the following research questions: With what electrical efficiency and over which distances can power be transferred wirelessly using the method of time reversal? What impact does the environment have on these values? Finally, how is this efficiency affected by the motion of the receiver? The methodology section of this paper lays out the plan of action TESLA will take in order to design a working TR power transmission system, test the system, collect data, and ultimately refine it to maximize its performance.

The basis of TESLA’s transmission system will be a Time-Reversal Mirror (TRM), a system that focuses EM waves onto a receiver, transforming those waves into usable energy. There will be three primary parts of TESLA’s TR system. The TRM will be connected to an energy source, and will transmit the EM waves during the powering process. The receiver will be a rectenna designed to reflect a unique EM wave pulse when an initial wave pulse strikes it. The behavior of the system is described in Figure 1.



**Figure 1:** (1) The TRM sends an exploratory wave into the environment at an original frequency, f, (shown in light blue). (2) This wave reflects back from and echoes off surfaces in the environment. Reflections coming from the nonlinear element are at a distinctive frequency, k, where k is an integer (shown in red). The total echo recorded by the TRM (pictured in the small box) has these frequencies embedded in it. (3) As the echoes die away, the TRM takes a Fast Fourier Transform to isolate the relevant frequencies, reverses them, and increases their amplitude. This amplitude increase is how power is introduced into the system. (4) The TRM broadcasts the modified wave into the environment. (5) After reflecting off of surfaces throughout the environment, the modified wave collapses directly onto the nonlinear element [22].

The testing of the qualities and capabilities of this device is the main focus of TESLA’s research. However, a significant amount of research time will be spent on the research, design, and construction of the TRM and receiver prototype. TESLA has split its research into four major milestones to be completed over the course of the team’s research. These milestones are the research, design and construction, testing, and analysis of the system.

## 3.1 Preliminary Research

TESLA is currently conducting background research on TR, TRMs, and rectennas, so that they may be able to better understand the factors that will influence the design of the prototype. A significant amount of preliminary experimentation will be done in Dr. Anlage's lab. Although the necessary equipment is very expensive, Dr. Anlage has generously invited the team to work with the TRM he is using for his own research, which will help minimize costs associated with experimentation. The preliminary work has been carried out in these task forces:

## 3.1.1 Rectenna Team

The purpose of the rectenna team is to optimize the rectenna, or receiving end of TESLA’s TR system, which converts the signal it receives into usable electrical energy. The first step in this process involves examining the nature of nonlinear response in common elements. The rectenna team has been measuring the amplitude of the second, third, and fourth harmonics (as well as the original frequency) output by frequency multipliers. By varying the input frequency and amplitude, the team can produce graphs of how these factors impact the amplitude of the harmonics from the component. Since TESLA's method of time reversal relies on a strong harmonic signal, knowledge of how best to produce one will be imperative.

Second, the team is looking at pulse inversion as a possible replacement of Fourier transforms for processing the signal. Recall that in TESLA's original idea, the TRM would receive a signal and take the Fourier transform to isolate the nonlinear, harmonic portion before performing the TR and sending it back. With pulse inversion, a "fingerprint" of the receiver is recorded beforehand. First, the response of the receiver to the signal pulse and to an amplitude inversion of that pulse is recorded. Then those two recordings are added together. The linear portions of the signal will destructively interfere and cancel each other out, leaving only a nonlinear fingerprint. TESLA is interested in seeing if this new method is computationally faster than computing the Fourier transform, which could improve the quality of the reconstructed signal.

## 3.1.2 Antenna Team

Similar to the goals of the rectenna team, the antenna team is focused on optimizing the provider side of the TR system, which will be sending the signal, and thus the energy to the target device. Since there are a wide range of different possible antenna geometries, which each have unique characteristics, the antenna team is currently building and testing different possible designs in order to determine which one will most efficiently and reliably transmit power within the context of TESLA's specific system. Once the design has been chosen, the antenna team will examine the effect of different frequencies on the amount of power transmitter by the antenna, again for the purpose of maximizing efficiency. Finally, the team will be investigating the application of impedance matching between the two antennas in order to minimize any unnecessary sources of energy loss.

## 3.1.3 Loss Analysis Team

TESLA is interested in seeing how different elements of an environment affect the quality of a TR reconstruction. To this end, the team is recreating some of Dr. Anlage's original experiments with TR in an idealized experimental environment (a hollow, metal box optimized for TR testing), but varying the contents and nature of the environment in a controlled manner. The focus is on materials expected to be lossy, such as carpet, microwave absorber, or water. These and other materials are placed in the environment so the team can measure how their presence affects the experiment. Additionally, the team is looking at the impact of introducing perforations in the box, another possible source of signal loss.

## 3.1.4 Modeling Team

Behind any good experiment is the "theoretical" data to test the experimental results against. It is the goal of this team to develop a solid theory of what TESLA should expect to see from the TR experiments. To accomplish this, the modeling team is making use of wave equation solvers such as HFSS (High Frequency Structural Simulator) to virtually model expected results of TR methods of WPT. This team aims to have a highly realistic model of wireless power transfer in place, which can both provide supplementary data to support experimental results and allow for collection of data that would otherwise be expensive or difficult to obtain in real-life experimentation.

## 3.1.5 Research Application

Finally, as a culmination of the knowledge and experience gained from this research, TESLA will create a preliminary implementation of a TR-WPT system by wirelessly powering a small vehicle inside a small, enclosed space. This goal has the advantage of being similar in nature to the final prototype TESLA aims to create, helping the team transition to the construction phase of the project. Unlike the standalone prototype, however, TESLA will make full use of laboratory equipment and resources, making this objective simpler and more straightforward to implement. This side project will give TESLA members valuable experience about the actual design and construction of a WPT system, which is sure to be useful in the construction of the real prototype.

## 3.2 Design and Construction of Prototype

Combining knowledge from the previous experiments and theoretical calculations, TESLA will create an initial prototype that proves TR can be applied to WPT as stated in the hypothesis. At this stage, aesthetics, size, convenience, compactness, and set-up will not be considered. By creating a rough prototype, TESLA can effectively demonstrate that the technology behaves as expected, without worrying about form. Additionally, a working system will allow for verification or falsification of more specific hypothesized properties such as whether or not the technique can also effectively power non-stationary objects.

In order to maximize the efficiency of the system when assembled, care will be taken to match the impedance between the components of the circuit. Impedance is a measure of how opposed a circuit is to a change in the current flowing through it. If a signal tries to pass between two areas with drastically different impedances, some or all of it will be reflected back rather than continuing on. TESLA is interested in this because matching the impedance of two circuits minimizes the reflection of the voltage signal, optimizing the amount of voltage transmitted through the circuit [23].

Impedance is directly dependent upon frequency, and TESLA will choose the frequency that will provide optimal impedance matching in order to achieve maximum transmission efficiency. This decision will be based primarily on the results of the experiments in the Research Phase. However, the decision is complicated by the necessity of avoiding frequency bands already reserved by FCC guidelines. The fact that most of the team’s work will be proof of concept in an isolated, laboratory setting lessens the need to avoid these bands. However, frequency availability would merit consideration in the event that TR-based WPT is applied to a public setting. In this scenario, TESLA would need to choose the optimal frequency for impedance matching based on the ISM band of legal microwave frequencies that are allowed for custom projects, such as the one proposed here.

## 3.3 Experimental Procedures

Once the rough prototype is created, TESLA will conduct experiments to determine efficiency and function of its prototype. TESLA then hopes to improve the prototype, by making it more energy efficient, cost-effective, and robust. Time permitting, multiple testing and refinement phases will be accomplished before the completion of the project.

TESLA will rely almost entirely on experimentation in its research. In order to demonstrate the effectiveness of TR WPT compared to other WPT techniques, TESLA will be measuring the efficiency of its prototype at varying distances between the TRM and the receiver. Since the data of interest can be defined quantitatively and it is possible to restrict many aspects of the study in order to achieve an appropriate control, an experimental design is ideal for TESLA’s purposes. Sources of error in could include interference from other EM wave frequencies, absorption of waves into the environment, and lack of chaotic structure in the environment. However, TESLA expects that by constructing an idealized environment with a number of metallic surfaces, no leaks, and ray chaotic elements, these concerns can be greatly reduced.   
        This ideal environment will consist of a small, fully enclosed area lined with reflective metallic surfaces to minimize the absorption of the EM waves by the walls. Metal surfaces will also minimize outside noise that can contribute to error. Similar chambers have been used in other electromagnetic TR studies [3][24].  
        The definition of “idealized” for a TR environment is unusual. TR is most effective in chaotic environments, where minute differences in a wave create large changes in the final behavior of the wave. The more objects the waves interfere with, the more distinct and consequently more effective the resulting pattern is. Chaotic elements will be added to encourage waves to disperse, promoting the wave-chaotic environment that TR needs. Thus, TESLA’s idealized experiments will include chaotic elements made out of a low-loss metallic material, using the same reasoning as the rest of the environment.

Should the TR WPT concept be shown to work in an idealized environment, TESLA will then begin testing with more representative scenarios. An eventual intent of the team is to test the system’s operation in a situation where it is influenced by other variables such as absorption by building materials, EM interference, leakage out of the area, etc. Lossy materials and other interfering phenomena will be introduced to the idealized environment to test the extent of these effects. All other aspects of testing will be kept constant between environments, to allow for accurate comparison.

The first experiment will consist of TESLA recording the efficiency of the power transfer with varying distances (approx. 1 cm) between the TRM and receiver. The closest testing point will be right next to the TRM – the farthest distance tested will be determined by the confines of the testing environment, or the point where the transmitted efficiency approaches 0%.

Next, a test will be conducted to determine the maximum speed that an object being charged can move and still receive power from the device. This test allows TESLA to determine the validity of the third hypothesis; that the movement of the load will have a negligible effect on efficiency of transfer. In theory, objects moving at everyday speeds (approximately 1.35 m/s [25]) will be moving so slowly compared to the speed of the EM waves that the system will still behave as a stationary object would. To determine at what speed the collapse of the TR pulse on the phone breaks down the device will be moved in a circle (so that the distance remains constant) at various speeds and measuring the efficiency of the power transferred.

Finally, tests to show independence of alignment will be determined by measuring efficiency with the receiver in various orientations, such as vertical, horizontal, or inverted, and comparing the induced voltages in each position. The third test is important because traditional WPT techniques like coupling are highly dependent upon orientation [26]. Theoretically, the orientation of the load device should be irrelevant to TR-based WPT, because the signal collapses directly on the antenna, but this remains to be proven.

Other tests may be done with the system, dependent on the resources available to the team. In addition to range, efficiency can also be measured based on input power. Previous experiments involving WPT have shown efficiency generally decreases as applied power increases. By keeping the distance constant and changing input power, this value can be obtained. TESLA will track input power versus efficiency to determine if TR-based WPT is also subject to this limitation.

## 3.4 Data Collection

To determine the efficiency of the power transfer, an ammeter/voltmeter will measure the current and the voltage across parts of the circuit in real time during each test. By finding the values of power in and power out at any given time, the efficiency can be calculated. The maximum range for TR-based WPT will be estimated from this data at the point where the power transferred is effectively zero.

The efficiency of the circuit will be measured in two ways. TESLA is interested less in the TRM efficiency and more in the efficiency of the WPT itself. Thus, a distinction will be made in testing between “transfer” and “total” efficiency. Here transfer efficiency refers to efficiency between only the antennae, rather than between the power source and the load. For example, high transfer efficiency with a low source-to-load efficiency would indicate that TR works well as a power conduit, but that energy is being wasted in the internal circuitry of the TRM. The transfer efficiency will be measured from antenna to antenna, while the total efficiency will be measured from power source to load. As before, multimeters will record the current and voltage drop at each distance tested.

Testing and data collection will proceed as follows: multimeters in the circuits between the wall and the TRM, and across the load in the client, will determine the power in each segment to calculate the wall-to-load efficiency. This efficiency will be measured as a function of distance; discrete data points taken at varying distances with a small (1 – 10cm) step size, starting from 1 cm up until no power can be detected, should yield enough information to generate a curve. The process will be repeated with antenna-to-antenna measurements to generate the corresponding efficiency curve. The difference between this series of data sets and their corresponding source-to-load efficiencies will indicate the amount of loss that can be attributed to the circuit design itself. By pinpointing the steps in the process where the most energy is lost, Team TESLA will refine the design and improve the offending components.

## 3.5 Data Analysis Procedures

Before appropriate methods of data analysis can be discussed, the metrics of behavior most important to WPT must be specified. There are two major quantities important to consider when comparing WPT techniques. The first is the maximum range at which a given technique can transmit a non-negligible amount of power. This value is low across the board for all WPT techniques - magnetic induction can reach only about twenty centimeters, while resonant coupling can have a maximum range of about four meters [13][14]. For magnetic coupling, power transmission is related to the strength of the magnetic field at the point where the receiver is located, and this strength is inversely proportional to the distance from the transmitter [8].

The second metric is the efficiency of power transfer at a given distance [14][26][27]. This can be defined as the ratio between the input power and output power achieved for each distance:

(Eq. 1 [28])

More generally, the efficiency of any given WPT technique can be written as a continuous function of r, the distance between the transmitting and receiving elements of the circuit. This function also dictates the maximum range of a system: it is the distance after which the efficiency is effectively zero. If a system loses large amounts of energy, or cannot send power across a reasonable distance, it is unlikely to find much use in the world at large.

Through the above analyses, TESLA hopes to gain a plot of efficiency between both source and load, and antenna-to-antenna, for stationary and moving targets. A function can be generated to fit each curve from the tests. Using a chi-squared optimization, the best-fit function will be found to match the data. From these functions, analysis detailed earlier in the paper may be applied. The range efficiency rating can be compared to that of other WPT technologies and thus used to prove or disprove the hypothesis that TR will have a greater overall efficiency.

## 3.6 Anticipated Results

The final aspect of TESLA’s research will be focused on the analysis and interpretation of experimental data. These analyses will be used to write TESLA’s final thesis - beyond satisfying the requirements of the Gemstone Program, this thesis will have the goal of suggesting routes for improvement in the field of TR wireless energy.

TESLA expects to find that the use of TR to transmit energy is both viable and comparable in efficiency to other WPT methods. Furthermore, the TR method is expected to remain viable in instances where the receiver is moving relative to the TRM powering it, and in instances where the receiver has a variable orientation from the TRM.

## 3.7 Team Organization

To successfully meet these milestones, TESLA members will split up into smaller groups and delegate tasks appropriately. Strict sub-teams, though easier to specify organizationally, do not have the flexibility required to manage such a diverse agenda. TESLA will instead employ a task-based, sub-team approach.

Each milestone consists of several distinct tasks, and sub-teams will be formed to tackle each task specifically. Each sub-team will consist of members who possess the skills most relevant to the completion of the task. When each task is completed or otherwise comes to an end, the sub-team will dissolve and its members will move onto new tasks. This process has already been applied to the formation of our preliminary research teams described in Section 3.1.

Being on a sub-team is not mutually exclusive, and individuals are able to be on other sub-groups as they see fit. However, the team as a whole will address contributions by various team members. Should a team member not be involved enough in team activities, or should members overcommit themselves, the team will force a more equal distribution of labor.

The work of team members will be monitored by using a grade system. All internal assignments on the team will be graded for timely completion, and will have an effect on a team member’s final grade. At the beginning of each semester, the team will meet internally and with the Gemstone Staff to determine a good breakdown for this grading system. Within certain bounds, sub-teams will be able to set their own internal deadlines, working in a similar fashion. The dependence of grade being only on final completion is due to the fact that TESLA does not want personal opinions to affect a team member’s grade – should an issue with the quality of a student’s work arise, it will be brought up with the Gemstone Staff outside of any academic process.

## 3.8 Possible Complications

TESLA is confident that using TR in a wave chaotic system will prove to be a highly efficient method for wirelessly transferring energy. However, TESLA must also account for the possibility of complications arising as the project moves forward. A variety of technical or logistical problems are possible at all stages of testing. TESLA is prepared to deal with these issues as they appear, and has already outlined solutions and action plans to address anticipated difficulties.

Technical expertise is a very apparent roadblock to the success of the project, and needs to be addressed before moving forward. The construction of a functional prototype requires a great deal of knowledge in a number of fields, including software engineering, signal processing, electronics, and wave physics. This is advanced knowledge that currently most TESLA is lacking. To increase general understanding in these areas, TESLA will engage in individual learning as well as group lectures by both the team mentor as well as team members on their areas of expertise. Technical tasks will also be delegated to those with the most experience in the area, reducing the burden on each individual member. With the wide range of engineering, math, physics, and computer science majors on the team, this specialization will allow TESLA to explore a wide range of technical fields without major difficulties.

Logistical issues with time constraints and funding are legitimate concerns in any major research endeavor. With only around two years to complete all research and a fairly small stipend for an initial budget, these problems are only magnified. Though TESLA has a tentative timeline for milestone progress and a preliminary budget to cover project costs, these are all likely to change as the project moves forward. To prepare for unforeseen circumstances or major changes in project direction, TESLA plans to begin preliminary experimentation as soon as possible, allowing for more time to adjust should the need arise. In addition, TESLA will attempt to both minimize costs by using mentor-provided lab resources for experimentation as well as favoring software simulations whenever possible, only purchasing hardware components when absolutely necessary. To complement this, TESLA will seek additional funding through grants from scientific, government, and academic communities, emphasizing the unique and innovative nature of the research to gather support.

The actual performance of the WPT device TESLA will create is another area to consider. If TESLA is successful in the creation of an efficient power transfer device, there are few problems to discuss. The alternative case, however, leads to possible complications and a threat to the validity and impact of the research. If TESLA’s device does not transfer power efficiently, it will be difficult to determine the sources of inefficiency. It could be the case that TR method of WPT is naturally inefficient in common environments. It could also be the case that incomplete or improper optimization of the device is to blame, and given a more efficient design, this method of WPT is actually extremely effective. Both these results are important conclusions, but it will be difficult to distinguish between them. TESLA will attempt to address this problem with supplementary laboratory and software modeling data, simulating ideal conditions and implementation, but further changes to methodology may have to occur to deal directly with this issue.

One final concern is regarding the pace of technological development in the area of WPT. Though ideas about WPT have existed for quite a while, the commercialization and realization of many of these ideas is just recently being explored. At the moment, there has been no specific research or exploration of the usage of TR and wave chaos as a method of WPT. In the current environment of competitive investigation, however, the situation could change at any point. TESLA will remain informed of changes in the field of WPT through constant review of recent news and publications. In the event another group supplants that TESLA’s current project, the team will attempt to adjust the direction of the investigation, narrowing the focus of the project to a smaller niche in the field.

# Chapter 4: Conclusion

## Research Contributions

Historically, time reversal has been investigated in the context of acoustic waves. Although very recently, research has demonstrated time reversal with electromagnetic waves for data transfer [3] and imaging [4][18], it is also applicable to a number of other, yet unexplored, applications, such as wireless power transfer. TESLA plans to contribute to both the scientific and engineering fields by initiating this research on WPT using EM-TR. Although there currently exists extensive research on a number of different methods of WPT, each have their own limitations, which prevent them from being practical in a wide variety of situations. Thus, the goal of TESLA’s research is to determine whether or not EM-TR is more practical than and advantageous to these pre-existing methods of WPT.

In the real world, outside of academia, WPT has already become a serious topic for many major companies, and the commercialization of WPT technologies, though extremely novel, is becoming more and more common. Although the future of WPT is uncertain, TESLA imagines WPT technology being employed in a wide variety of applications, including basic consumer use, military operations, space exploration, and medical practice. Though TESLA does not intend to design a consumer-oriented product directed towards any one possible application during the course of the Gemstone research program, the prototype created, if successful, would be an important proof of concept for the technology, improving its domain of application with a higher efficiency, higher range system.

## Research Limitations and Suggestions for Future Research

However, TESLA must also recognize the limitations of its research. Due to time constraints and a focus on delivering a proof of concept rather than a consumer-ready product, TESLA will not collect and analyze any data regarding the effect of a WPT using TR on human biological tissue. That is not to say, however, that safety will be ignored in TESLA’s research. In theory, the device that TESLA plans to construct, as outlined in Chapter 3. To reiterate briefly, the transmission process consists of alternation between a low-energy exploratory ping, which locates the device, and a high-energy (high amplitude) ping, which provides power to the device by time reversing a recording of the exploratory ping. Considering the theoretical principles behind time reversal, it is not possible that the initial exploratory ping would choose a path going through human tissue, because any reflections of the ping that reached human tissue would be absorbed by it, and thus would not contribute to the locating signal recorded by the transmitter. Furthermore, even when the high energy ping is sent from the transmitter, it reflects into a number of waves which propagate which much lower energy on their own, and only add up to the initial total power sent at the exact location determined by the exploratory ping. Thus, by nature of how the device operates, any human tissue in the vicinity would experience only minor contact with any EM waves.

In order to ensure that this is safe, TESLA will consult prior research, rather than conducting their own. Although not in the context of power transfer, the effect of EM waves on human tissue has been thoroughly investigated by the scientific community. In general, it has been found that certain frequencies, such as microwaves, have more harmful effects than other frequencies, such as radio waves, and that there is a certain amplitude threshold before which biological tissue would be affected. Thus, when deciding upon which frequencies and amplitudes to utilize, TESLA will only consider those proven to have minimal effect on biological tissue. While these theoretical implications should be sufficient for this study, it is impossible to entirely predict how a technology might behave in a different context. Thus, these safety issues could constitute a topic for further research, if it turns out that TR is indeed practical, and advantageous to other methods.

The only other major limitation of the project deals with the aforementioned aspect of product design. As TESLA prioritizes scientific results and contribution to the scientific community over commercialization, there will be no initial investigation of the end consumer. The purpose of TESLA’s research is ultimately to create a proof of concept prototype, which simply demonstrates that EM-TR can indeed be used to transmit power wirelessly. Thus, the device will be constructed and designed with functionality and energy efficiency in mind over practicality and affordability. It is already clear, from observations of other companies currently developing WPT technologies, that there is a significant interest in any form of WPT, which is sufficient to justify an attempt at this new method. In the event that TESLA succeeds in producing such a prototype, the most logical next step for future research would be to examine how to make the device as small and as affordable as possible by substituting smaller and cheaper electrical components.

## Final Remarks

Just as the development of Wi-Fi technology revolutionized the Internet and opened up countless unforeseen applications for the personal computer, wireless power technology will soon revolutionize the way we use electronic devices. By applying the concept of time reversal to WPT, TESLA hopes to advance the field of WPT, creating awareness of another possible method of WPT, and, most optimistically, eliminating some of the largest limitations that currently exist on the technology.

# Appendix A - Glossary

**Orientation:** The 3-dimesional angular rotation of a device relative to some reference point, typically the transmitting device.

**Induction:** A method of WPT that is derived from Faraday’s law. Given the range limitations of Faraday’s law, induction is a method that has an extremely limited range, rarely extending past 10-15cm at best. This method requires no additional components, calibration, or specifications to transmit power and is considered the cheapest and easiest method of WPT.

**Coupling:** The concept that the resonant frequency of two circuits are kept the same and that the effects of one circuit will impact the other circuit, such that they exhibit similar wave behavior when a voltage or current wave is introduced to either circuit.

**Faraday’s Law:** States that a changing magnetic field around a wire induces a current, and that a current flowing through a wire induces a magnetic field. When a magnetic field is induced by a current, the magnitude of the field is inversely proportional to the distance from the wire.

**Wave Chaos/Wave Chaotic System:** The concept that the waves being tracked are not distinct and cannot easily be mathematically identified or understood.

**DORT Method:** An iterative process of acoustic time-reversal where each iteration tries to identify the one distinct scatterer more distinctly. This was one of the first methods of having a much focused time-reversed signal.

**Time-Reversal:** The process of flipping a waveform such that f(x,t) becomes f(x,-t) and the time range flips from [t initial, t final] to [t final, t initial]. This process causes the time reversed signal to collapse back at the point f(x0, t initial).

**Reciprocity:** The property of being able to flip a waveform and have the waveform exhibit the opposite behavior during propagation compared to its non-flipped waveform. This allows location to be determined using time-reversal.

**Wireless Power Transmission:** Any means of creating a current in a circuit that does not have its own power supply.

**Nonlinear Element:** A circuitry component that can perform the transformation of creating wave frequencies that are multiples of an input wave signal.

**Rectenna:** An antenna that transforms the signals it receives into useable energy, and, importantly, produces strong harmonics when struck by an electromagnetic wave.

**Lossy**: Causing attenuation or dissipation of electrical energy

# Appendix B – Budget

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Item | Quantity | Cost per Unit | Total Value | Total Cost | Vendor |
| High Speed Coaxial Microwave Switches | 2 | $2,500 | $5,000 | $5,000 | Pasternack |
| Frequency multipliers | 5 | $50 | $250 | $250 | Mini-Circuits |
| Power Amplifier | 1 | $1,600 | $1,600 | $1,600 | Mini-Circuits |
| Circuitry Components | N/A | N/A | $500 | $500 | Radioshack |
| Computer Work Station | 1 | $1,000 | $1,000 | $1,000 | Tigerdirect |
| Camera | 1 | $75 | $75 | $75 | Tigerdirect |
| Numerical Simulation Software | 1 | $2,000 | $2,000 | $2,000 | UMD |
| Lab Workspace (in kind) | N/A | $50/hr | 5,000 | $0 | UMD |
| Stub Tuner (in kind) | 1 | $700 | $700 | $0 | UMD |
| US Patent | 1 | $10,000 | $10,000 | $10,000 | US Patent Office |
| Machine Shop | N/A | $2,000 | $2,000 | $2,000 | UMD |
|  |  |  | Total | $22,425 |  |

# Appendix C – Timeline for Milestones

Ongoing Projects

Continuation of Literature Review

Researching and Writing Grant Proposals

Intellectual Property Research

Preliminary Experiments –  **Due February 21st, 2014**

Rectenna Testing

Antenna Design

Computer Modeling

Loss Analysis Testing

Research Application (WPT Vehicle)

Design of Full Prototype (Circuit) –  **Due May 9th, 2014**

Design of System Structure –  **Due March 7th, 2014**

Optimization of Structure –  **Due April 25th, 2014**

Pricing of Parts –  **Due May 2nd, 2014**

Ordering of Parts –  **Due May 9th, 2014**

Creation of Full Prototype – **Due August 29th, 2014**

Assembly of Modules –  **Due June 6th, 2014**

Creation of Testing Procedure –  **Due June 6th, 2014**

Testing of Individual Modules –  **Due August 8th, 2014**

Assembly of Entire System –  **Due August 29th, 2014**

Debugging –  **Due October 3rd, 2014**

Basic Testing –  **Due September 5th, 2014**

Error Identification –  **Due September 12th, 2014**

Error Repair –  **Due October 3rd, 2014**

Testing and Revision of Prototype

Design of Testing Apparatus –  **Due October 3rd, 2014**

Testing of Prototype –  **Due November 7th, 2014**

Junior Colloquia – **November 19/20, 2014**

Analysis of Results –  **Due December 6th, 2014**

Refinement of Design –  **Due January 23th, 2015**

Second Round of Testing –  **Due February 20th, 2015**

Analysis of Results –  **Due March 20th, 2015**

Undergraduate Research Day – **April 25, 2015**

Refinement of Design –  **Due May 8th, 2015**

Third Round of Testing –  **Due June 12th, 2015**

Analysis of Results –  **Due July 17th, 2015**

Refinement of Design –  **Due Aug 28th, 2015**

Final Performance Analysis –  **Due December 4th, 2015**

Final Thesis Paper –  **Due March 4th, 2016**

Thesis Defense Presentation – **April 15, 2016**

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