WIRELESS BATTERY CHARGING SYSTEM USING RADIO FREQUENCY ENERGY HARVESTING

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It seems these days that everyone has a cellular phone. Whether yours is for business purposes or personal use, you need an efficient way of charging the battery in the phone. But, like most people, you probably don't like being tethered to the wall. Imagine a system where your cellular phone battery is always charged. No more worrying about forgetting to charge the battery. Sound Impossible?

It is the focus of this thesis to discuss the first step toward realizing this goal. A system will be presented using existing antenna and charge pump technology to charge a cellular phone battery without wires. In this first step, we will use a standard phone, and incorporate the charging technology into a commercially available base station. The base station will contain an antenna tuned to 915MHz and a charge pump. We will discuss the advantages and disadvantages of such a system, and hopefully pave the way for a system incorporated into the phone for charging without the use of a base station.

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PREFACE

A special thanks to Dr. Marlin Mickle of the Electrical and Computer Engineering department for his support and guidance throughout this project. Also, special thanks to the Provost for sponsoring the project.

1.0 INTRODUCTION AND MOTIVATION

Cellular telephone technology became commercially available in the 1980's. Since then, it has been like a snowball rolling downhill, ever increasing in the number of users and the speed at which the technology advances. When the cellular phone was first implemented, it was enormous in size by today's standards. This reason is two-fold; the battery had to be large, and the circuits themselves were large. The circuits of that time used in electronic devices were made from off the shelf integrated circuits (IC), meaning that usually every part of the circuit had its own package. These packages were also very large. These large circuit boards required large amounts of power, which meant bigger batteries. This reliance on power was a major contributor to the reason these phones were so big.

Through the years, technology has allowed the cellular phone to shrink not only the size of the ICs, but also the batteries. New combinations of materials have made possible the ability to produce batteries that not only are smaller and last longer, but also can be recharged easily. However, as technology has advanced and made our phones smaller and easier to use, we still have one of the original problems: we must plug the phone into the wall in order to recharge the battery. Most people accept this as something that will never change, so they might as well accept it and carry around either extra batteries with them or a charger. Either way, it's just something extra to weigh a person down. There has been research done in the area of shrinking the charger in order to make it easier to carry with the phone. One study in particular went on to find the lower limit of charger size [1]. But as small as the charger becomes, it still needs to be plugged in to a wall outlet. How can something be called “wireless” when the object in question is required to be plugged in, even though periodically?

Now, think about this; what if it didn’t have to be that way? Most people don’t realize that there is an abundance of energy all around us at all times. We are being bombarded with energy waves every second of the day. Radio and television towers, satellites orbiting earth, and even the cellular phone antennas are constantly transmitting energy. What if there was a way we could harvest the energy that is being transmitted and use it as a source of power? If it could be possible to gather the energy and store it, we could potentially use it to power other circuits. In the case of the cellular phone, this power could be used to recharge a battery that is constantly being depleted. The potential exists for cellular phones, and even more complicated devices - i.e. pocket organizers, person digital assistants (PDAs), and even notebook computers - to become completely wireless.

Of course, right now this is all theoretical. There are many complications to be dealt with. The first major obstacle is that it is not a trivial problem to capture energy from the air. We will use a concept called energy harvesting. Energy harvesting is the idea of gathering transmitted energy and either using it to power a circuit or storing it for later use. The concept needs an efficient antenna along with a circuit capable of converting alternating-current (AC) voltage to direct-current (DC) voltage. The efficiency of an antenna, as being discussed here, is related to the shape and impedance of the antenna and the impedance of the circuit. If the two impedances aren’t matched then there is reflection of the power back into the antenna meaning that the circuit was unable to receive all the available power. Matching of the impedances means that the impedance of the antenna is the complex conjugate of the impedance of the circuit. The energy harvesting circuit will be discussed in Chapter 3.

Another thing to think about is what would happen when you get away from major metropolitan areas. Since the energy we are trying to harness is being added to the atmosphere from devices that are present mostly in cities and are not as abundant in rural areas, there might not be enough energy for this technology to work. However, for the time being, we will focus on the problem of actually getting a circuit to work.

This thesis is considered to be one of the first steps towards what could become a standard circuit included in every cellular phone, and quite possibly every electronic device made. A way to charge the battery of an electric circuit without plugging it into the wall would change the way people use wireless systems. However, this technology needs to be proven first. It was decided to begin the project with a cellular phone because of the relative simplicity of the battery system. Also, after we prove that the technology will work in the manner suggested, cellular phones would most likely be the first devices to have such circuitry implemented on a wide scale. This advancement coupled with a better overall wireless service can be expected to lead to the mainstream use of cell phones as people's only phones. This thesis is an empirical study of whether or not this idea is feasible. This first step is to get an external wireless circuit to work with an existing phone by transmitting energy to the phone (battery) through they air.

2.0 PROBLEM STATEMENT

The goal of this thesis is to determine if is possible to capture enough power in a cellular phone in order to charge the battery. The requirements for the system to be presented are that it be incorporated into a base station and the operating frequency is set. The design of the board and choice of antenna for the stand are the focal point of the experiments that are to be performed. In order to prove the concept, power needs to be supplied to the energy harvesting circuit by an external transmitter. This transmitter will send a signal at the set frequency. Our test system will then receive this signal through the energy havesting circuit. This circuit is the fundamental design problem of this thesis. This circuit will convert the received signal into DC voltage to charge the battery. The RF transmitter, the analysis of the cellular phones to be used, and the modification of cellular phone stands to accommodate the circuitry to be designed are elements of the research covered in this section. A set of experiments will be conducted to demonstrate the feasibility of wirelessly charging a cellular phone battery.

2.1 THE TRANSMITTER

The most basic transmitter setup consists of a piece of equipment that generates a signal whose output is then fed into an amplifier that is finally output through a radiating antenna – the air interface. A condition must be met where the antenna operates optimally at the desired frequency output from the signal generator. In the current case, an antenna was connected through an amplifier to a radio-frequency (RF) source. The RF source is a circuit that outputs a signal at a user-specified frequency and voltage. The range of frequencies of the signal generator resides in the radio frequency band, 3 mega-hertz (MHz) to 3 giga-hertz (GHz). The output power of this device is limited. For this reason, an amplifier is required on the output. The transmitting antenna is called a patch antenna and is fabricated from copper plating that is soldered to a feed wire and has a ground plane. The frequency of 915MHz was chosen for this project because it is one at which our team has experience, and it falls in one of the Industrial-Scientific-Medical (ISM) RF bands made available by the Federal Communications Commission for low power, short distance experimentation. This frequency was chosen mostly for simplicity in using the available equipment. It is not used for mass communication or anything else on a major scale, and therefore is not going to be interfered with, or interfere with other devices at low power levels. This also means that transmitters for short distances are readily available. In fact, 915MHz is a very common frequency used in RF research. This makes a transmitter system easy to construct and manage. The source is nothing more than a signal generator, capable of outputting a low-noise AC signal at 915MHz. This setup results in the antenna beaming approximately 6mW of power per square meter. This was the limit of the gain of the amplifier.

2.2 THE PHONES

The design aspect of this project is focused on the receiving side. For this stage of research, of which the goal is to prove that the wireless battery charger idea is feasible, it was decided to incorporate the energy harvesting circuitry and antenna in some sort of base station or charging stand. It is necessary to hide the components for demonstration purposes. This being the case, two phones were chosen that have accessories currently available to use as our charging stands. The Nokia 3570 was the first phone that was received for the research. This phone comes standard with a battery and an AC/DC travel charger. The battery included with the phone has a voltage range from 3.2V - when the phone shuts off - to 3.9V when fully charged. This battery only takes about 2 hours to charge when plugged into the wall through the travel charger supplied with the phone. This charger has an unloaded, unregulated direct current (DC) output voltage of 9.2V. When connected to the phone, the charging voltage goes to the battery voltage, approximately 3.6V, and then slowly increases until it saturates at 3.9V. This charger regulates the current to around 350mA.

The other phone that was chosen is the Motorola V60i. This phone has many of the same features as the Nokia above, and it also comes standard with its own battery and travel charger. The battery for this phone is a 3.6V battery like the Nokia battery. The travel charger shown is quite different from its Nokia counterpart. First of all, there are 3 pins going to the phone, not just the 2 needed for power and ground. Two of these pins are at a ground potential, and the other one is 6.09V higher than the other two. This is very close to the regulated voltage of 5.9V seen by the phone during charging. It runs at 400mA, a little higher than the Nokia charger.

2.3 THE STANDS

Before starting the design of the circuitry for charging the phones, it is beneficial to know the space available for the board. The Nokia DCV-15 desktop stand and Motorola SYN8610 hands free speakerphone have commercially available accessories for holding the phones. The Nokia stand, Figure 2.1, is used additionally for synchronization purposes between the phone and a personal computer. It does incorporate a circuit board that connects to the phone for charging. This board is simply a bridge from the phone to the PC, using a switch. The power supply plugs into the back of the stand underneath, and its jack is also located on the printed circuit board. Since there is a lot of wasted space inside that can be used for the energy harvesting board and

Figure 2.1: Nokia DCV-15 Desktop Stand

antenna, all that is needed to do is to tap into this existing board to supply the power for the phone. This facilitates replacing the existing board with a newly designed printed circuit board. This would be difficult because the jack the phone plugs into, on the existing board, is difficult to replace. It appears to be a proprietary device available only from Nokia. Thankfully, there is enough room in the stand for both boards to exist, along with the antenna.

For the Motorola phone, there is a similar product available, but it is not really a stand. The Motorola SYN8610, Figure 2.8, is a hands-free speakerphone that accommodates the phone. This device also allows the user to charge the phone while the phone is in the stand. It is similar to the Nokia stand in that there is a printed circuit board that connects the power from the wall to the phone through the stand itself. This allows for the same option as the Nokia stand to just tap into the existing board to power the phone from our printed circuit board. However, because there is not as much space in this stand as in the Nokia stand, to use this accessory, it was necessary to hollow out the inside to make room for the energy harvesting circuitry. This meant removing the speakerphone functionality. Whereas the Nokia phone's desktop stand could still be used to connect to the PC, this item will no longer perform its original function.

Figure 2.2: Motorola SYN8610 Hands-Free Speakerphone

3.0 BACKGROUND

This project is based on a very simple concept, capture RF energy using an antenna, input it into a charge-pump and use this energy to power some other circuit. As a precursor to this thesis, there have been many projects involving charge pumps. These projects range from tuning the charge pump to using results from existing charge pumps to drive other circuits. For the tuning projects, usually the testing is done using a light emitting diode (LED). RF energy is transmitted to the circuit and the charge pump stores the energy in a large capacitor. When the amount of charge is large enough, the LED uses the stored energy to light for a moment. This is called a charge-and-fire system. In other research, charge pumps were tested from earlier projects that were used to power other circuits. This type of technology is very useful in Radio Frequency Identification (RFID) applications. The way RFID systems work is that when a chip passes through a scanner device, power is sent to the chip from the scanner. In older systems, the frequency or amplitude of this signal was modulated by the chip and sent back. This technique is called backscatter. But, in more recent systems, the chips are getting more complicated and require much more power to run. The RFID system is unsuitable for batteries mostly because they have to be small, but also because the batteries will eventually die and require changing. But, with a good antenna, a charge pump should be able to handle the powering of these circuits and never will need to be serviced. Because the circuits are small, the power required is minimal.

3.1 THE CHARGE PUMP

At this point, it is necessary to explain what exactly a charge pump is, and how it works. A charge pump is a circuit that when given an input in AC is able to output a DC voltage typically larger than a simple rectifier would generate. It can be thought of as a AC to DC converter that both rectifies the AC signal and elevates the DC level. It is the foundation of power converters such as the ones that are used for many electronic devices today. These circuits typically are much more complex than the charge pumps used in this thesis. Power converter circuits have a lot of protective circuitry along with circuitry to reduce noise. In fact, it is a safety regulation that any power-conversion circuits use a transformer to isolate the input from the output. This prevents overload of the circuit and user injury by isolating the components from any spikes on the input line. For this thesis, however, such a low power level is being used that a circuit this complex would require more power than is available, and it would therefore be very inefficient and possibly not function. In that case, it is necessary to use a simple design.

The simplest design that can be used is a peak detector or half wave peak rectifier. This circuit requires only a capacitor and a diode to function. The schematic is shown in Figure 3.1. The explanation of how this circuit works is quite simple. The AC wave has two halves, one positive and one negative. On the positive half, the diode turns on and current flows, charging the capacitor. On the negative half of the wave, the diode is off such that no current is flowing in either direction. Now, the capacitor has voltage built up which is equal to the peak of the AC signal, hence the name. Without the load on the circuit, the voltage would hold indefinitely on the capacitor and look like a DC signal, assuming ideal components. With the load, however, the output voltage decreases during the negative cycle of the AC input, shown in Figure 3.2. This

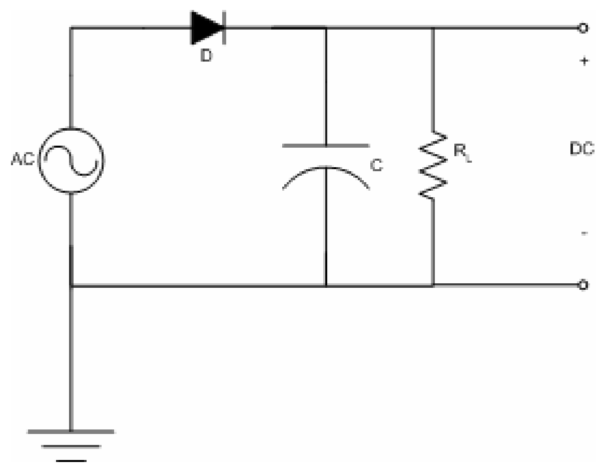

Figure 3.1: Peak Detector

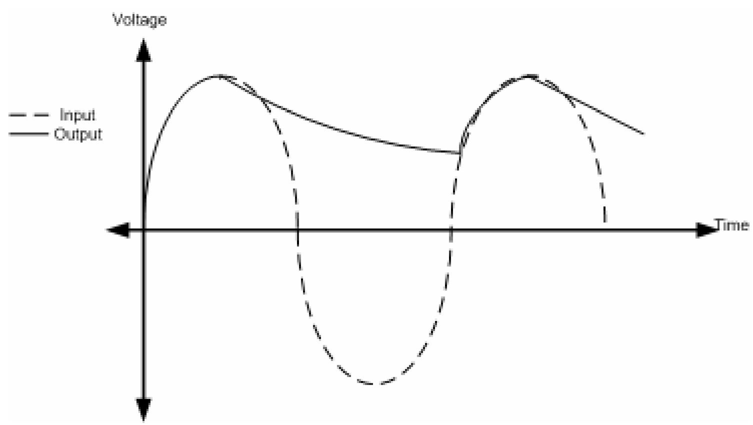

Figure 3.2: Half-wave Peak Rectifier Output Waveform

figure shows the voltage decreases exponentially. This is due to the *RC* time constant. The voltage decreases in relation to the inverse of the resistance of the load, *R*, multiplied by the capacitance *C*. This circuit produces a lot of ripple, or noise, on the output DC of the signal. With more circuitry, that ripple can be reduced.

The next topology presented in Figure 3.3 is a full-wave rectifier. Whereas the previous circuit only captures the positive cycle of the signal, here both halves of the input are captured in the capacitor. From this figure, we see that in the positive half of the cycle, *D1* is on, *D2* is off and charge is stored on the capacitor. But, during the negative half, the diodes are reversed, *D2* is on and *D1* is off. The capacitor doesn't discharge nearly as much as in the previous circuit, so the output has much less noise, as shown in Figure 3.4. It produces a cleaner DC signal than the half-wave rectifier, but the circuit itself is much more complicated with the introduction of a transformer. This essentially rules this topology out for this research because of the space needed to implement it.

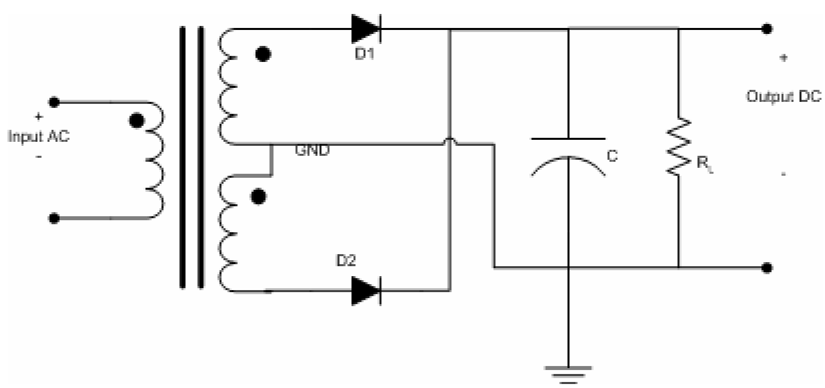

Figure 3.3: Full-wave Rectifier

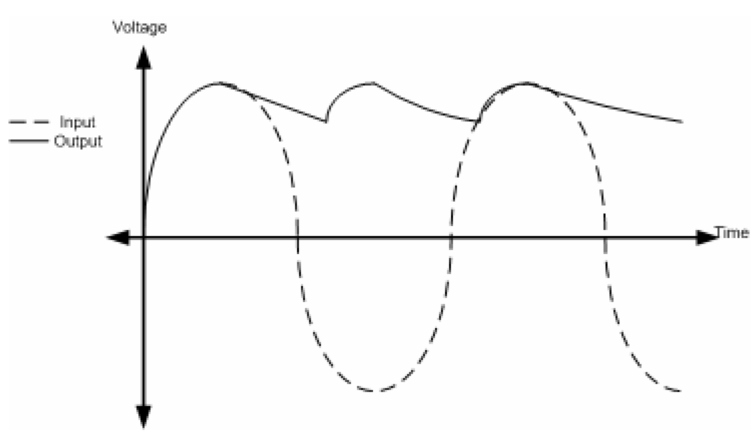

Figure 3.4: Full-wave Rectifier Output Waveform

There are other topologies for charge pumps but they will not be covered here. The others are more complex and all involve transformers, like the full-wave rectifier, and therefore take up more room than there is real estate for in this project. Instead, the circuit that was chosen to be used will now be presented. The charge pump circuit is made of stages of voltage doublers. This circuit is called a voltage doubler because in theory, the voltage that is received on the output is twice that at the input. The schematic in Figure 3.5 represents one stage of the circuit. The RF wave is rectified by *D2* and *C2* in the positive half of the cycle, and then by *D1* and *C1* in the negative cycle. But, during the positive half-cycle, the voltage stored on *C1* from the negative half-cycle is transferred to *C2*. Thus, the voltage on *C2* is roughly two times the peak voltage of the RF source minus the turn-on voltage of the diode, hence the name voltage doubler.

The most interesting feature of this circuit is that by connecting these stages in series, we can essentially stack them, like stacking batteries to get more voltage at the output. One might ask, after the first stage, how can this circuit get more voltage with more stages because the output of the stage is DC? Well, the answer is that the output is not exactly DC. It is essentially

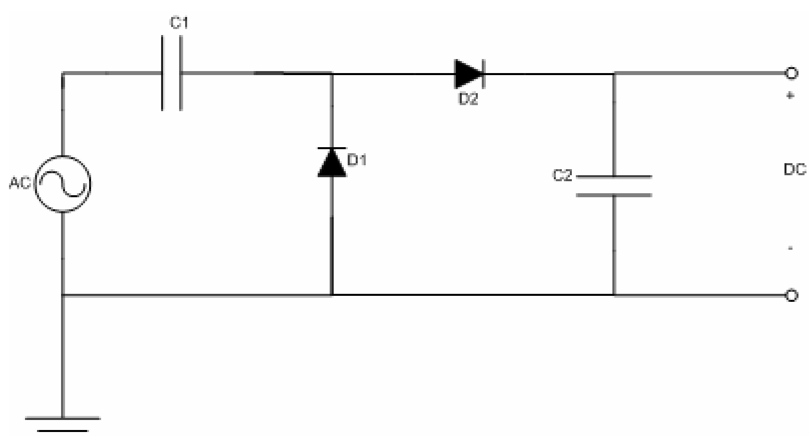

Figure 3.5: Voltage Double Schematic

an AC signal with a DC offset. This is equivalent to saying the DC signal contains noise. This can be seen in Figure 3.6. This is where the other stages come in. If a second stage is added on top of the first, the only wave that the second stage sees is the noise of the first stage. This noise is then doubled and added to the DC of the first stage. Therefore, the more stages that are added, theoretically, more voltage will come from the system irregardless of the input. Each

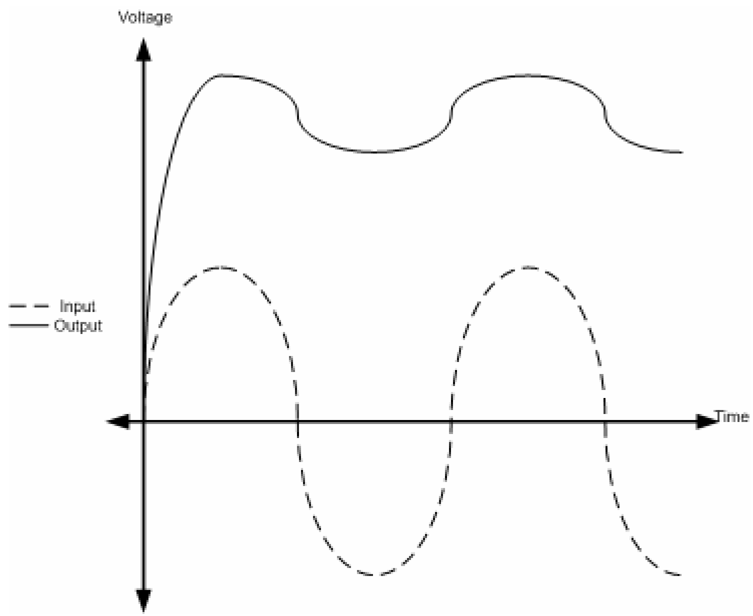

Figure 3.6: Voltage Doubler Waveform

independent stage, with its dedicated voltage doubler circuit, can be seen as a battery with open circuit output voltage V_O and internal resistance R_O. When n of these circuits are put in series and connected to a load of R_L, the output voltage will be given by Equation (1).

$$V_{out} = \frac{nV_0}{nR_0 + R_L} R_L = V_0 \frac{1}{\frac{R_0}{R_L} + \frac{1}{n}} \tag{1}$$

From Equation (1), we know that the output voltage V_{out} is determined by the addition of R_0/R_L and $1/n$ if V_0 is fixed [2]. With V_O, R_O, and R_L all constants, we can see from the equation that as n increases, the increase in output voltage will be less each time. At some point, the voltage gained will be negligible.

There was a recent project using a charge pump design that involved stages of voltage doublers. This project required a minimal amount of optimization to the parameters for the charge pump in order to get a cellular phone battery to charge. This charge pump printed circuit board (PCB) is shown in Figure 3.7. On this board, you can see that the antenna is input to the system through a Subminiature version A (SMA) connector. An SMA to Bayonet Neill Concelman (BNC) connector is also included. An antenna was purchased to use instead of being specifically fabricated for this particular project. Once the signal is brought into the system, it passes through seven stages of charge pump. The capacitors for this test are through-hole making it easier to modify for optimization. The diodes are surface-mount Agilent HSMS-2820 Schottky diodes, but the diodes are fixed and are not the subject of optimization or tuning. This system uses an output capacitor for the DC leveling of the output voltage and to hold a charge.

The testing setup for this project is shown in Figure 3.8. As you can see, the output of the charge pump circuit is input directly into the battery. This is one of two ways to charge the battery. The other is to power the phone through its DC input circuitry, and let it charge the battery. But, for the early project, all that was specified was to get the circuit to charge a battery directly. The power the circuit was able to get from the system was enough to charge the battery at a rate of 2mV per second. This was an average result, calculated by letting the battery charge for a minute and checking the voltages both before and after. This result was promising enough to try charging a phone directly although obvious that a lot of work was going to be needed to get better results.

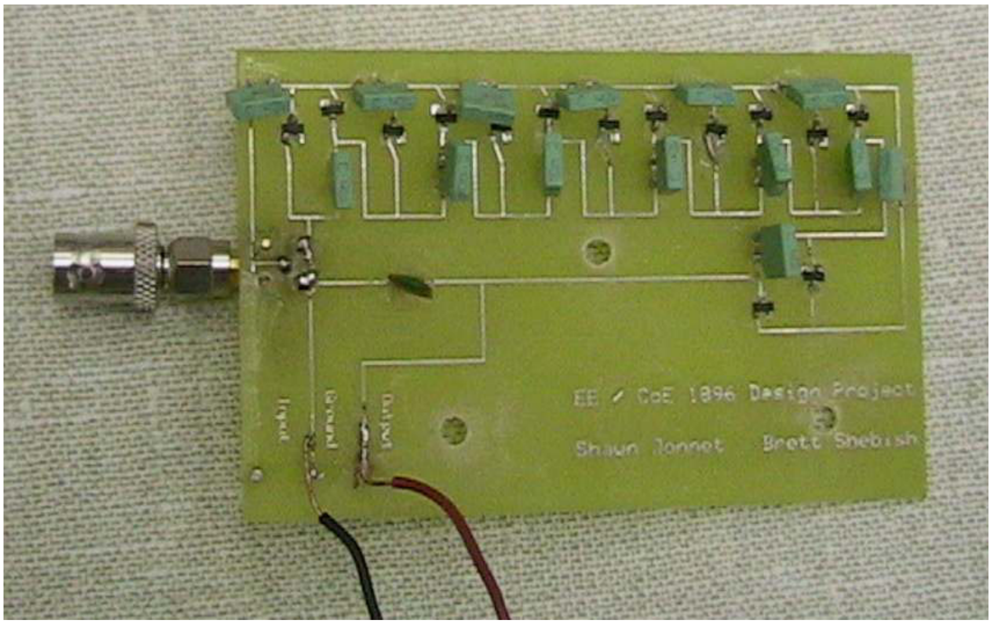

Figure 3.7: Previous Project Board

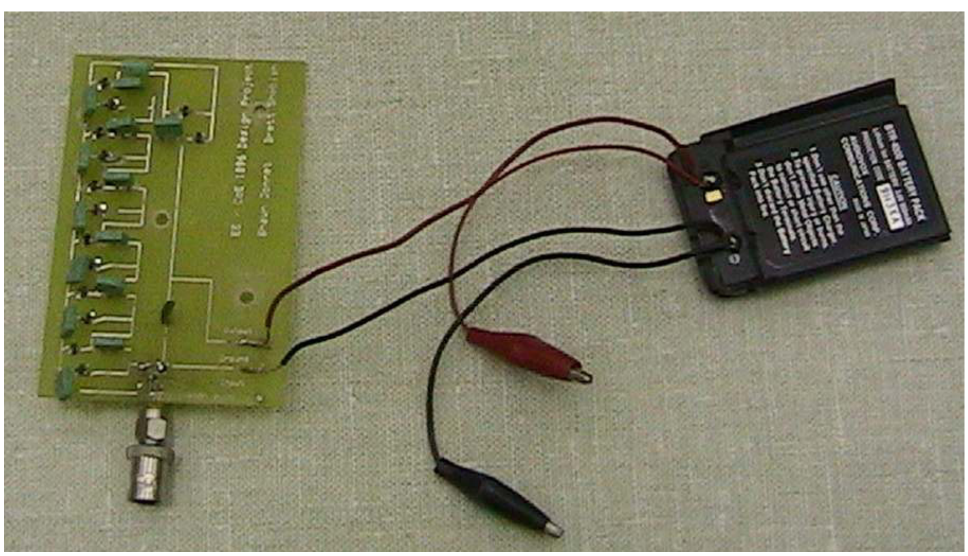

Figure 3.8: Test Setup Using Previous Board

3.2 THE ANTENNA

The most straightforward option for the receiving antenna is to use an existing antenna that can be obtained commercially. This idea was explored along with fabricating a new antenna. As can be seen from Figures 3.1 and 3.2, there is a coaxial connector to connect to the antenna. For the initial research, a quarter-wave whip antenna was used for all the testing purposes. This antenna is similar to that used on car radios. It is called a quarter-wave antenna because it is designed so that its length is approximately one quarter of the wavelength of the signal. This means that for a 915MHz signal, with a wavelength equal 32cm, a quarter-wave antenna would have an 8cm length. The main dilemma in using this type of an antenna is that it requires a rather large ground plane in order to work properly. This is fine for car radios that can be grounded to the frame of the car. But, for this project, the ground plane needed to receive enough of a signal to power the charging circuit is larger than the form factors of the charging stands chosen to house the circuits. A picture of the quarter-wave whip antenna is shown in Figure 3.9.

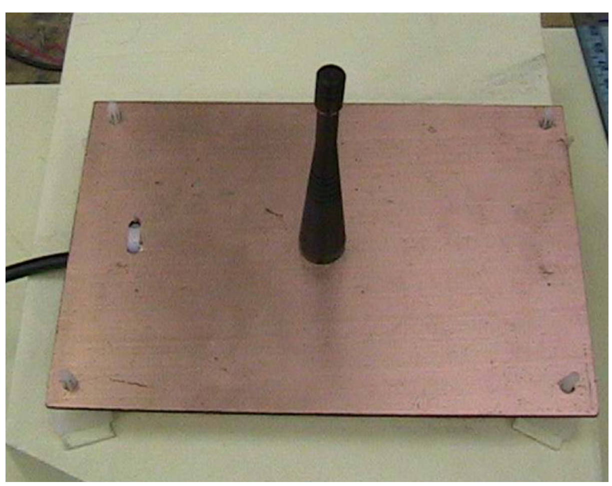

Figure 3.9: Quarter-wave Whip Antenna

The large copper plate is the ground plane. The antenna is attached to the copper, with an SMA connector on the under side of the ground plane. This type of connector uses a simple screw mechanism allowing for easy connectivity with other circuits and test equipment. The cord is connected on the other side to the BNC connector of the board. As you can see, this ground plane is rather large, too large to be used inside the stand for a cellular phone. It covers almost 50% more area than the stands that were selected for this research. With this in mind, a different type of antenna needs to be researched and tested. Other types of antennas to consider are patches, microstrips, dipoles, and monopoles. The patch antenna has two major problems when being used with a research project like this. The first is that it also needs to be relatively large, on the order of the ground plane for the quarter-wave whip antenna. The second reason is that it is highly directional, meaning that it only radiates, and accepts radiation, in one direction, i.e., it does not have a good coverage area. These reasons rule out this option. A microstrip antenna can be any type of antenna discussed previously, but what makes it unique is that it is "painted" on to a surface so that it is in the same plane as the printed circuit board. This type of antenna is used mostly on small surfaces such as silicon die to be used by the circuit on the same die. By "painted" on, what is meant is that on a silicon die it is etched onto the surface, or on a printed circuit board, it is part of a conductive layer. This means that it can be patch, a dipole, or a quarter-wave whip, as long as all the metal is in the same plane. The main problems with this antenna are its gain and its directionality. These types of antennas are appropriate to be used in RFID, but for this project they would be a hindrance. It is possibly an option to explore in future research.

The last two types of antennas, dipole and monopole, are similar in characteristics and structure. The difference is that a monopole has one connection point to the circuit, while a dipole has two connection points. For this project, the monopole antenna was the antenna of choice because of its relative ease of use. A monopole antenna basically consists of a piece of copper wire with one end connected to the circuit, and the other left open. Probably the best reason for using an antenna such as this is that it fits nicely into the chosen stands. The wire is attached to the circuit and then wound once around the inside of the case; making sure that it does not touch any other part of the circuit or itself. Another good quality of this type of antenna is that its operating frequency range is fairly large. For this research, this is helpful because precise tuning of the antenna is not required. The wire that was wound around the stand functioned as an antenna and was power effecient at 915MHz, which is the frequency of choice.

A dipole antenna, while also easy to design, would be more difficult to be made to fit the stands that were chosen for testing. The dipole requires two connections with the wires running in separate directions from each other. The effective length of each of these separate wires is half that of the monopole, since these two pieces cannot touch and there is little room for overlap. With its simple design and acceptable operating characteristics, the monopole was thought to be the best antenna for this research.

4.0 SYSTEM SPECIFICATIONS

This research project is primarily empirical. There are many variables in the system that can change the voltage that is developed. The stage capacitors need to be optimized. The number of stages needs to be determined that, combined with the capacitor values for each stage, will result in a sufficiently high voltage level to turn on the phone and charge the phone's battery. Also, a capacitor can be used across the output as a filter to provide a flat DC signal and store charge. The value of that capacitance also needs to be determined. There really are no fixed parameters for any of these values. The only specified value for any element in this research is the frequency that is being transmitted to the station. This frequency is to be 915MHz.

As discussed in the previous chapter, there have been projects completed to lay the foundation for this research. One of these projects involved the charging of a cellular phone battery directly from a charge pump. The results of this experiment were sufficient to provide a starting point. The previous project used the same charge pump we have chosen, i.e., stages of voltage doublers.

4.1 NUMBER OF STAGES

The number of stages, as shown in Figure 4.1, in the system has the greatest effect on the output voltage. The capacitance, both in the stages and at the end of the circuit, affects the speed of the transient response and the stability of the output signal. The number of stages is essentially directly proportional to the amount of voltage obtained at the output of the system. Generally, the voltage of the output increases as the number of stages increases. This is due to how the voltage doubler works as explained in the previous chapter.

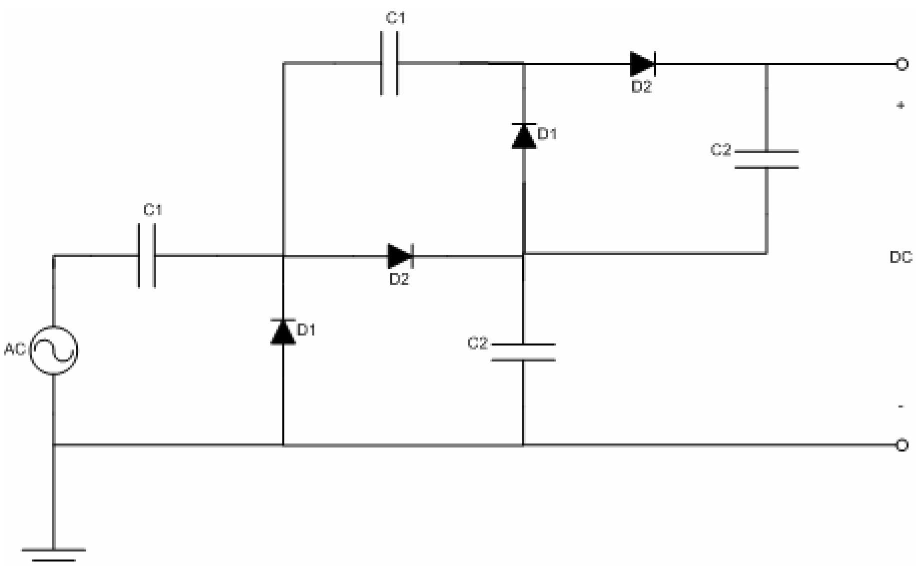

Figure 4.1: 2 Stages of Voltage Doubler

4.2 STAGE CAPACITANCE

The stage capacitance, Figure 4.2, is difficult to work with. Sometimes, minimal changing of the capacitance will have a drastic effect on the output voltage. But, other times the change is negligible. The capacitance parameter is definitely very sensitive. To change the capacitance of each stage in the system required resoldering of all the capacitors. This is especially difficult and time consuming when working with surface mount components. The surface mount capacitors were used to make the board and overall system as small as possible. Empirical testing can be a bit tedious. There are a couple of different values that can be used for the capacitance. The first, and most obvious, is to keep all the values in all the stages the same. A second way is to gradually decrease the value of the stage capacitors as the number of stages increases. Each stage uses two capacitors, and those are kept the same, but the change is made from one stage to

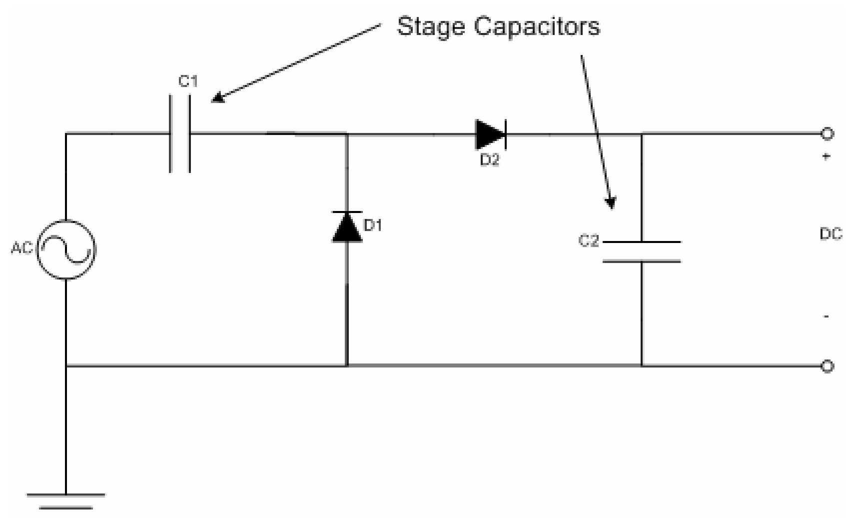

Figure 4.2: Stage Capacitor of Voltage Doubler

the next. If the first stage uses 100pF capacitors, then the next stage would use 50pF. To halve the previous stage capacitor seemed to be reasonable mainly for ease of testing, and availability of parts. This comes from the equation for charge in a capacitor, Equation (2).

$$Q = C \bullet v(t) \tag{2}$$

In Equation (2), the voltage in a capacitor is inversely proportional to the capacitance with relation to the charge. This being the case, if the voltage in a system increases, it would stand to reason that a lower capacitance value would be needed to keep the same charge. These two different methods of using the stage capacitance were simulated and tested, and the final results will be presented in Chapters 5 and 6.

4.3 OUTPUT CAPACITANCE

The variable that has the least affect on the overall system is the output capacitance as shown in Figure 4.3. Generally, the value of this capacitor only affects the speed of the transient response. The bigger the value for the output capacitance, the slower the voltage rise time. This does not mean, however, that the smallest capacitor will work the best, or that no capacitor should be used. Without a capacitor there, the output is not a good DC signal, but more of an offset AC signal, meaning that it will be DC with ripple.

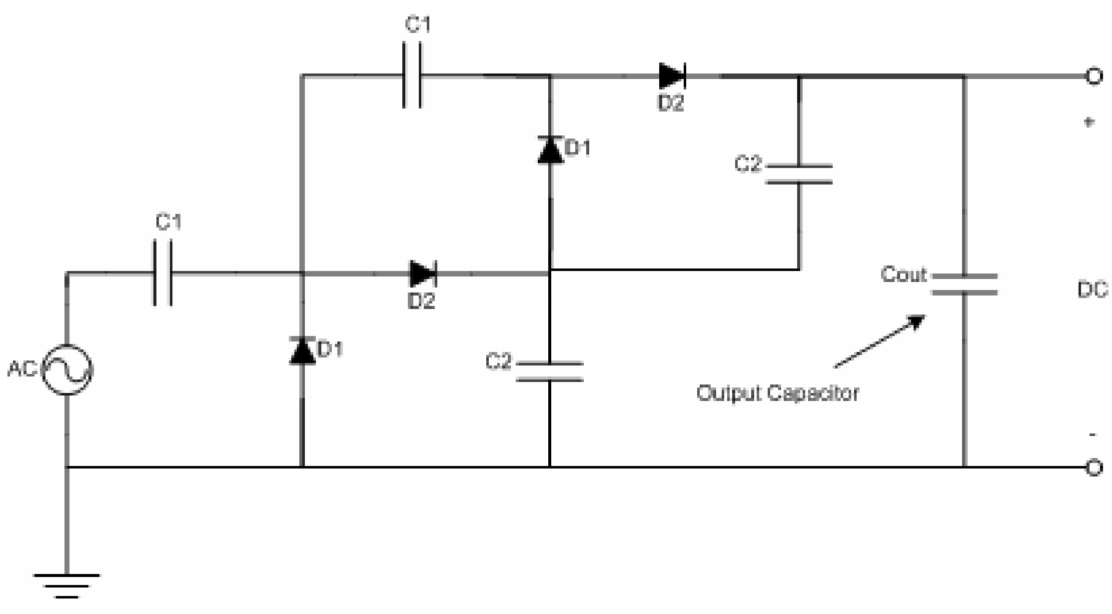

Figure 4.3: Voltage Doubler with Output Capacitor

5.0 SIMULATION

Using the previous project results as a starting point, the actual prototyping for the charging circuit was begun. One of the specifications of this research is to make the circuit fit inside a base station for a phone. In this case, the printed circuit boards (PCB) need to be made small to fit the available area. As presented in Chapter 3, the previous research used discrete, through-hole components in the PCB. But, in order to make the PCB small, surface mount components were used. Using surface mount components allows us to make the boards sufficiently small. However there are drawbacks to using components this small, especially when the testing is largely trial and error. Due to the small size of the surface mount components, the components are rather difficult to handle and solder in the circuit. Also, the pads to which the components are attached are small, and they do not have enough solder to allow them to be removed and replaced more than 3 or 4 times. Plus, when the components are constantly being unsoldered and resoldered, the conductive solder covering on the board loses its solder, and it becomes increasingly difficult to solder new components to the PCB. Carrying out empirical testing like this therefore calls for very good simulation software. The piece of software most people are familiar with when simulating electronic circuits is SPICE or some variation. SPICE stands for Simulation Program for Integrated Circuit Emphasis. “SPICE is a powerful general purpose analog circuit simulator that is used to verify circuit designs and to predict the circuit behavior. This is of particular importance for integrated circuits. It was for this reason that SPICE was originally developed at the Electronics Research Laboratory of the University of California, Berkeley (1975) [2]." This software, however, is too limited for this project. It is difficult to simulate complex circuits at very high frequencies, such as 915MHz, which is the desired frequency for this research. It can be done, but only for very small and less-intensive circuits, and it still takes a very long time – on the order of hours - to compute the response. However for the energy harvesting circuit, any SPICE program that was used crashed before it could complete its calculations. This means that some other program was needed for simulating the circuit. The program chosen was one that has been around a while and has an established reputation for simulating circuits and antennas at high to very high frequencies. This program is marketed by Ansoft. The first iterations were known as Serenade, but the newest versions of the software are called Ansoft Designer. A screen shot is shown in Figure 5.1.

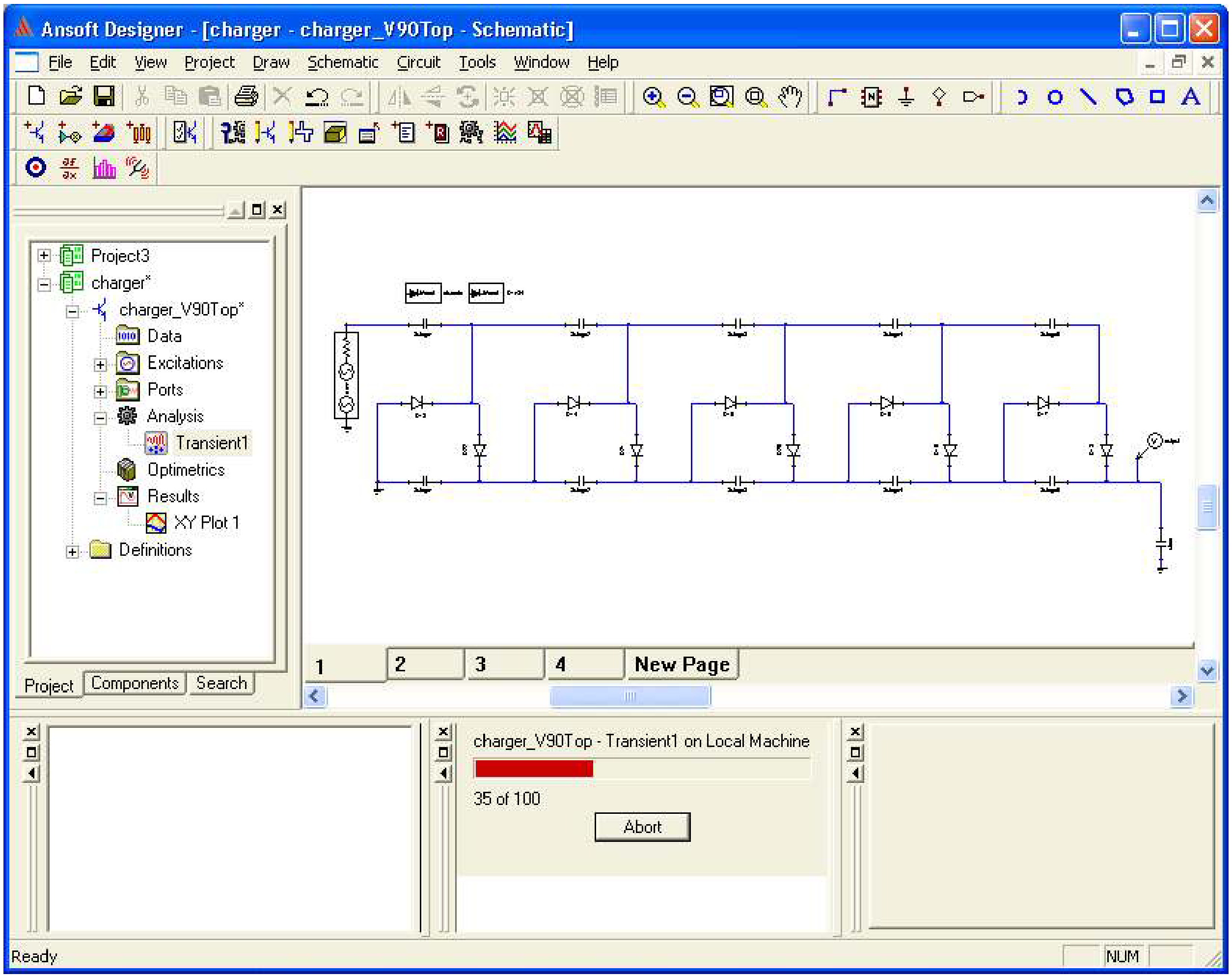

Figure 5.1: Ansoft Designer

5.1 TUNING AND OPTIMIZATION

Ansoft Designer is used much like any other circuit modeling and simulating program. The components are placed and wired together into a coherent circuit, given specified values, and then simulations are run over and over while changing the variables in the circuit. This is the standard way to simulate circuits in most programs, including those that use SPICE. However, this software has a convenient feature that most SPICE programs do not have. This feature is the ability to optimize, or tune, certain variables during simulation. This tuning function allows you to specify a range of values for all variables in the circuit, including all component values, and tests them all at certain increments specified by the user. This comes in handy for a circuit like the one under consideration. As discussed in the previous chapter, we have two ways to manage the stage capacitance. The first is to keep all stages the same value. This is the simplest. The other way is to vary the stage capacitance between stages based on the charge in the circuit. This software gives us an easy mechanism to simulate both of these ways in the same simulation and compare the results.

The only variable that can not be optimized easily with this software is the number of stages. This means that simulations need to be performed for every change in the number of stages. The question is; where is the limit? Obviously we are limited by space. This makes it impossible to go too high with the number of stages. As presented in the previous chapter, the previous project was successful in charging a cell phone battery with roughly the same properties as the ones used for this project with 7 stages of voltage doublers. This provides a good starting point. This number is used as a center value. Therefore the number of stages was ranged from 4 to 9 stages.

The first thing to be done was to lay out all the components in an organized fashion so that the circuit can be easily manipulated and anyone else looking at the schematic is able to understand what is being shown. In this case, it was chosen not to display the circuit as in previous figures, but in a stackable, left-to-right design. The first schematic shown in Figure 5.2 is a seven stage design with all the stage capacitors being the same value. Starting on the left

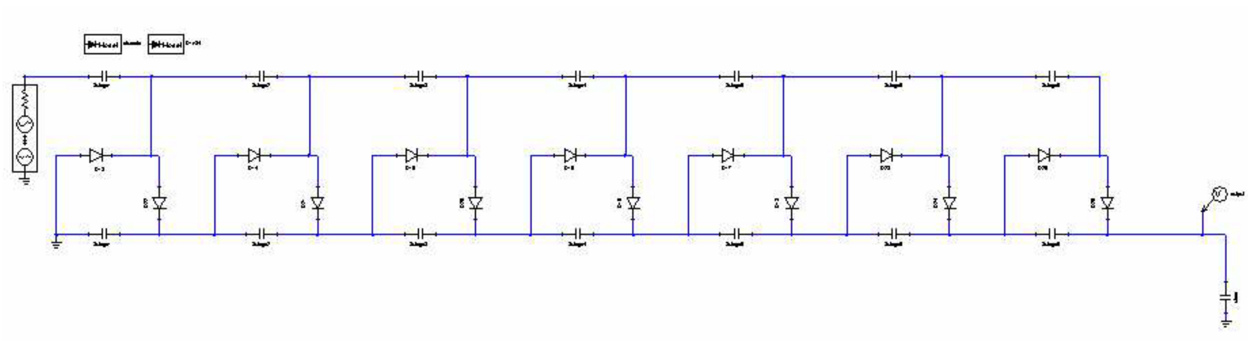

Figure 5.2: 7-Stage Voltage Doubler in Ansoft Designer

side, there is a signal source for the circuit followed by the first stage of the circuit. Each stage is subsequently stacked onto the previous stage, with the connections the same as in Figure 4.1. Instead of stacking from bottom to top, as is usually done, stacking was done from left to right, for simplicity. This method is the easiest to show, and for others who may be interested in the circuit, this design offers the easiest accessibility. It is also obvious where one stage ends and the next begins. This is invaluable when having to adjust the number of stages frequently in order to simulate all possibilities. With the copy and paste capability of the program, all that is needed to add a stage is to first remove the output wire, move the output capacitor to the right to make space, then copy and paste the last stage next to itself, and finally rewire the output to the capacitor. It is even easier to remove stages by selecting the entire stage, wires and all, and deleting the components.

At the right of the circuit, the output capacitor is connected to the circuit and to ground. The object that is shown before the output capacitor is a voltage probe. This is a program specific device that acts as a voltage meter, and it is necessary in the circuit to be able to see the voltage on that connection after the simulation has been completed. This program uses what it calls "reports" to show the results of the simulation. It is not necessary for the reports that the probes available in the program be used in the schematic because all the connection points of the circuit can be displayed. The problem with doing it this way is that the labels for the connection points come from the netlist[1] that is created when the circuit is simulated. These labels are very ambiguous in that it is not easy to recognize exactly which point of the circuit that is needed to display. Therefore, the probe that is added to the schematic is given a common name that can be found easily when displaying reports.

5.1.1 Diode Modeling

The two blocks that are shown in the upper left side of the schematic in Figure 5.2 are model parameters for two different diodes. The different diode models were the Agilent HSMS-2820 Schottky diode and the 1N34 Germanium diode. The Agilent Schottky diodes were the diodes used in the previous project that was able to get the cellular phone battery to charge. The HSMS-282x series comes in many flavors contained within either a three or four pin package. They are described by Agilent as being good components for RF mixer/detector circuits [2]. The

[1] The netlist is a file that contains not only the names of wires and components, but also all of the different parameters associated with individual components. These values are the device parameters that are declared in models and are related to materials and manufacturers specifications. These are the same files used in SPICE programs.

difference in the last digit of the model name describes the configuration that the diode(s) come in within the package. The HSMS-2820 that has been modeled for the energy harvesting circuit comes in a one-diode configuration as shown in Figure 5.3. The package has three pins, two on one side and one on the other. The third pin in this configuration is unused. For other configurations, such as the HSMS-2822, there are two diodes connected in series, Figure 5.4. This and all other configurations use the unused pin from the HSMS-2820. The modeling

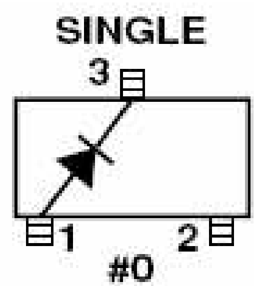

Figure 5.3: Agilent HSMS-2820

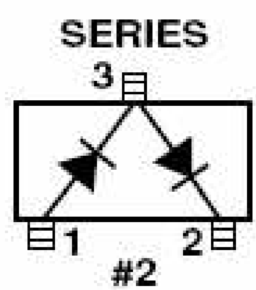

Figure 5.4: Agilent HSMS-2822

parameters for these diodes are given by Agilent in their data sheets. These parameters are used for SPICE simulations, but Ansoft Designer is able to take these parameters to be used for its own modeling purposes because it does a similar type of simulation using netlists. The SPICE parameters are shown in Table 1. The modeling is done by transforming the diode into an equivalent circuit using passive components. These equivalent components are described by the parameters in Table 1. The equivalent circuit for a diode is shown in Figure 5.5.

Table 1: HSMS-282x SPICE Parameters

Parameter	Units	Value
B_V	V	15
C_{J0}	pF	0.7
E_G	eV	0.69
I_{BV}	A	1E-4
I_S	A	2.2E-8
N	*no units*	1.08
R_S	Ω	6.0
P_B	V	0.65
P_T	*no units*	2
M	*no units*	0.5

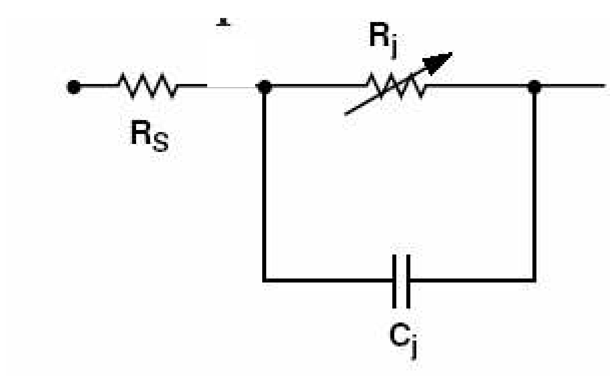

Figure 5.5: Diode Equivalent Circuit

In this equivalent circuit, R_S is the series resistance and C_J is the junction capacitance. Both are given in Table 1. These two factors have the most effect on the diode giving it a unique turn-on voltage and rise time. The lower the series resistance, the lower the voltage needed to turn on the diode, and the lower the junction capacitance the faster the voltage will rise. A large C_J and R_S will reduce the output voltage, especially with high frequencies, such as 915MHz. The resistance R_J is the junction resistance and is given by a formula based on other parameters from Table 1. This formula also comes from the data sheet for the diodes and is given in Equation (3).

$$R_J = \frac{8.33\times10^{-5} \bullet N \bullet T}{I_b + I_S} \tag{3}$$

In this equation, N and I_S are given to us in the SPICE parameters table above. N is the ideality factor. I_S is the saturation current and is given in the parameters. The other two parameters in Equation (3) are applied externally. T in this equation is the temperature given in degrees Kelvin. This is supplied by the program doing the simulations. I_b is the bias current on the circuit if there is one. This also is supplied by the simulating program. With this information, the program can make an accurate simulation of the circuit using the model supplied to it.

The other diode model that was used for simulation was the 1N34 series of germanium diodes. This is an older model component that has been used in many RF applications because of certain features, which include low turn-on voltage and fast rise time. The problem with it being an older device is that there is very little information available. Only one SPICE model could be found for this diode, and when used in Ansoft Designer, the circuit does not work at all. As it turns out, this diode will not work for this particular energy harvesting application because the form factor is only available in a through-hole design. This would take up much more space than is available for the circuit board. Thus, this diode was abandoned.

5.1.2 Agilent Diode Simulation Results

Focusing on the Agilent HSMS-2820 Schottky diode, simulations were begun starting with four stages of voltage doublers that all had the same stage capacitance. The simulations were run from 4 stages to 9 stages. In the previous research, the capacitance for the stages was 1nF. This is where the simulations were started. The input is a power source, which is setup to model the RF source used in testing. The only value of output capacitance used for these results is 15nF. According to the simulations, the rise time for the circuit is under 2 milli-seconds. A sample of the simulation result can be seen in Figure 5.6. Simulations were performed with other values of the output capacitance, but the rise time does not change enough to cause any drastic changes to the output. The value of 15nF was the first one tested, and because all other values performed similarly, this value was retained. The results of the simulations are presented in Table 2.

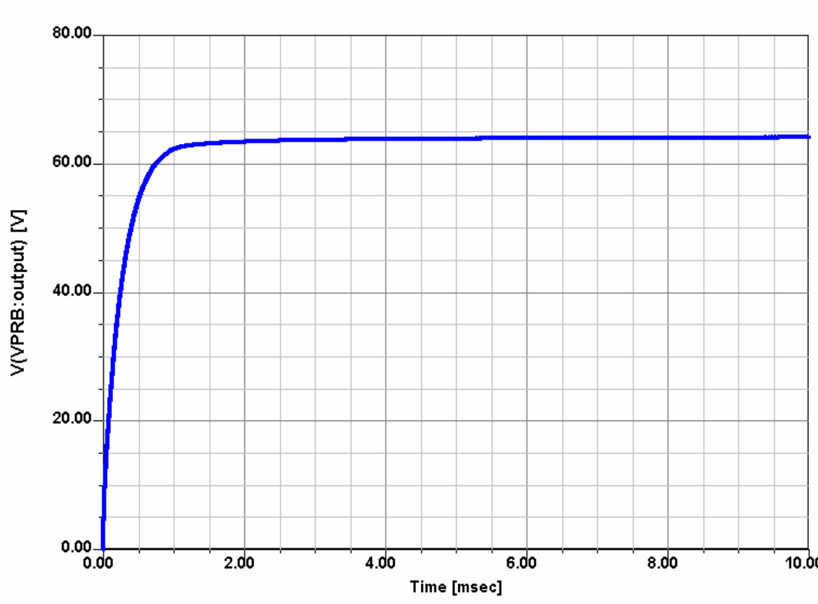

Figure 5.6: Simulation Result for 6-Stage Voltage Doubler

Table 2: Simulation Results

Stage Caps (nF)	**# Stages**	***DC Voltage (V)***
0.47	4	*42*
1.0	4	*42.5*
2.2	4	*42.5*
4.7	4	*42*
10	4	*42.5*
47	4	*42*
0.47	5	*52.5*
1.0	5	*52.5*
2.2	5	*52.5*
4.7	5	*53*
10	5	*52.5*
47	5	*52.5*
0.47	6	*62*
1.0	6	*62*
2.2	6	*62*
4.7	6	*63*
10	6	*64*
47	6	*62*
0.47	7	*72*
1.0	7	*74*
2.2	7	*75*
4.7	7	*74.5*
10	7	*74*
47	7	*72.5*
0.47	8	*80*
1.0	8	*84*
2.2	8	*85*
4.7	8	*85*
10	8	*86*
47	8	*85*
0.47	9	*87*
1.0	9	*90*
2.2	9	*91*
4.7	9	*92*
10	9	*92*
47	9	*91*

Figure 5.7, shows a 7-stage voltage doubler, and it also shows that changing the number of stages does not affect anything else in the circuit except the output voltage. The rise time is almost identical to the 6-stage simulation shown in Figure 5.6.

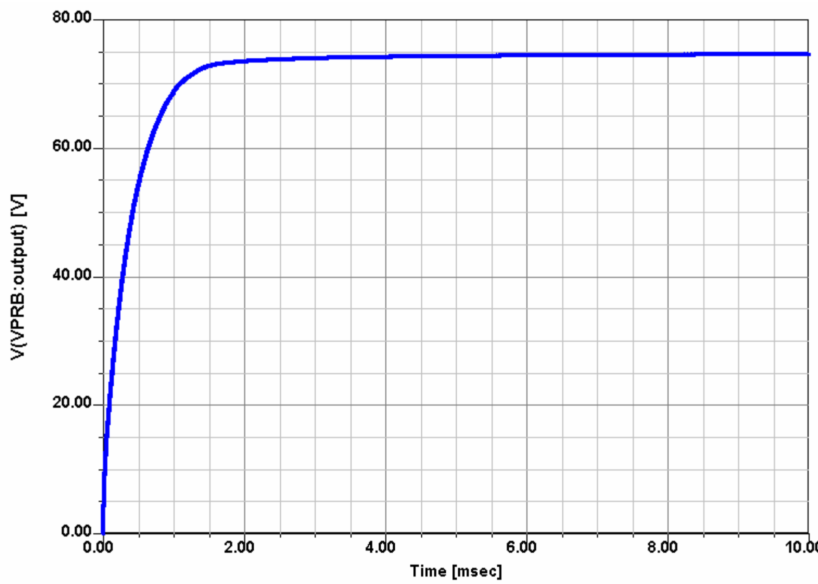

Figure 5.7: Simulation Result for 7-Stage Voltage Doubler

After all the simulations were run using the same capacitance for each stage, a simulation was run using varied stage capacitances between stages. The capacitance was varied in such a way that, from one stage to the next, the capacitance was halved. So, if the first stage was 1nF, the second was 0.5nF, third was 0.25nF, and so on. But, values were used so that they matched a component that was available in commercial components for testing. This meant that the 0.5nF capacitors were actually 0.47nF, and the 0.25nF capacitors were 0.22nF. The next two figures show the difference between these two different ways of using the stage capacitance. The first one, Figure 5.8, shows a 5-stage voltage doubler with equal stage capacitance values between stages. The next figure, Figure 5.9, has the stage capacitance value varied as mentioned above.

The first stage is 1nF, the second is 0.47nF, the third is 0.22nF, the fourth is 0.1nF, and the fifth is 0.047nF.

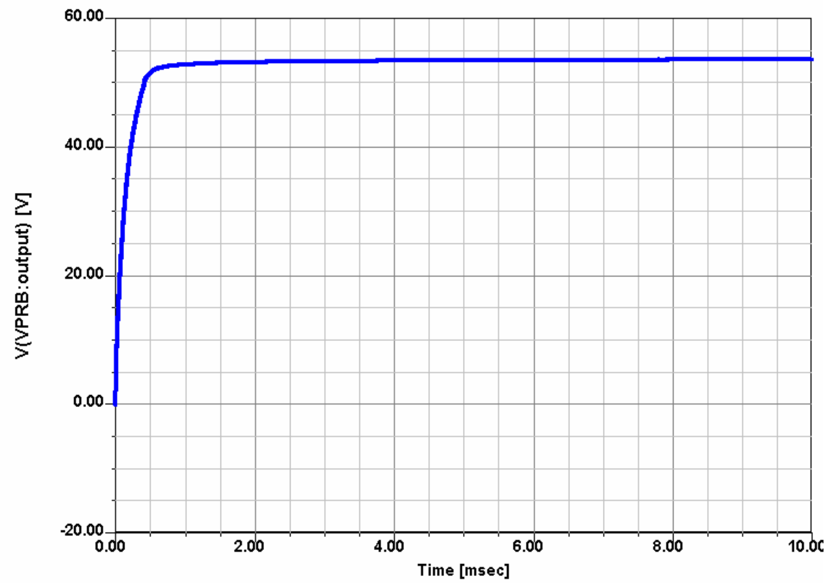

Figure 5.8: 5-Stage Voltage Doubler with Equal Stage Capacitance

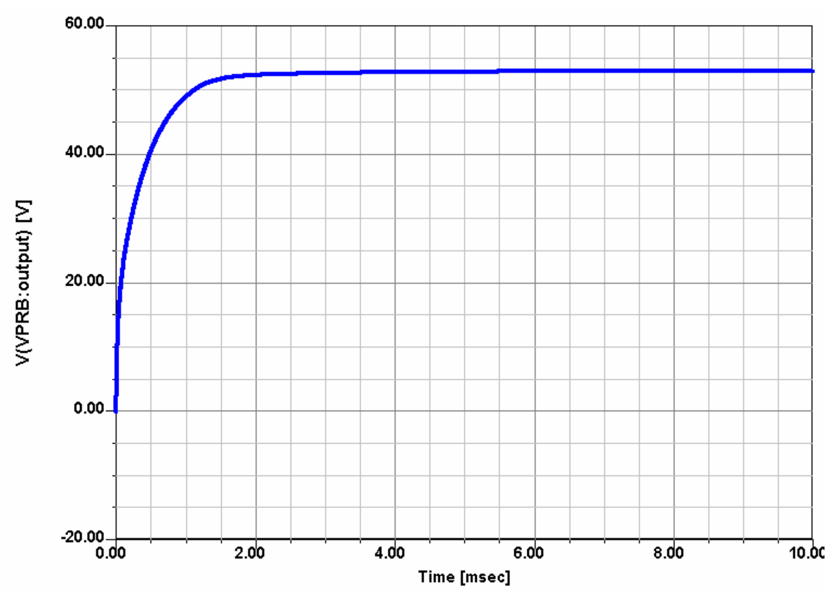

Figure 5.9: 5-Stage Voltage Doubler with Varied Stage Capacitance

After studying these two simulations, it can be observed that the resulting voltages are equivalent. The only difference between these two graphs is the rise time of the circuit with modified capacitance is a somewhat slower. But, again, it is still under 2ms. This difference is negligible. With this simulation, the variation in capacitance research was considered completed. It can be concluded that the output capacitance should not have an effect on the output voltage in testing; having equal stage capacitances should be work mostly the same if not better than varied stage capacitance; and the more stages in the system should result in more voltage. The next step is to verify the simulation by actually testing the different circuits.

6.0 SIMULATION VERIFICATION

In conjunction with the simulations that were performed, a testing board was fabricated to verify the results that were being given by the simulation software. The software used to make the board is free software from ExpressPCB, shown in Figure 6.1. This software is not the most

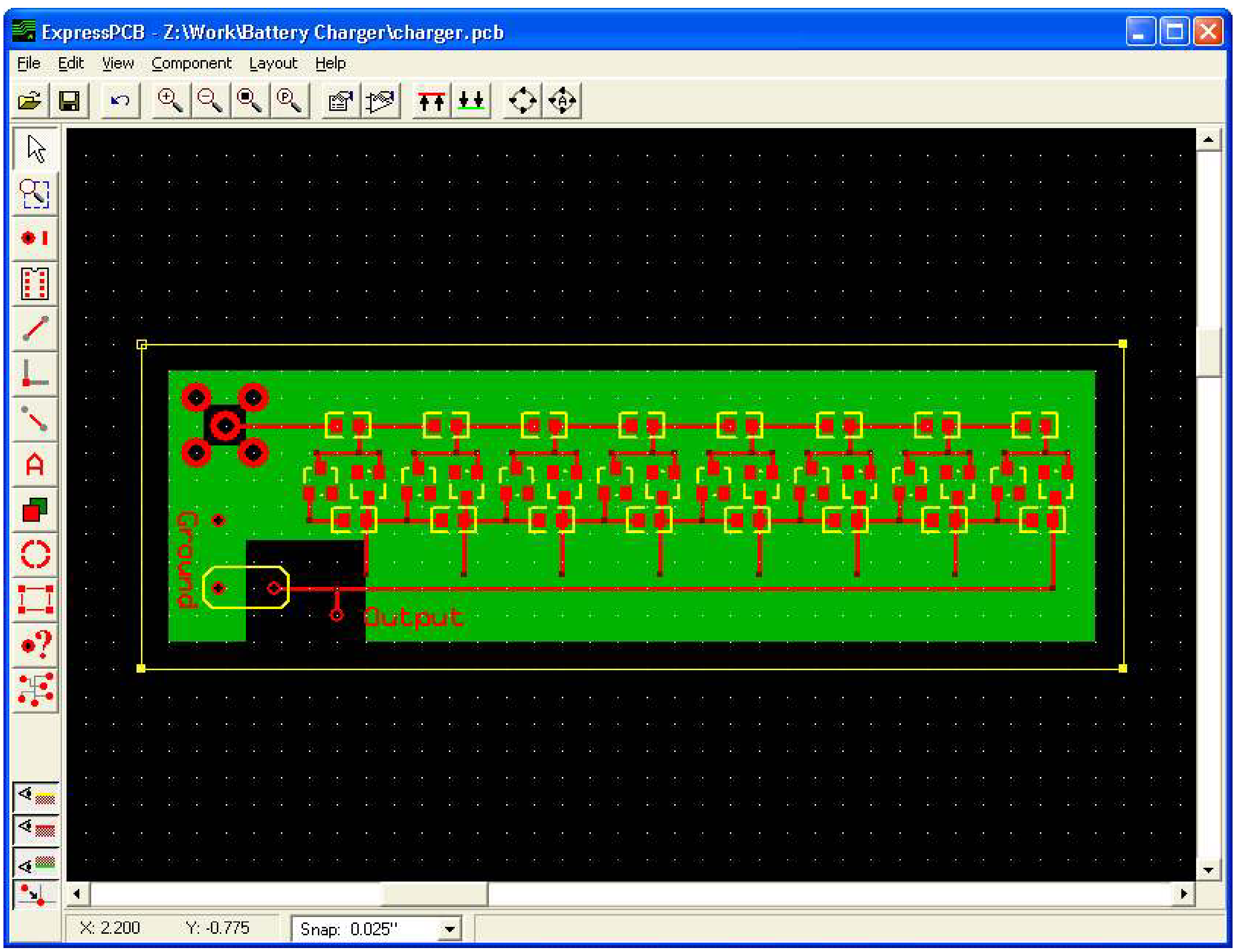

Figure 6.1: ExpressPCB

elaborate, and there are definitely better software packages available. But, being free, having minimal cost and low turnaround time by the manufacurer for producing a small number of boards, this program is the best choice for this project. This software is also very easy to use. It is as easy to use as any simple picture drawing program for any operating system, i.e., Microsoft Paint. This software has all the necessary instances, or component layouts, that are needed for this project. All these factors combined meant that laying out boards is efficient with quick turnaround time.

The PCB made first, shown in Figure 6.2, was not optimized to save space. It was fabricated simply to condense all the through-hole capacitors down to surface mounted components and allow us to try different combinations of capacitor values and stages. The PCB can accommodate up to eight stages of the charge pump. If a number of stages below eight is desired, the connection can be shorted to the output trace with a small amount of solder. The last stage is connected because there is no path for current without the components for those higher stages being mounted on the board. For this board, the output capacitor is still a through-hole design. This was done to accommodate using larger capacitors that are not available in surface mount packaging. Using this board for empirical purposes, component values that work the best can be found.

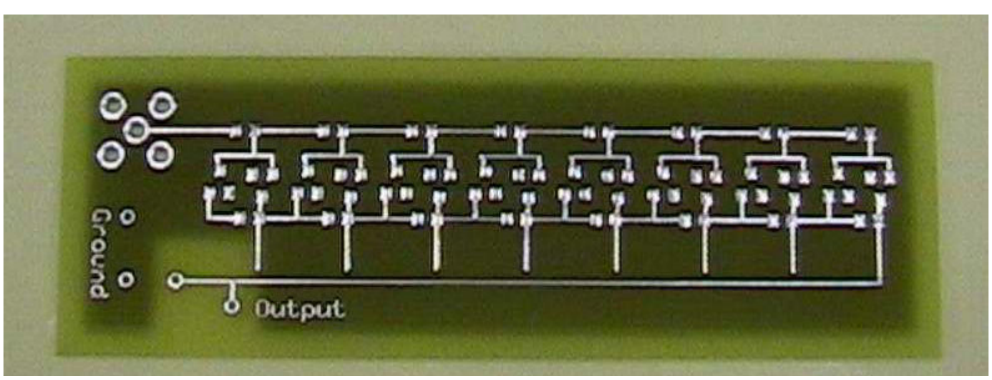

Figure 6.2: Test Board 1

The first test that was performed was an open circuit test. This means that the voltage was measured directly at the output of the energy harvesting circuit without a resistive load, or without it being connected to a phone. This is the form of the simulations. This was to get an idea of the accuracy of the simulations. The voltage was measured with a standard Fluke multimeter. Before comparisons are made to the simulations, some issues need to be cleared up. First of all, the output capacitance was the same as in simulations, 15nF, but other tests were performed using different values. These tests performed no differently than the tests presented in Table 3. The next issue is the test of equal capacitance compared to varied capacitance. This test was also performed and showed that equal stage capacitance was consistently higher with output voltage. Using this board, we get the voltage test results shown in Table 3.

Table 3: Test Results Using Board

Stage Caps (nF)	**Store Cap (nF)**	**# Stages**	**Antenna**	***DC Voltage (V)***
1	1.5	6	¼ Whip w/ GP	*~70*
1	1.5	5	¼ Whip w/ GP	*~60*
1	1.5	4	¼ Whip w/ GP	*~40*
1	1.5	6	¼ Whip w/o GP	*~20*
1	1.5	5	¼ Whip w/o GP	*~10*
1	1.5	4	¼ Whip w/o GP	*~5*
0.1	1.5	6	¼ Whip w/ GP	*~80*
0.1	1.5	5	¼ Whip w/ GP	*~50*
0.1	1.5	4	¼ Whip w/ GP	*~40*
0.47	1.5	7	¼ Whip w/ GP	*~60*
0.47	1.5	6	¼ Whip w/ GP	***~100***
0.47	1.5	5	¼ Whip w/ GP	***~90***
0.47	1.5	4	¼ Whip w/ GP	*~40*

Focusing solely on the effect of the number of stages, we can see that to a certain point, the voltage increases with every stage that is added. However, once we pass 6 stages, the voltage falls off considerably, approximately 40V. This is contradicted in the simulation results, where the voltage was greater with more stages. This phenomenon is not understood. Going back to Equation 1 in Chapter 3, at some point the voltage gained is going to be negligible, but from that equation, nothing shows that the voltage will fall. The other thing to notice is that the quarter-wave whip antenna does not work without a ground plane attached to it. This was pointed to be a problem in Chapter 3, and is of no consequence because we can not use this antenna in the final product because of its size. As is shown, the best results are with a stage capacitance of 0.47nF in the 6-stage voltage doubler. The 5-stage circuit performs to a similar extent, with a minor falloff in voltage. This becomes important later because, as will be presented shortly, space in the stands is very limited. Keep in mind that the antenna needs to be changed to fit in the stand. These results were just to verify that the energy harvesting board is working as well and even better than predicted through simulation.

6.1 PHONE TESTING

Since the goal of this thesis is to charge the battery within the phone, the next step in testing was to try to charge the phone batteries through the phones with this setup. The Nokia phone was the first to be tested because the power it needs to charge was calculated to be less than that of the Motorola phone. The power in a system is equal to the current in the system multiplied by the voltage in the system, Equation (4).

$$P = I \bullet V \tag{4}$$

For the Nokia phone, it was calculated that we will need approximately 3.6 Volts x 0.35 Amps, or 1.26 Watts of power in the system in order to get the Nokia phone to charge the battery. However, the Motorola phone needs 5.9 Volts x 0.4 Amps, or 2.36 Watts, of power. These ratings were taken from the chargers that were supplied with each phone. These chargers were discussed in Chapter 2. For this reason, concentration at first was focused solely on getting the Nokia phone to work, and then to come back to the Motorola phone once the Nokia phone was working. Figure 6.3 shows the setup used for the tests. The antenna is connected to the board through an SMA connector. The output of the circuit is sent straight to the phone through the plug that is used for charging the battery. Figure 6.4 shows a close up view of the phone connection. The jack plugged into the phone was the phone connector end cut from the travel charger and connected to the board.

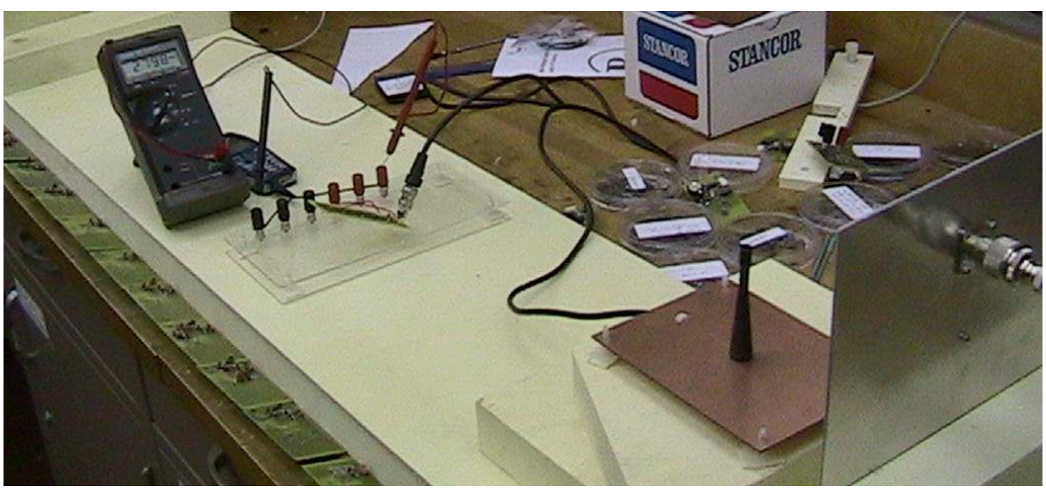

Figure 6.3: Test Setup

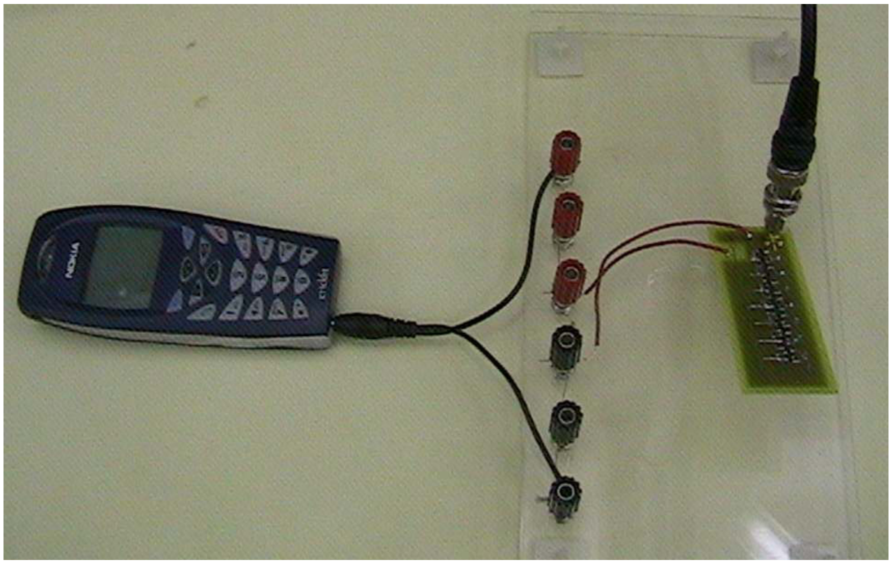

Figure 6.4: Nokia Phone Test Setup

The test was performed using the board configuration that presented the highest voltage from the tests. This was the 6-stage version with 0.47nF stage capacitors. First and foremost, the phone does turn on. Its LCD screen comes on and reveals that it is beginning to function. At first it was thought that the board was working and actually charging the battery, although very slowly. However, further tests revealed the phone is not actually charging the battery. Using the voltage meter, the battery voltage can be read while the board is operating and attempting to charge the phone. This voltage could actually be seen falling, meaning that the phone is drawing current from the battery. It turns out that the phone itself had more circuitry to charge the battery than was anticipated. This circuitry and the LCD screen also need power before charging can begin. When power is applied through the energy harvesting board, the charging circuitry and other electronics, such as the LCD screen, turn on and draw power. However, the power that is being supplied from the energy harvesting board is not enough to feed all the extra circuitry along with charging of the battery. The phone starts drawing current from the battery to compensate for the lack of power, thus draining it. After a short elapsed time, the LCD screen turns off, but the charge circuitry must still draw current because the battery continues to drain.

This being the case, it was decided to switch phones. After all, this is one reason why we chose to test two phones. Maybe the Motorola phone doesn't require as much power for its other circuits that are on while charging is commencing. But, looking back at the power calculations and the reason for testing the Nokia phone first, it was very likely that this phone would perform the same, if not worse, than the Nokia phone. And, this was confirmed by the tests. The setup can be seen in Figure 6.5. As it turns out, this phone has the same problem, but to a greater extent, meaning that the phone shuts off quicker than the Nokia phone while the energy harvesting board is operating.

Even though the overlying goal of this research is to use the external connections of the phone connected through the phone's internal charging circuitry, with these test results in mind,

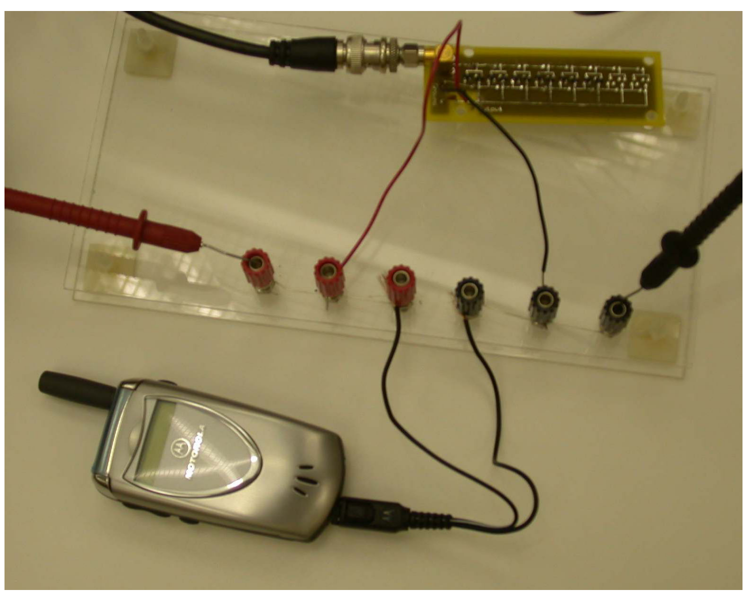

Figure 6.5: Motorola Phone Test Setup

it was determined that an alternative approach would be required. Instead of trying to charge the battery through the phone, it might be possible to charge the battery directly from board. The Nokia battery was the first to be tested in this manner, followed by the Motorola battery. The Nokia battery test setup can be seen in Figure 6.6.

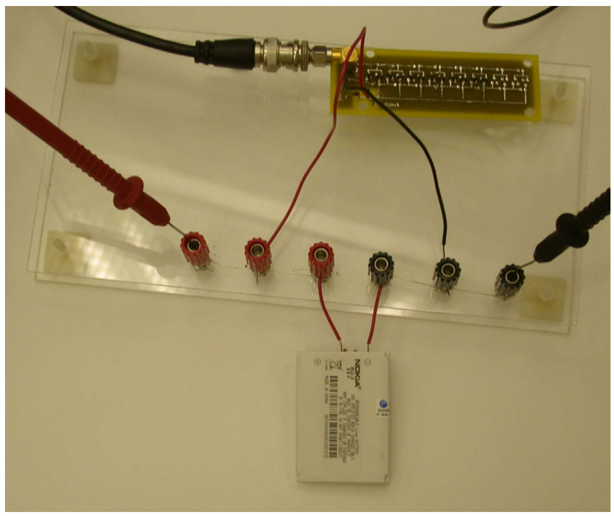

Figure 6.6: Nokia Battery Test Setup

The test was done using the same high output voltage board from the phone tests. Leads were soldered directly to the battery and were then clamped to the output of the board. With power applied to the energy harvesting board, the battery voltage increases and the results are better than those previously obtained. Where they were getting about 2mV per second, this board is able to achieve a charging rate of about 5-6mV per second on both batteries. This proves that these batteries are very similar. It is worthwhile to note that the previous research was done using an older battery that was used extensively for testing purposes. This result is important because it means that this research was not done in vain.

Now with useful test results, it was suggested that the battery be placed in the phone and wires be run from the terminals of the battery through the inside of the phone down to the bottom of the phone where the connections are for charging the phone normally. This would serve the purpose of having everything contained inside the phone, which was one of the overall goals of the project. The first problem that was encountered was that the Motorola phone could not be disassembled sufficiently without major alterations to be able to do this. In addition, there is not a lot of room left in the phone for extra wires. This leaves us with the Nokia phone. The phone came apart surprisingly easily. A picture of all the layers of the phone is given in Figure 6.7. One end of the wire was soldered to the phones circuit board where it was in contact with the battery terminal. The other end was soldered to the charger input, which was disconnected from the rest of the phone. Severing this connection made it so that the phone could no longer be charged normally but is preemptive in trying to solve the problem of the phones circuitry drawing power. The two connections made to the circuit board can be seen in Figures 6.8 and 6.9. Now the test was done using the same board as in previous tests. However, this test did not

Figure 6.7: Layers of Nokia Phone

work. It had the same problem as the phone tests did earlier. The problem arises from that fact that there are more than two terminals on the battery. There is one for power, and one for

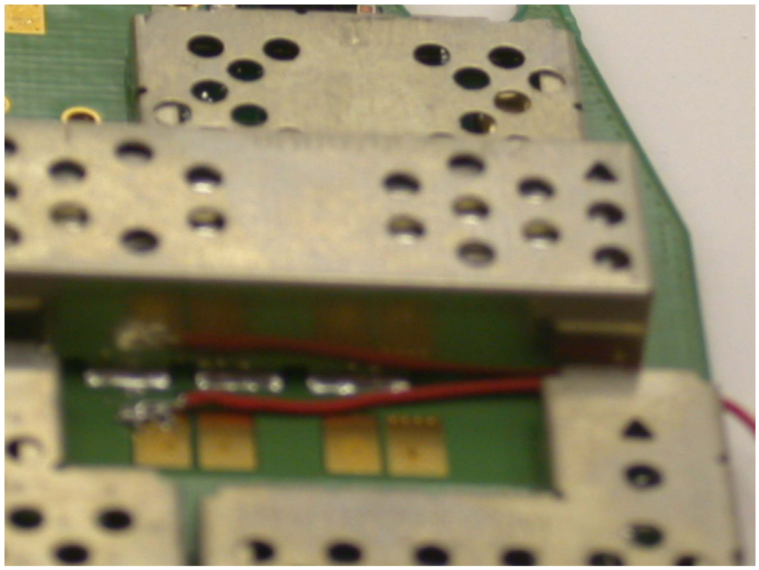

Figure 6.8: Close-up of Connection to Battery Terminal

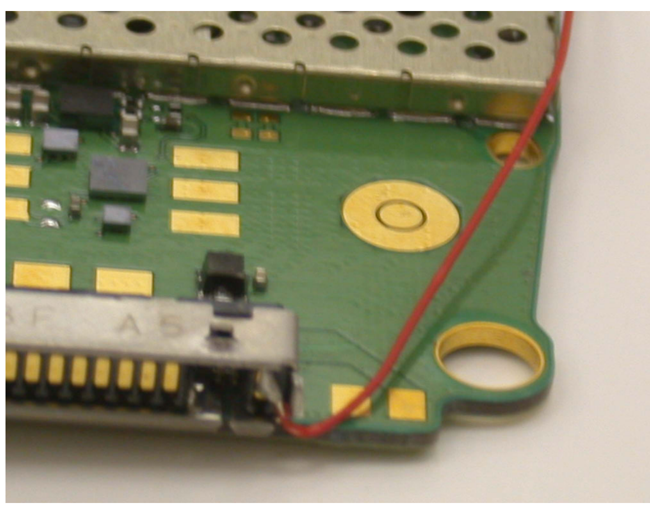

Figure 6.9: Close-up of Connection to Charging Input

ground, but there are two more that are used by the phone circuitry. This is the case for both the Nokia phone and the Motorola phone. There was insufficient information available that explains the ultimate purpose of the other two terminals.

More testing was then performed involving the use, or removal, of these unknown terminals. The first test was to disconnect the two known terminals from the phone to prevent the phone from being able to draw power. This was done using electrical tape placed over the terminals so no connection would be made when the battery is inserted into the phone. This worked to the point where the battery was charged in the same manner as it was with the battery separated from the phone. As expected, there was no lighting of the LCD screen of the phone, which is good because that would waste needed power. However, without the connections to these terminals, the phone will not operate normally. It was thought that maybe the connections inside the phone were not reliable. So, the leads were soldered back to the battery terminals and the charging was tested. This can be seen in Figure 6.10. However, these tests had the same problem. Because losing the functionality of the phone does not justify the addition of this charging circuitry, more testing was required. But, without knowing what the other terminals do, it is rather risky to

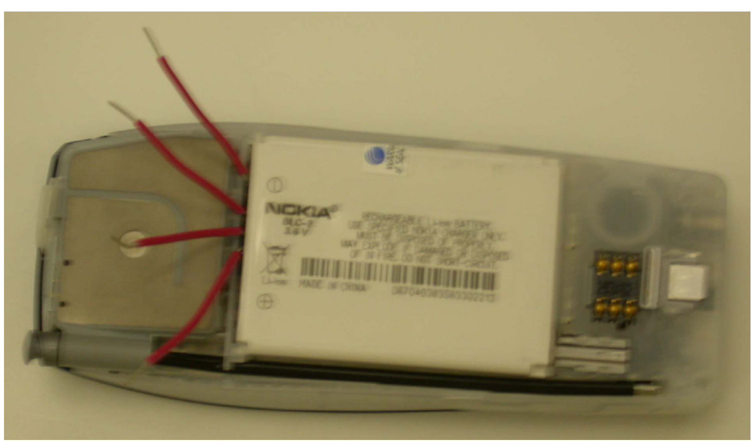

Figure 6.10: Battery In Nokia Phone with External Leads

attempt to short them or connect them in any other fashion. For the sake of experimentation, tests were performed where the terminals were connected together, connected to ground, or connected to power. None of these tests produced successful results. Some might have even damaged the battery that was being tested.

While the tests of the phones themselves did not have good results, it was determined that the act of charging the battery directly through the phone was promising enough to continue with design of the prototype to be put in the stand.

7.0 PROTOTYPE IMPLEMENTATION

In the previous chapter, it was shown that while an energy harvesting board could not give sufficient power to charge the battery while it was in the phone, it did a good job of charging just the battery. With that in mind, it was decided to go forward with the fabrication of a second board that would fit in the charging stands. This board would be used in both stands, thus it had to be small enough to fit the smaller of the two stands. Width wise, the Nokia stand is smaller than the Motorola stand. This being the case, the board was designed mainly for the Nokia stand but was also easily fit into the Motorola stand.

7.1 THE NOKIA DESKTOP STAND

In order to get the charging board to fit the stand, some slight modification to the Nokia stand was necessary. There is a solid piece of metal, probably copper, about one quarter of and inch thick that is attached to the inside of the stand with screws in the area where the charging board was to be added. This metal is most likely a counter-weight for the stand to make it heavier and more resistant to capsizing when the phone is in the cradle. Without this metal, the stand functions normally. The stand weighs less without it, but this is of no concern in this phase of testing. Once this weight was removed, there was sufficient room in the upper area of the stand for a PCB. The dimensions of this area were obtained using calipers. The last modification to this stand came in the form of a screw hole. The screw hole was placed in the upper section of the stand in between two holes already there for holding the top piece onto the bottom. This hole is to be used to attach the charging board to the stand using a nut and bolt. With the dimensions and the placement of attachment hole known, a second testing board was fabricated to fit within this stand. Board 2, Figure 7.1, was designed specifically for this stand. This board, however, only has 5 stages. This is not a problem though. Going back to Table 3 from Chapter 6, it was shown that 5 stages outputs almost as much voltage as the board with 6 stages. Just to be on the safe side, the same tests that were performed in Chapter 6 with the 6-stage charge pump. These were also done with the 5-stage charge pump. The tests performed equally well, with a negligible drop in charging rate.

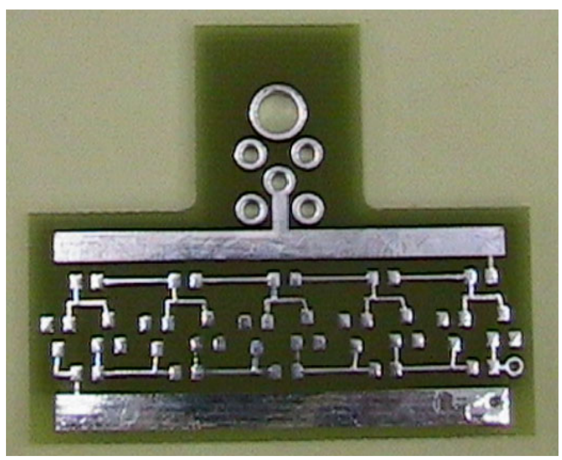

Figure 7.1: Test Board 2

Now that the board was completed, an antenna can be fabricated. The difference between the antenna and the board design is that one antenna cannot be designed to fit in both stands. Therefore, two separate antennas need to be molded. Looking back at the previous chapter reminds us that while the board was being tested with an off-the-shelf antenna designed specifically for 915MHz, the phone would not charge the battery. Knowing this, it was somewhat doubtful that a crudely shaped antenna can be made that will outperform the quarter-wave whip. But, it can be assumed that if a wire is wrapped around the inside of the stand, and connected to the input of the circuit, it will act as an antenna. Combined with the energy harvesting board, the combination should be sufficient to supply voltage to demonstrate that the power is being applied to the phone. With this assumption, a copper wire about 1/16 of an inch thick was soldered to the input of the testing board number 2 and then wrapped around the inside of the base station so as to allow for resealing, and phone placement. A picture of the board attached to the monopole antenna and placed inside the stand can be seen in Figure 7.2.

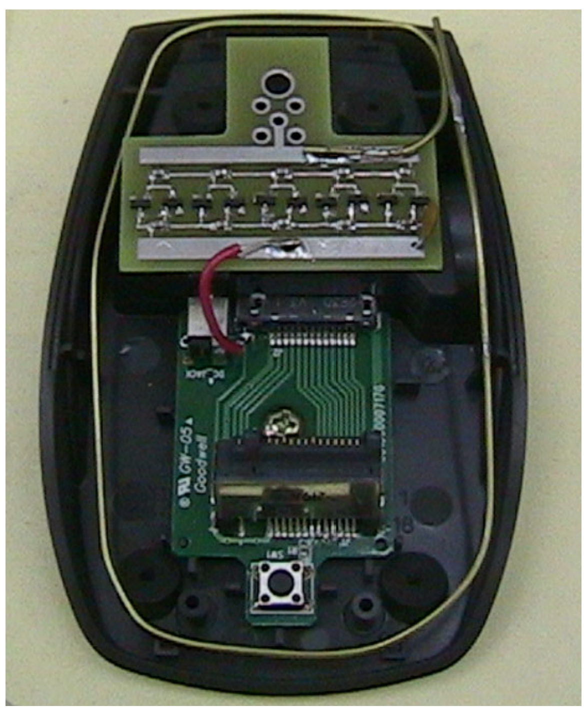

Figure 7.2: Board 2 with Monopole Antenna

7.2 THE MOTOROLA HANDS-FREE SPEAKERPHONE

The Motorola phone stand required more complicated modification of the original design in order to work with this board. The main complication that results from this is the loss of the original functionality. But, since this is a proof-of-concept project, this was of no immediate concern. Because the original concept of this stand was a speakerphone, there is a speaker housed within the stand. The stand itself is molded plastic, and the speaker is secured to the stand with 3 screws. The stand separates into two parts, a front where the phone is placed, and the back where the speaker is attached. The main PCB is placed in the front piece at the bottom. This allows Motorola to place the connection to the phone directly on the board. The speaker is connected to the board through a pair of wires. These wires connect to the board through a small plug. Once the speaker is unplugged, the front and back can be separated. The speaker was unscrewed and taken out of its housing in the back of the stand. All that is left is the molded plastic. The problem was that with all the plastic in the stand, there was no room for the board to be added. Therefore it was necessary to remove this plastic and leave a smooth, rounded back to the stand. This is rather simple with a rotary sanding tool. With the inside hollowed out, there is a nice quarter of an inch depth for the new board and antenna to be placed into this system. A side by side view of the original back piece and the hollowed out back piece are shown in Figure 7.3. As with the Nokia stand, the new board was attached with a wire soldered to each board. The wire is attached to the pin which goes into the phone to charge the battery. The stand with the board attached is shown in Figure 7.4.

Figure 7.3: Side by Side View of Original Motorola Stand and Hollowed-out Stand

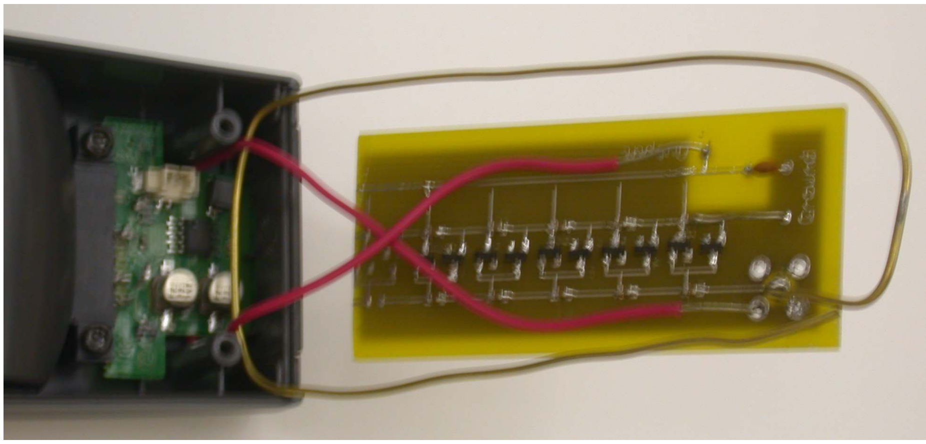

Figure 7.4: Motorola Stand with Charging Board and Antenna

7.3 PROTOTYPE TESTING

With a PCB and antenna in each stand, testing was done to show that the phones were able to be turned on by power provided by the energy harvesting circuit. The two phones placed in their stands for testing are shown in Figure 7.5. Tests were also performed to get the unconnected

Figure 7.5: The Nokia and Motorola Phone in their Respective Stands for Testing

voltage reading. The previous board, using the quarter-wave whip, was able to produce ~90V DC unloaded, but this board with the monopole antenna can only produce about ~45V DC. This confirms the point brought up in the previous sections about the antenna not being able to perform as well as the off-the-shelf counterpart. However, considering this voltage is about half of the original voltage, the phone is still able to turn itself on to show that the power is being supplied. And in tests that were performed with direct connections to the battery terminals, this board and antenna combo performed almost as well as with the quarter-wave whip antenna. Previously, the board was able to charge at about 5-6 mV per second, resulting in about 2 hour charging time from 3.2 V to 3.9 V. Here it was about 4 mV per second, resulting in about 3 hour charging time. In previous research, the battery charged at about 2 mV per second. That is almost 6 hours charging time, so we have almost cut the charging time in half.

8.0 SUMMARY AND CONCLUSIONS

In this thesis, we submit a first step towards a goal that would have profound ramifications on the cellular phone industry and the portable electronic device industry as a whole. Experimental results show that while we were not completely successful at achieving our overall goal of having the charging circuit in a stand be able to charge the battery of a cellular phone while it was within the phone using a wireless RF source, we have completed the goal of being able to charge the battery while the phone is in its stand. Circumventing the proprietary circuitry in the charging path will allow future adaptation of the wireless RF energy harvesting concept produced by this research.

8.1 AREAS OF CONSIDERATION

Some issues remain that need to be studied before work can continue. The first thing to look at is the antenna being used to harvest the RF energy. As was shown in Chapter 7, the antenna used in the stand was about half as efficient, from a voltage standpoint, as the off-the-shelf quarter-wave whip antenna used in earlier tests. There needs to be much more emphasis put on antenna design in order to get the power transfer to a sufficiently high level, i.e., to the level of the quarter wave whip antenna. Right now, the monopole is about 50% of the efficiency of the commercial product. Another thing to consider is the circuit itself. Perhaps there are other ways of laying out the circuit that could be more power-efficient or even other topologies to be tried. The last thing to try would be to be able to involve the cellular phone company directly or at least be willing to divulge the circuitry involved.

8.2 CONTRIBUTIONS

The most important result is that I successfully proved that the concept of charging a cellular phone battery while in a phone using wireless RF energy harvesting is feasible. We were able to get enough power to turn the phone on. This is an important result because it shows that the circuit that was designed, simulated, and tested throughout this research can be used to accomplish our ultimate goal. Because of this result, future work in this area can be expected. It is probable that with more focus placed on the antenna, and, as energy harvesting technology becomes more advanced, this work will be successful at achieving a commercial product. The ultimate goal, of course, is to get everything in the phone and use ambient RF energy to charge the battery. In this thesis, we have laid the foundation for this work to continue by accomplishing the following goals: We were able to charge the battery directly faster than had been done previously; we were able to power the phone using an RF signal transmitted to the phone and stand; we provided simulated and empirical data that can be used as a reference for future work in the area; and we were able to condense the circuitry down to a sufficiently small size to conceal the charging circuitry and antenna within a commercially available stand. Involved in achieving these goals were the modeling of the circuit in a program suitable for simulating high frequency circuits, the design of a testing board and procedure for verifying the simulation results, and finally creation of a board and antenna combination that would be small enough to be contained within a commercially available stand, yet be able to show that indeed we are able to power the phone.

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