SELF POWERED WIRELESS SENSORS:
REMOTELY POWERED WIRELESS SENSORS USING WIRELESS POWER TRANSFER

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
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To my parents, brother, and two sisters.

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Wireless sensor networks have recently started showing more interest towards issues of power consumption due to the high dependency on battery power. When the battery energy capacity is diminished to the point of inadequate voltage level, the wireless node would shut down, which might cause loss of information, resource limitation, intelligence, and perhaps cause network failure in some cases. Therefore, it is necessary to have a backup secondary power source that would deliver energy to the wireless node in case of a power scarcity. In the case of wireless nodes, backup power would have to be delivered, obviously, without using any wires, which means that, power would have to be delivered in the form of thermoelectric, solar power, mechanical, vibration of piezoelectric material, or radio energy propagation. The latter is referred to as wireless power transfer (WPT), which is the main concentration and focus of alternative power source of this thesis, is discussed in detail. The concept of WPT is as simple as generating a high power radio signal and beaming it towards the wireless sensor. The wireless sensor has the ability to detect this radio signal and turns it into usable DC voltage for storage.

CHAPTER 1
INTRODUCTION

Problem Statement

As technology advances, we notice that electronic devices have the natural ability to eventually shrink in physical size in time. This can be obviously seen from the evolution of computers from mechanical computers, to transistor IC computers, and now to ultra compact embedded sensor platforms, and wearable computers. The size and performance of integrated circuits ICs was predicted by Intel's co-founder Gordon Moore in 1965 that the number of transistors in a microchip would double every 18 months, which was then adopted as Moore's law. Generally speaking, if the number of transistors doubles every two years, then the power consumption would also double according to the following equation for calculating rough estimate power consumption:

$$\text{Power Consumption} = \tfrac{1}{2} * C * V^2 * f \qquad (1\text{-}1)$$

Where C is the transistor equivalent capacitance, V is the transistor voltage supply, and f is the transistor switching frequency. Therefore, the amount of power consumed by a sensor node is proportional to the amount of power a single active transistor consumes scaled by the number of active transistors on the sensor node. This tells us that the simpler the architecture deign is the less power is consumed. This of course has the draw back with the amount of intelligence and limitation a sensor node would have at that point, so there is a tradeoff with sensor smartness and power consumption. This is an obvious argument since nothing is free, as system complexity grows, more transistors are used to get the job done, and thus more power consumption is used. The argument here is that the simpler you keep the design the more likely you would consume less power at the cost of sensor intelligence limitation. Another argument is how fast the transistor switches on and off, which is the effect of the variable f in the above equation, also known as the switching frequency or system clock. The switching frequency of the transistor is a tricky variable since one would basically think of reducing the frequency to consume less power, however, there is more to it than just operating at slower speeds. On the hardware level of things, using a high crystal clock requires more current to drive than a lower frequency crystal. For example, a microprocessor from Microchip PIC16F688 running on a 4 MHz crystal and voltage supply 2 volts would consume about 220uA vs. a 32 KHz crystal that would only consume 9uA running under the same conditions. However, the problem is that a 32 KHz crystal would take 128 times the time to complete the same job. With wireless sensor nodes the highest power consumption block is the radio frequency (RF) transmitter, which consumes constant power as long as there are information bits to be sent. Therefore, if information bits are transmitted faster, then the RF stage would be on for a shorter period of time, and thus, system power consumption would be considerably lower. This method was successfully implemented and patented by Nordic VLSI company as the ShockBurst™ effect, such that information data is clocked in at a slower rate (32 KHz), but transmitted at 1 or 2 Mbps. Nordic ShockBurst™ radio architecture became popular in low power wireless devices such as keyboards, mice, computer presentation controllers, active RFIDs, heart monitoring watches, and others. This clearly shows that a slower switching frequency is not always a lower power consumption approach, but that it really depends on the rest of system design and how it is affected by the switching frequency.

Moore's law states that the number of transistors doubles every 18 months (SEMATECH research shows a 24 months roadmap), as seen in figure 1-1. This is actually because the transistor size (gate-length barrier) is reduced to half, and thus you are able to fit twice the number of transistors on the same silicon die area, which in effect reduces cost.

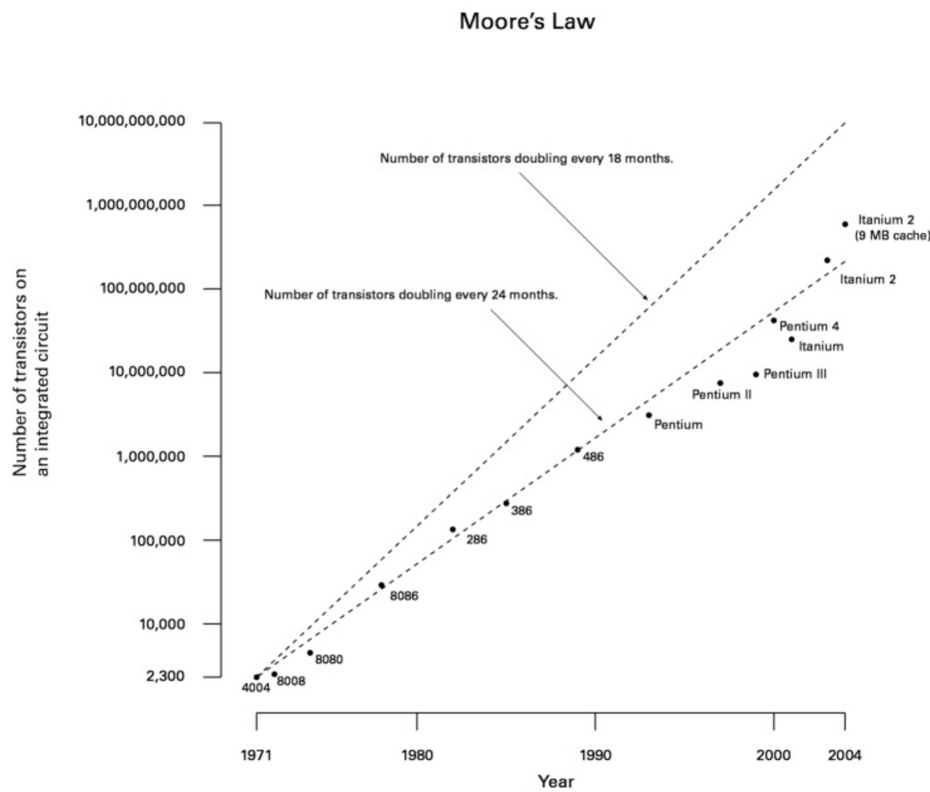


Figure 1-1. Moore's law showing growth of transistor count for the Intel processor (dots) every 24 months. Figure taken from Wikipedia.org.

This shows a simple observation that power consumption scales linearly with the amount of transistor doubling and the speed in which the transistor switches states. Also, higher switching frequency requires higher bias voltages, which in return affects power on a quadratic scale. In order for a wireless sensor node to keep up with Moors law power consumption requirements, the battery industry would also have to double their battery capacity every two years, or put twice the amount of batteries on each sensor node. The later approach is highly unsuitable for wireless sensor network due to cost, size, and weight constraints. Also, some nodes have to be deployed in isolated environments, which require long operating life and years of maintenance-free operation. Thus, the need to reduce power consumption and the need for alternative power sources becomes a real concern for wireless sensor network.[1,2,3,4]

To solve the ever increasing demand on power, wireless sensor nodes would require deployment of low power hardware design, software selectable low power operation modes, short active duty cycles, and harvesting energy from different external sources. These constraints in wireless sensor network gave lead to the ZigBee technology with it's comparable low power consumption in full active mode of about 50 mA (Transmitter = 25 mA average, Receiver = 20 mA, and DSP = 5 mA) from Cirronet© , when compared to a WiFi node that could consume up to a total of 700mA of active average current from DPAC© , and BlueTooth with an average of 150mA from BlueRadios©. The advantage of ZigBee over Bluetooth includes lower power consumption, higher radius of operating range, and larger number of supported nodes.

Power Harvesting Sources

Another solution for the high demand on power consumption is to harvest energy from the surrounding environment.[5] Clean energy sources can be found around wireless sensor nodes and harvested into usable energy to recharge batteries or to charge large local capacitors, also known as super or ultra capacitors. Ultra capacitors have midrange capacity storage between rechargeable batteries and regular capacitors. However, unlike rechargeable batteries, ultra capacitors do not require a special way to be charged, as they would accept any kind of voltage level or waveform, that being AC or DC. This sets fewer constraints on the method of recharging super capacitors from different power source.

Available sources for power harvesting include the use of solar panels seen in figure 1-2 A. Solar panels are found everywhere and are easy to harvest energy from, such that as the light intensity increases, the output produced voltage is a DC voltage easily charged on a super capacitor. Solar panels exhibit conversion efficiencies between 10% and 20% in direct sun light[5]. For example, HARP's NE-Q5E2E photovoltaic module exhibits a 16.4% conversion efficiency under direct sun light. Consequently, solar panel do not work very well indoors, in which they exhibit only 1% efficiency, and are useless for harvesting energy for a sensor network constantly operating in a dark environment.

Piezoelectric material has gained some recent popularity in power harvesting for wireless sensor network.[6] As a matter of fact piezoelectric material goes back to 1880 when two brothers Pierre and Jacques Curie demonstrated that some crystals (tourmaline, quartz, topaz) generate electrical polarization from mechanical stress. This effect was then named "piezoelectricity" after the Greek piezein, which means to squeeze or press.[7] Piezoelectric material really gained large popularity when it was used to maintain accurate timing in clocks, wrist watches, and crystal (XTAL) oscillators used in electronic systems today. However, the problem with using piezoelectric material for power harvesting is that you need a constant source of vibration or mechanical taps, stress, push, or pull to keep generating power, which would be a perfect application to deploy a sensor network around vibrating motors or engines in an industrial environment. Seen in figure 1-2 B is a flexible piezoelectric sheet made by Measurement Specialties© company that produces very high open-circuit voltage close to a hundred volts when physically struck hard. However, when a low impedance load is used the output voltage becomes extremely low depending on the actually load value.

Mechanical power can also be turned into electrical energy as seen in figure 1-2 C using windmills, and today using MEMS figure 1-2 D. A recent popular device in the market is the self powered flashlight uses a combination of mechanical shaking and electromagnetic induction of current. By shaking the flashlight, a magnet slides between the north and south pole of the winded coil inducing current in the copper wire to be stored on a super capacitor, which is then used to power an ultra-bright LED when the on button switch is closed. The same exact device can be use to power a wireless sensor node, however running around to shake every single node becomes an impractical method, unless you are planning to use this system to work out, and I would guarantee you by the time you run to the second node, the message would already be lost. Another very popular device that uses mechanical energy to recharge a battery is the famous $100 laptop from MIT, which uses a hand crank to recharge the system's battery, low power processor, and low power software selectable user modes. Future updates mention that the hand crank would be replaced with a power supply that uses a foot crank instead, which reduces damage and stress caused to the laptop's chassis.

Thermal energy can also be transformed into electrical energy by using thermoelectric generators as seen in figure 1-2 E. Thermoelectric generators are composed of a thermocouple comprising a p-type and n-type semiconductor connected electrically in series and thermally in parallel. The thermoelectric generator produces an electrical current proportional to the temperature gradient between the hot and cold junctions. An electric load is connected electrically in series with the thermoelectric generator creating an electric circuit, such that the temperature grading between the two electrodes can be harvested into a super capacitor.[8]

Wireless power transfer is gaining significant popularity and is heavily used in technologies like RFIDs seen in figure 1-2 F, where batteries become essentially nonexistent. Such technology eliminates the bottle neck with power availability from battery capacity and the ever increasing demand on available energy capacity. This technology essentially creates a transparent radio channel that either constantly feeds power to the sensor node or charges a local capacitor over a constant duty cycle. Wireless power transfer requires two separate systems. The first system is the RF generator that generates the high power wireless energy and radiates it towards the wireless sensor node vicinity, and the second system, which is the wireless sensor node, receives the wireless power rectifies it and turns it into usable DC power to be stored for future use.

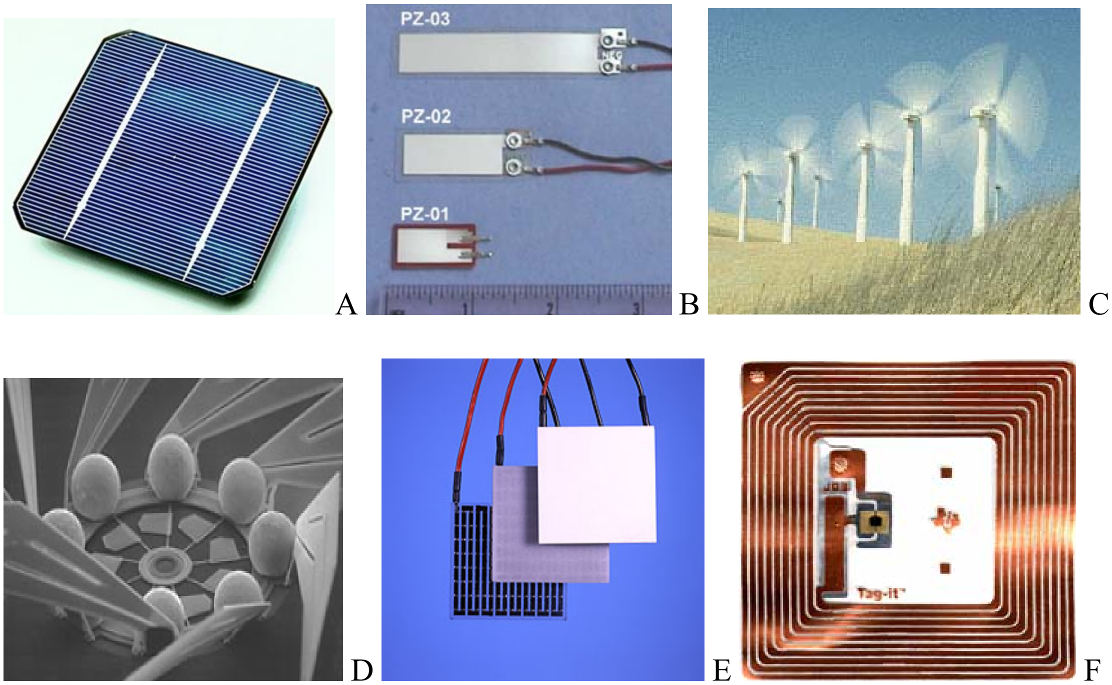
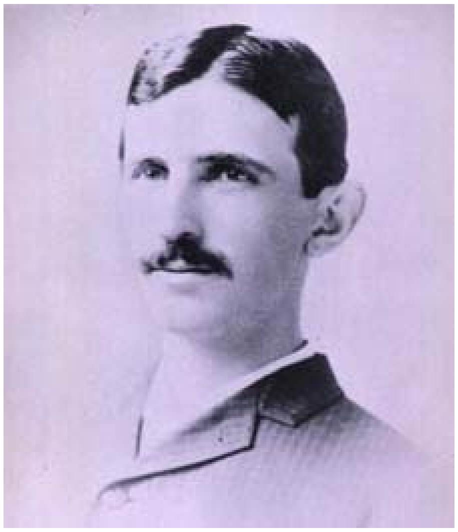


Figure 1-2. Power harvesting sources. A) Solar Panel. B) Piezoelectric sheets. C) Windmill D) MEMS E) Thermoelectric generators. F) RFID

A History of Wireless Power Transfer

Wireless power transfer was first explored by the famous scientist Nicolas Tesla, seen in figure 1-3 A. Nicolas Tesla was the first to invent the AC inductive motor in the late 1870s. Edison hired Tesla to work for him and proposed to pay him $50,000 if he was to succeed in creating AC power, mainly because Edison thought it was too difficult. Tesla took this as an easy job and came up with the AC power using his inductive AC motor, seen in figure 1-3 B. Edison was perhaps shocked when he found out that Tesla had succeeded and refused to pay him saying that the offer had been made in jest. Tesla immediate resigned, and challenged one of the greatest scientists Thomas Edison with his AC power invention. Tesla took his AC power invention and considered it to be far more superior in nature than Edison’s DC power station.


A 

B

Figure 1-3. Nicolas Tesla and the AC motor. A) Scientist Nicolas Tesla B) First AC inductive motor

Tesla and Edison stood in competition to harness the power of the Niagara Falls. With Tesla’s Chicago exposition “City of Light” in 1890, where he proudly showed off his AC power station lighting hundreds of thousands of incandescent lamps in the city, and with the 27 million people who attended the fair, it was dramatically clear that the power of the future was the AC power. Tesla’s proposal to harness the power of the Niagara Falls was his childhood dream, and it was the only proposal to be accepted, and came into existence in 1893. Even Thomas Edison was finally convinced that AC power was a must and essentially powered all his labs with it. Another one of Tesla’s invention was the so called “Tesla coil,” where he would take his regular AC power and by using transformers, he was able to boost the voltage, while dropping current to maintain conservation of power, up to couple hundred of thousands of volts which created a high electrical field between the negative end terminal of the transformer and earth ground, which essentially caused sparks to jump off, or channel through. He also noticed that the sparks where creating a high magnetic field that was illuminating incandescent lamps in the vicinity. In reality, this is the effect of electrons releasing photons off the surface of the copper wires of the transformer and creating radio waves that would propagate around the transformer, such that the high power radio waves would light up the incandescent lamp in the vicinity. This discovery essentially consumed Tesla with excitement, and perhaps drove him crazy with the endless possibilities he could make of it. He immediately proposed his theory that power can be channeled through air to light up incandescent lamps and essentially an entire city, and was actually successful at demonstrating it, seen in figure 1-4 A. To prove his power transfer theory, he built the highest Tesla coil that stood as a tower in Pikes Peak looking over Colorado Springs as seen in figure 1-4 B. At the point of completion and testing, Tesla turned on the giant Tesla coil and electricity arced out hundreds of feet over the tower causing a complete burn out of all incandescent lights in the city and the Tesla tower had set itself on fire. Thus, causing a complete blackout of the entire city, and was then charged for the damages caused, which led to his bankruptcy. Tesla even proposed to transmit information wirelessly around the globe, seen in figure 1-4 C, such that people would be able to share information such as messages, pictures, audio, and secure military communication, and was the first to propose the concept of the radar. He was also the first to create the first remote controlled robot boat in 1898, as seen in figure 1-4 D. However people thought that all his proposals where too dreamful and impractical which is understandable since he lived in a time period when people where astonished to even witness Edison’s creation of the light bulb. However, it was not just one lamp he wanted to light up; it was millions of lamps and essentially the entire city. Tesla, with his over 700 patents, is now known as the scientist born out of his time.[9] Indeed, here I am now, a 100 hears later demonstrating what Tesla had wanted to do. Tesla coil effect can be seen today in devices sold as taser-guns for self defense purposes. Also, ionizers use the same concept Tesla proposed to ionize the air which gives us the feeling of fresh air. However, Tesla wanted to use this electricity to create a channel to transfer the power to other locations without using expensive copper wires. If Nicolas Tesla was to say three last words before he died he would have said "Wireless Power Transfer."

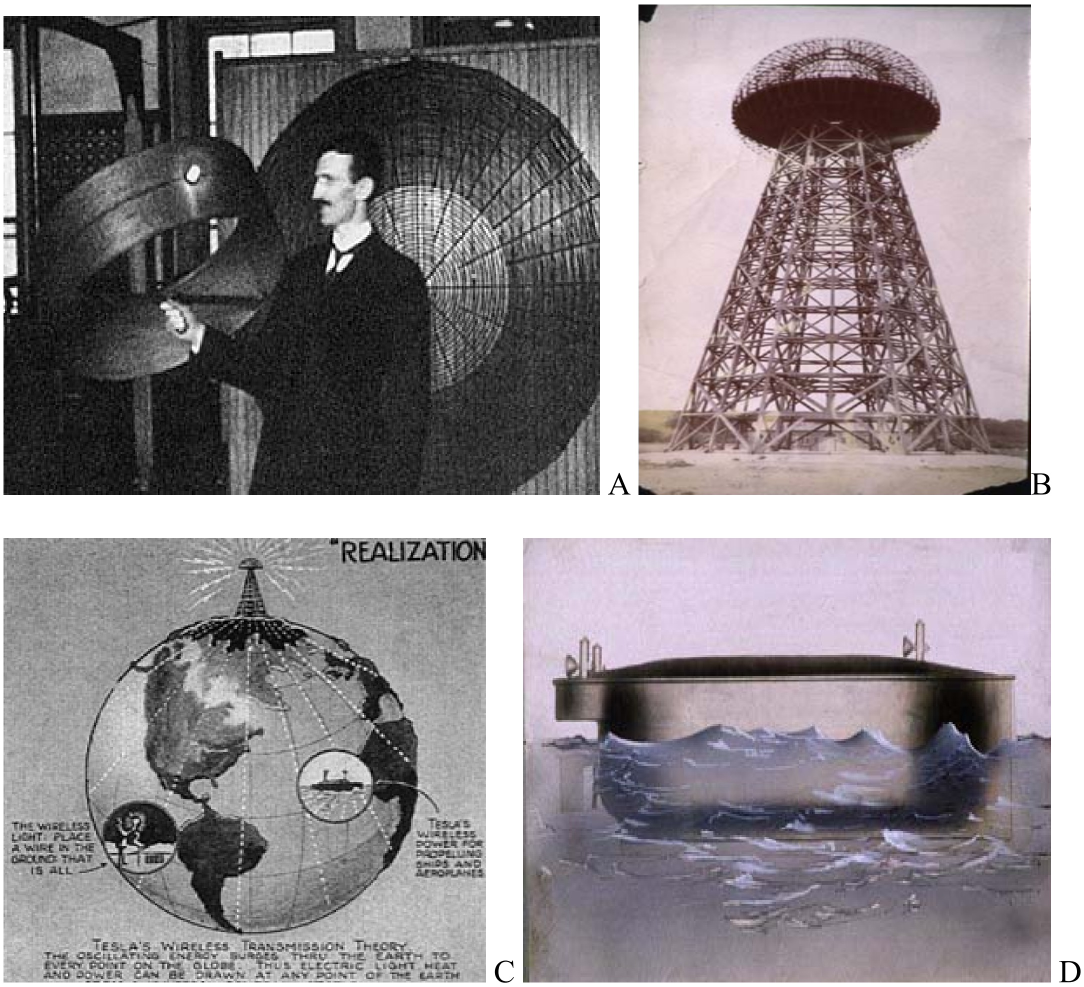


Figure 1-4. Tesla, master of lightning. A) Tesla demonstrating wireless power transfer B) Tesla attempts to build a wireless power supply tower. C) Tesla plan to transfer wirelessly power the world and transfer wireless information around the globe. D) First remote controlled robot built by Tesla.

CHAPTER 2
DESIGN PLANNING AND CONSIDERATIONS

Friis Free Space Loss

In order to achieve wireless power transfer at high frequencies, we would need to closely study the derived equation of Harald T. Friis, know as the Friis free space loss equation, or just Friis equation.[10] Friis explains through his derived equation what effects the radio signal exhibits while propagating through the air. However, before we look at the Friis equation, we will set up the typical scenario of the system from the transmitter (also know as the generator) to the receiver end (also known as the detector, or RF to DC sensor), as seen in figure 2-1.

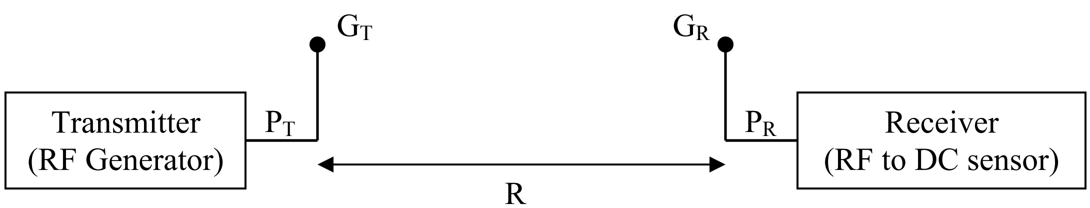


Figure 2-1. Basic system setup for wireless power transfer showing the antennas on both the transmitter and receiver, separated by radius distance R.

Shown below is the Friis equation describing RF signal strength received as a function of distance R, transmitted power P_t, and antenna gains G_t and G_r.

$$P_r := \left(\frac{\lambda}{4\pi \cdot R}\right)^2 \cdot G_t \cdot G_r \cdot P_t \qquad (2\text{-}1)$$

Such that, P_r is the power received, lambda is the wavelength of the radio signal, P_t is the power transmitted by the RF generator, G_t is the directivity gain of the antenna attached to the RF generator, and G_r is the directivity gain of the antenna attached to the RF to DC sensor. The receiver is also known as "RF to DC sensor", which is a description chosen by the author simply because the receiver could also be used as an RF radiation sensor for a particular band depending on the frequency of choice. By taking the 10Log( ) of the Friis Equation, we transform the power from units of mWatts to dBm, and thus we obtain the equation below.

$$P_r := P_t + 20\mathrm{Log}\left(\frac{c}{f}\right) - 20\mathrm{Log}(2\pi \cdot R) + G_t + G_r \tag{2-1}$$

In equation (3) we have replaced lambda with its equivalent value (c / f), such that c is the speed of light (299,792,458 meters / second), and f is the frequency of the RF signal in Hz. Also, P_r and P_t are described in units of dBm, G_t and G_r both have units of dB, and R has units of meters. Next, we plot the effect of frequency f on the power received P_r in terms of the distance between transmitter and receiver, such that P_t =0dBm, P_r=0dBm, G_t=0dB, and G_r=0dB as seen in figure 2-2. We notice from Figure 2-2 that power attenuation is less for lower frequencies. For example, at one meter and 2.45 GHz signal, the power received is about -40dBm from transmitter. While at 434MHz, the power received is about -25dBm. This means that at higher frequencies the signal suffers from more atmospheric absorption than lower frequencies. This effect is shown in figure 2-3. The question is now which frequency should be considered for wireless power transfer and at what cost? This question could be answered in many ways depending on the particular purpose of the application. Also one should consider all the complications and effects the frequency has on the system design. For example, the antenna size is characterized by the wavelength which is indirectly proportional to frequency. Therefore, as frequency decreases the antenna dimensions increase. This might be problem for self powered wireless sensors that have size constraints to meet, which would set a limit on the lowest choice of frequency. Therefore, due to size constraints, the author has chosen a higher frequency to enable wireless power transfer at 2.45GHz. Another advantage with operating at 2.45GHz is the high transmit power allowed at that frequency by the FCC. In addition, due to the popular

2.4GHz ISM band, components are readily available at relatively cheap prices.

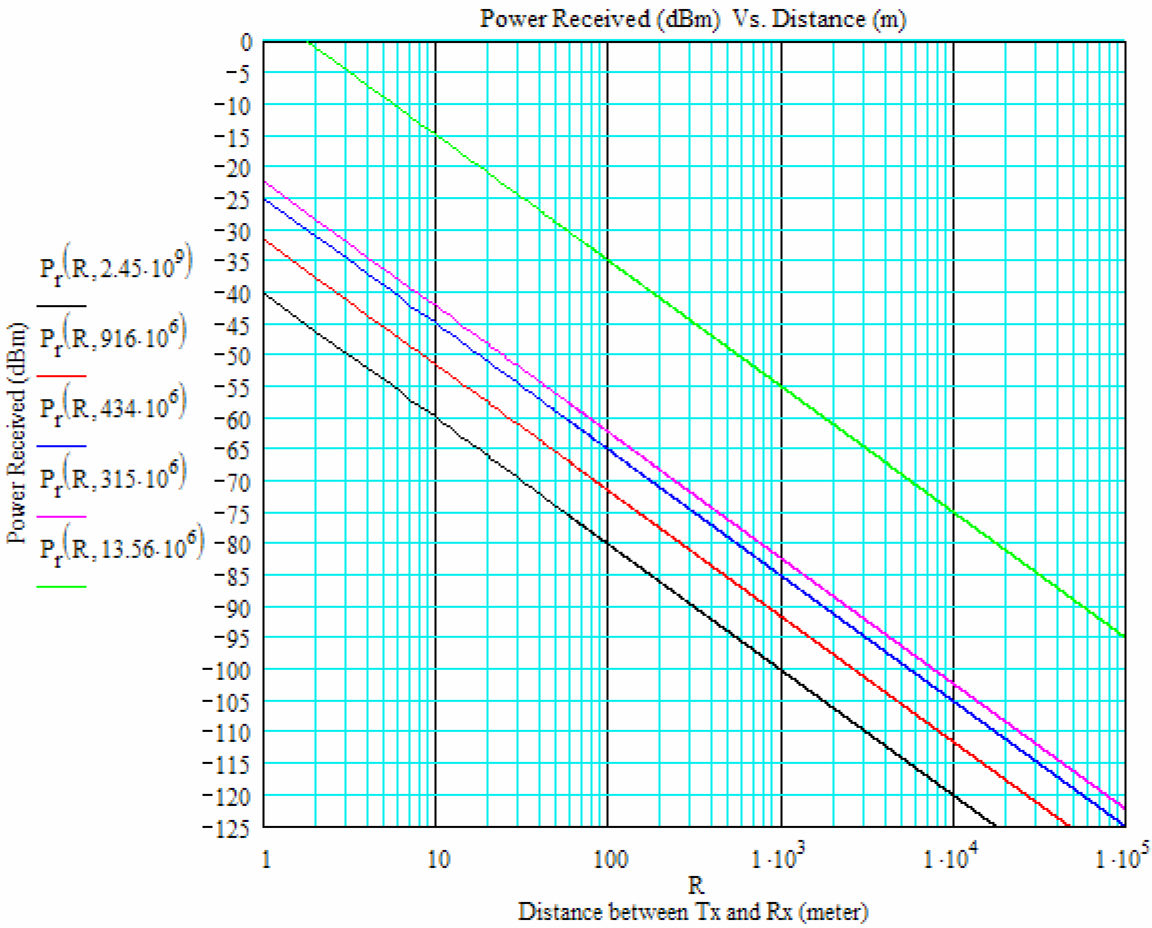


Figure 2-2. Received power (dBm) at the receiver vs. distance (meter) away from receiver, such that P_t =0dBm, P_r=0dBm, G_t=0dB, and G_r=0dB.

The main focus of wireless power transfer is to increase the received power P_r as much as possible, such that one would be able to operate at further distances. Looking at equation (2-1) we notice that we can play around with a number of variables that would allow us to achieve maximum power transfer, using the following methods:

- Increasing the transmitted power would be an obvious solution to increasing the received power. The concept is simple here, the more power you transmit, the more power you receive.

- By choosing antennas with higher directivity gain on both the transmitter and the receiver would increase the delivery of wireless power to the receiver by means of concentrating the radio beam in one direction.

- Another obvious solution for increasing received power would be to decrease the operating distance R, in other words, operate at a closer distance to the transmitter.
- By decreasing the signal frequency we would also be able to increase the received power at the receiver.

There are a number of complications for each of the above solutions. First, increasing the transmitted power means that the generator would have to use a higher power amplifier. High power amplifiers become more expensive and mostly sold to defense contractors. Also, high power amplifiers consume significant amount of power and usually have low efficiency 40% to 60%, which means that the rest of the power is transformed into heat. Therefore, heat-sinks and temperature sensors become a must in order not to destroy the expensive amplifier. The author was able to purchase a relatively cheap amplifier ZRL-3500 from minicircuits.com with maximum output power of +21dBm, which equivalent to an output power of 125mW. The ZRL-3500 is considered to be a relatively low power amplifier for the purpose wireless power transfer. However, ZRL-3500 is priced at $135 as compared to the ZVE-8G $1,095 with an output power of 1Watt, seen in figure 2-3.

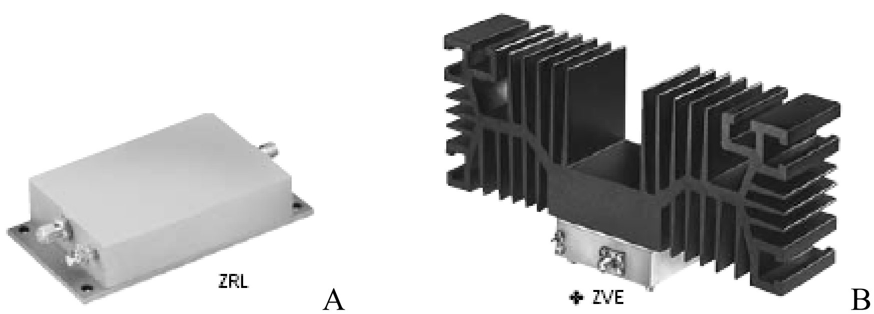


Figure 2-3. Medium power amplifiers. A) ZRL-3500 with output power 125mW B) ZVE-8G with output power 1Watt.

Second, the antenna of choice is usually dependant on the type of the application such that the antenna size could be a constraint. If the antenna size is not an issue, then one could design an antenna or choose to deploy antenna arrays with higher directivity gain at the cost of size and narrower radiation beam. Many other issues are involved with the choice of antennas, which is why there is a separate section that discusses the choice of antenna in more details.

Third, by brining the receiver closer to the transmitter, the signal received would be of higher power, which is a trivial solution. However, one might require the receiver to be at a minimum distance away from the transmitter for a particular application to be feasible. On the other hand, some other applications, requiring wireless power transfer, might not have a constraint on a set distance between transmitter and receiver, such as recharging a device that is completely submerged in water. One would remove the device from under water to recharge it without disassembling it, which might cause wear and tear and eventually might start leaking water. Therefore, distance between the device and transmitter could be as close as possible.

Finally, by decreasing the operating frequency one would be able to transmit power at further distances. However, there are many issues with choosing the right frequency for the right application, and in effect the frequency of choice would affect all other variables. For this reason, one would have to carefully choose the operating frequency of the system. In addition, many factors could affect the choice of frequency such as the Federal Communications Commission (FCC) regulation, Industrial Scientific and Medical (ISM) available bands, antenna size, and available resources. FCC has a set of available license free bands called the ISM bands seen in table 2-1 located at different parts of the frequency spectrum seen in figure 2-4. ISM bands are regulated by the FCC with allowed effective radiated power ERP, effective radiated isotropic power EIRP, active time period in transmit mode, interference, band width, and more. Table 2-1 shows the popular ISM bands available with the allowed output power transmission. It is important to note the wavelength of the available ISM band because antenna dimensions are dependent on it.

Table 2-1. Available ISM bands for wireless power transfer and applications

Frequency Band	Allowed output power, application
<125 KHz	Near Field Inductive RFID
1.95, 3.25, 8.2 MHz	Near Field Inductive theft tags
13.56 MHz	Near Field Inductive RFID, RC Toys
27 MHz	0.1 Watt ERP
138MHz	0.05 Watt ERP, Duty Cycle <1%
402 - 405	Medical Implants, 25uW ERP
433.05 - 434.79	25mWatt ERP, Duty Cycle <10%, RF controllers, and keyless entry
869.4 - 869.65 MHz	0.5Watt ERP, Duty Cycle <10%, RF controllers, and keyless entry
902 - 928 MHZ	4W EIRP 802.15.4 Zigbee, wireless modems, keyless entry, WPT
2400 - 2483.5 MHz	4W EIRP, 802.11b,g , 802.15.4 Zigbee, WPT
5725 - 5875 MHz	25mWatt EIRP 802.11a
24.00 - 24.25 GHz	0.1Watt EIRP, police radars
61.0 - 61.5 GHz	0.1Watt EIRP
122 - 123 GHz	0.1Watt EIRP
244 - 246 GHz	0.1Watt EIRP

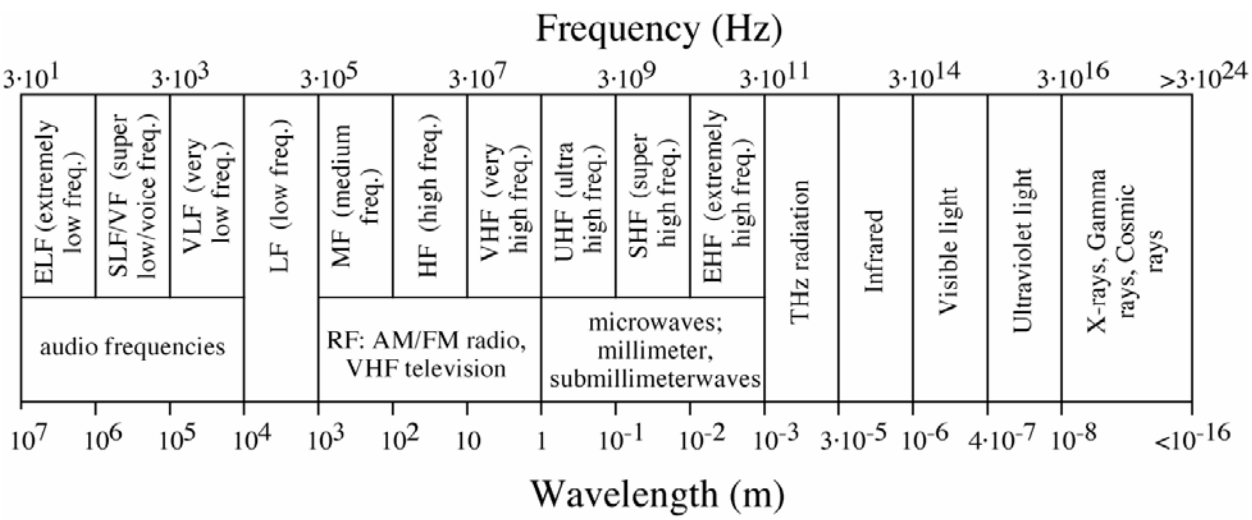


Figure 2-4. Electromagnetic frequency spectrum and associated wavelengths. Borrowed from "The RF and Microwave Handbook"

Antenna Types

Antennas are made in many different shapes, sizes, lengths, power ratings, and for different purposes. However, antennas are mainly chosen to fit the application rather than the other way around. Therefore, usually antennas are specially designed or specially ordered to fit the purpose of the application. There are, however, many commercially available antennas one can choose from, and due to the high availability of antennas, one could easily shop around for an antenna that would work for the application, or at least close enough. However, in a project such as wireless power transfer, we notice that the type of antenna is, indeed, an important factor of making power transfer feasible, which will be explained in later sections. Common popular antennas have relatively known attributes and aspects and are discussed below.

Popular antennas include the monopole "whip" antenna,[11] which has omni-directional radiation pattern, directivity gain typically about 3dBi, length equal to ¼ wave length on top of a ground plane, and 10% band width, as seen in Figure 2-5. They are cheap to produce, and get the job done fairly well in communication systems. Monopole antennas might work well for wireless power transfer applications requiring even power distribution in all directions. However, the low directivity gain and omni-directional radiation pattern might also consider this type of antenna unattractive for an application requiring high concentrated power that is focused in one direction towards an area of wireless sensor nodes. For a good performance monopole whip antennas, one could use a solid tinned copper wire anywhere from 14 to 18 AWG for good conductivity and low thermal loss.

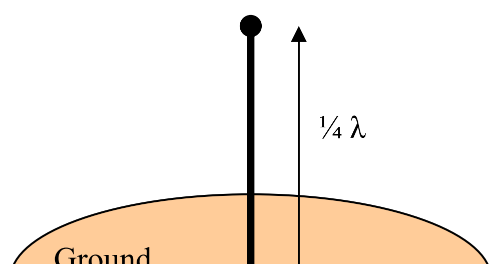


Figure 2-5. Monopole whip antenna on top of a ground plane

The dipole antenna is also another popular type of antenna with very similar properties to that of a monopole. The difference between a dipole and a monopole is that a dipole has twice the length ½ λ of that of a monopole. Also, another main difference is that a dipole can be fed differentially. A dipole can be turned into a monopole by replacing one of the dipoles into a ground place, essentially what is seen in Figure 2-5. Dipoles are just as attractive as monopoles for wireless power transfer, and application dependent. A good point to make about both monopoles and dipoles is that they are greatly affected by ground planes, and the only ground plane in the vicinity should be constructed as seen in Figure 2-5. Mounting a monopole or dipole around objects and metals greatly changes the characteristics of the antenna, such as impedance, radiation patter, and bandwidth. A dipole antenna is seen in Figure 2-6.

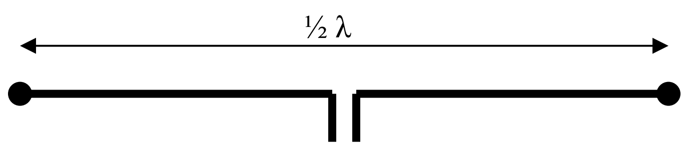


Figure 2-6. Dipole antenna on

Another similar antenna to the dipole and monopole is the helical antenna. A helical antenna operates in two complete different modes. The first mode is the normal mode, seen in Figure 2-7A, which is also know as the broadside helical antenna. The naming broadside comes from the omni-directional radiation pattern of the farfield. In normal mode, the main advantage is the short length of the antenna such that the windings of the antenna are shorter than the wavelength. In normal mode, the antenna acts as short monopole with omni-directional radiation pattern and poor gain. However, the small factor of a helical antenna makes it attractive to mobile devices such as mobile phones. For wireless power transfer, a normal mode helical antenna would not be good choice for RF generator due to its low gain. However, on the receiver side, the RF to DC sensor could be a good possible choice if the remote sensor is restraint to size. The second mode of operation is called the axial mode, which is also known as end-fire mode, as seen in Figure 2-7 B. The endfire mode naming comes from the high directivity gain of the antenna and concentration of radiation at the end of the helical structure. The biggest advantage of the endfire mode is the high high gain >10dB and its simplicity. The disadvantage is the larger dimensions. This form of antenna is found in satellite communication and long distance communication. As discussed in the previous section, higher directivity gain antennas can deliver more wireless power and increase operating distances. Therefore, axial mode antennas can be very useful and attractive for wireless power transfer applications especially on the generator side. However, an axial mode helical antenna might not be very practical for operation on the wireless sensor node due to size constraints. Therefore one could choose two different antennas for operation the large axial mode on the generator, and the compact normal mode on the wireless node.

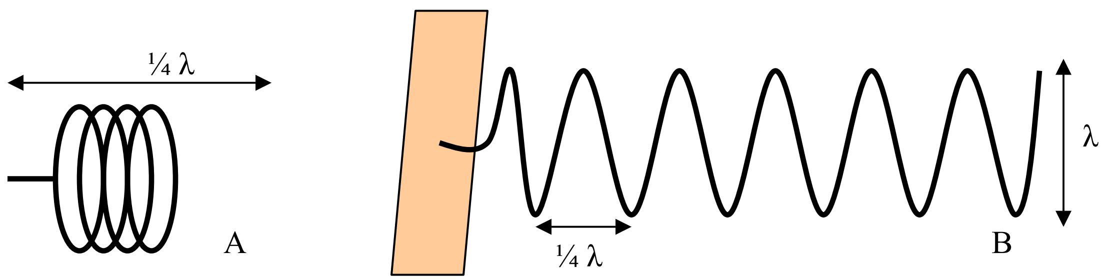


Figure 2-7. Helical antennas. A) Normal mode helical antenna B) Axial mode helical antenna

The Yaggi antenna is a worthy antenna to mention due to its high directivity gain >10dB. It was first discovered by a Japanese professor during the world war two, and was named after him. Yaggi antennas are also very attractive for wireless power transfer for the same reason described in the axial mode helical antenna.

There are so many different types of antennas one can choose from, however, the author is mainly interested in printed patch antennas, which will be described in details in the next section.

Printed Patch Antenna

The patch antenna was chosen for this project due to the many advantages patch antennas have over others. Listed below are the basic advantages of using a patch antenna.

- Cheap fabrication costs over other antennas, such that it does not require any components other than etching a copper trace on a printed circuit board (PCB).

- Patch antennas have flat surface which gives them a low profile compared to other antennas like a monopole.
- Due to their flat surface, patch antennas are less susceptible to break or wear and tear.
- Patch antennas can be mounted on top of metals without affecting antenna impedance.
- Readily available tools can simulate a patch antenna very easily.
- Patch antennas can be combined in arrays to increase directivity gain.
- Patch antennas have narrow bandwidth which acts as a natural band pass filter.

The simplest form of a patch antenna is composed of three levels, seen in figure 2-8 A. The top layer is the copper patch of length L and width W. The resonant frequency is affected by the length L, such that L is approximately equal to ½ λ before fringing. Therefore, the wavelength is initially equally to twice the length before fringing. The middle layer is the dielectric material, which is the fiber glass material known as FR4 with relative dielectric constant (ε_r) ranging from 4.2 to 4.7 and thickness h, as seen in figure 2.8 B. The third layer is the bottom ground layer. The simulation software used in this project to model the patch antenna is Ansoft Designeer©, which uses dielectric material average for FR4 equal to 4.4 value.

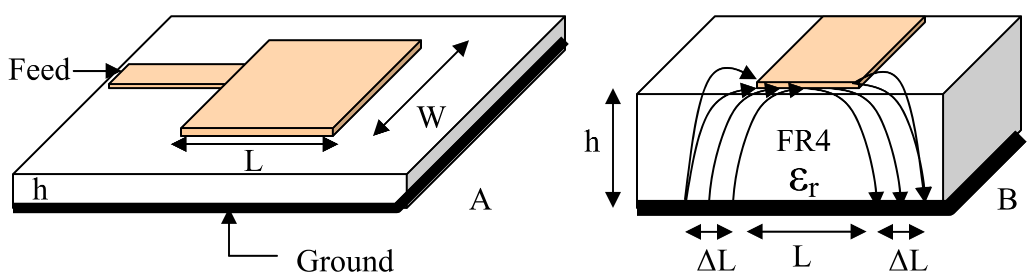


Figure 2-8. Patch antenna. A) Square patch antenna on a printed circuit board B) Cross section of board showing fringing effect.

Patch antennas have the same characteristics as a transmission line, and are modeled the same way as a transmission line. Radiation occurs from the fringing fields, which extend the actually dimensions of the patch by ΔL,[12] as seen in figure 2-8 B. FR4 material was chosen for this project due to its low cost and availability. Other dielectric materials can be used for patch antennas that would actually enhance many features of the antenna.[13,14] However, it would cost significantly more, which is inconvenient for a large number of self powered wireless sensor nodes.

Mathematical Description

This section describes the mathematical model of a transmission line used as a patch antenna. A patch antenna is nothing but a transmission line modeled to resonate at a high frequency. Since this patch antenna will be used for self powered wireless sensors, the dimensions will have to be fairly small to fit in as many situations as possible, which is done one way by increasing frequency. However, by increasing frequency, the signal suffers more attenuation. Therefore, the author chose to operate at the frequency 2.45GHz, which is a popular ISM band used for WLAN, thus, components are more readily available than other frequencies.

$$\lambda := \frac{c}{f \cdot \sqrt{\varepsilon_r}} \tag{2-2}$$

In equation (2-2), λ is the wave length in the dielectric material, f is the frequency (2.45GHz), c is the speed of light (299,792,458 meters / second), and ε_r is the dielectric constant of the FR4 material (4.4). From equation (2-2), we get a rough estimate of the wavelength λ=5.834 cm, such that ½ λ is equal to L which is equal to 2.917cm. However, we need a better estimate than that.

$$w(k) := k \cdot L \tag{2-3}$$

In equation (2-3) w is the width of the patch, L is the length of the patch before fringing, and k is a constant coefficient representing the ratio of the width to length, such that k is equal to one for a square patch. In addition, the notation w(k) represents the width of the antenna as a function of k.

$$u(k) := \frac{w(k)}{h} \tag{2-4}$$

In equation (2-4), u is the ratio of width w to the height h (1.5mm) of the dielectric material. For a square patch, u(k) is equal to 19.455.

$$\varepsilon_{re}(k) := \left(\frac{\varepsilon_r + 1}{2}\right) + \left(\frac{\varepsilon_r - 1}{2}\right)\left(1 + \frac{12}{u(k)}\right)^{-0.5} \tag{2-5}$$

In equation (2-5), ε_{re} is the effective relative dielectric constant. For a square patch, ε_{re} is equal to 4.037. Notice that ε_{re} is slightly lower than ε_r because the fringing fields around the patch are not completely confined in the dielectric material.

$$\Delta L(k) := 0.412 \cdot h \cdot \left(\frac{\varepsilon_{re}(k) + 0.3}{\varepsilon_{re}(k) - 0.258}\right) \cdot \left(\frac{u(k) + 0.264}{u(k) + 0.813}\right) \tag{2-6}$$

In equation (2-6), ΔL is the added virtual length to the actual length of the microstrip patch antenna, due to fringing effect. For a square patch, ΔL is equal to 0.7mm, such that the total length is now L + 2ΔL, or L + 1.4mm. This is a significant change for a high frequency patch that is characterized by narrow bandwidth, and this is why we can not just estimate the length from equation (2-2).

$$f_o(k) := \frac{c}{2 \cdot (L + 2\Delta L(k)) \cdot \sqrt{\varepsilon_{re}(k)}} \tag{2-7}$$

In equation (2-7), f_o is the resonant frequency of the patch antenna as a function of width to length k, and after the fringing effect. By plotting f_o in terms of k, we can solve for k that would produce a resonant frequency equal to 2.45GHz, as seen in figure 2-9.

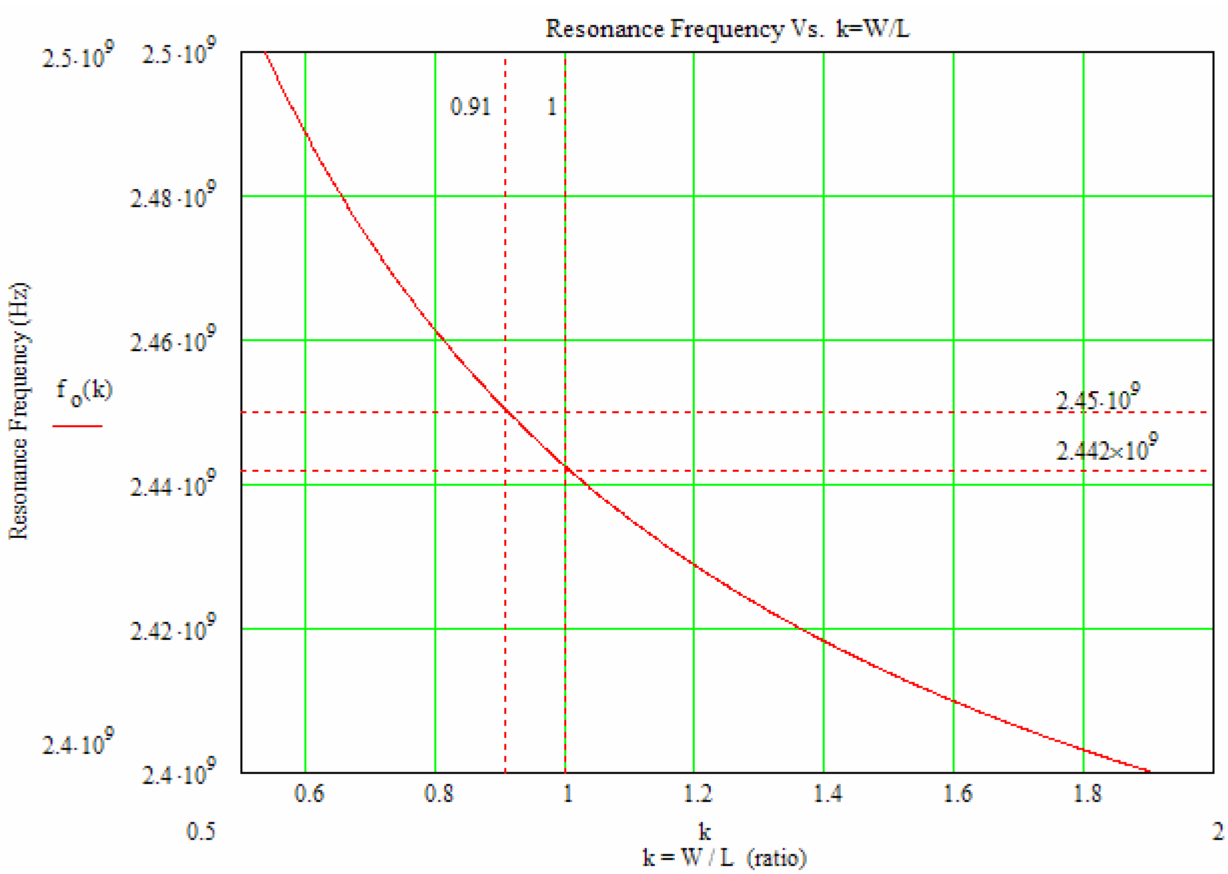


Figure 2-9. Effective length of patch after fringing effect Vs. ratio of width to length k.

We notice from figure 2-9 that the resonant frequency 2.45GHz occurs at a k value equal to 0.91, which is slight less that a square patch.

$$L_e(k) := \frac{c}{\left(2 \cdot f \cdot \sqrt{\varepsilon_{re}(k)}\right)} - 2 \cdot \Delta L(k) \tag{2-8}$$

In equation (2-8), L_e is the effective length after fringing, f is the resonant frequency. By graphing L_e as a function of k, we find the resonant length L that corresponds to a frequency of 2.45GHz, as seen in Figure 2.9 below.

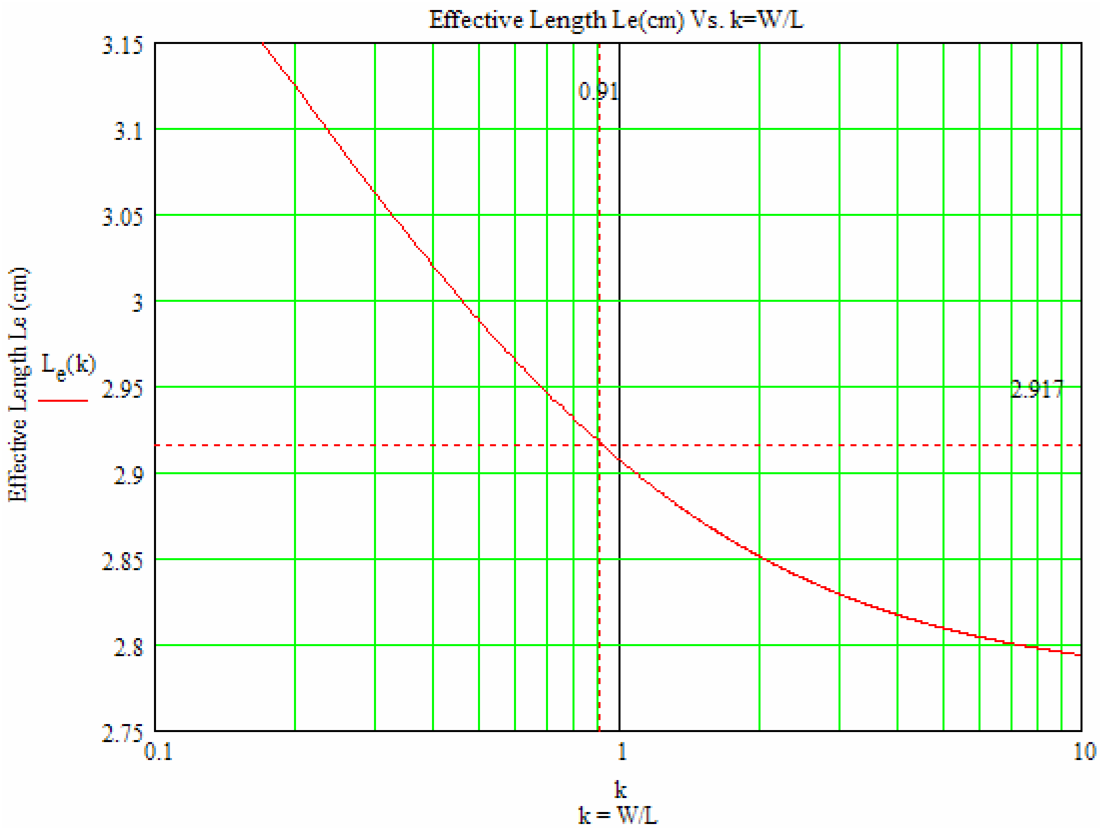


Figure 2-10. Effective length of patch after fringing effect Vs. ratio of width to length k.

From figure 2-10 we notice that for a resonant frequency 2.45GHz, given k is 0.91 from Figure 2-9, we find that the effective length of the patch antenna is 2.917cm.

From equation (2-3) we find that the width of the antenna is about 2.654cm.

Antenna Simulation Results

There are many software that will do electromagnetic simulation based on method of momentum (MoM). The author had chosen two softwares (PCAAD© and Ansoft Designer©) for simulation to make sure that the two results were similar and consistent with the mathematical model. The first software PCAAD uses regular mathematical equations to calculate antenna characteristics as opposed to Ansoft Designer© that simulates the electromagnetic field to find the characteristics of the patch antenna. Seen in figure 2-11 is the simulation results for a patch antenna using PCAAD©.

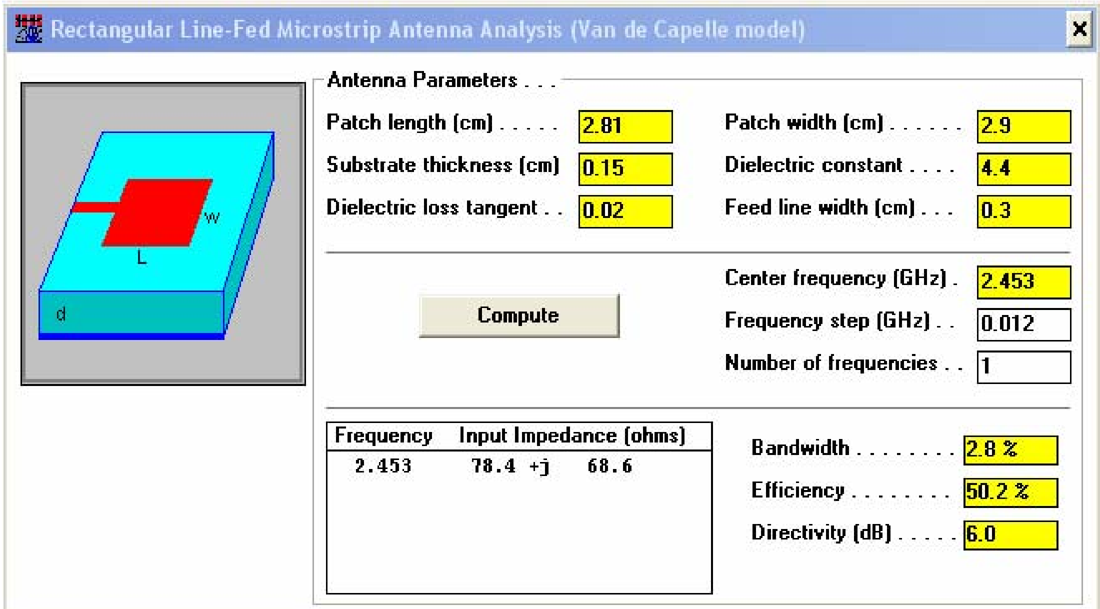


Figure 2-11. Patch antenna simulation using PCAAD©.

In figure 2-11 the author varied the antenna dimensions length and width to obtain a resonant frequency as close to 2.45GHz as possible. The length found was 2.81cm and the width being 2.9, which is close enough to the mathematical model described previously. We notice that the bandwidth is only 2.8%, efficiency is about 50.2% and gain is 6.0dB. In addition, the magnitude of the input impedance of the feed line is about 104Ω, which would need to be matched to standard 50Ω.

Using Ansoft Designer© is not as straight forward as PCAAD, however, it allows for much more in depth analysis of the patch antenna. Seen in figure 2-12 is the layout of the patch antenna in Ansoft Designer after optimizing dimensions 50Ω match.

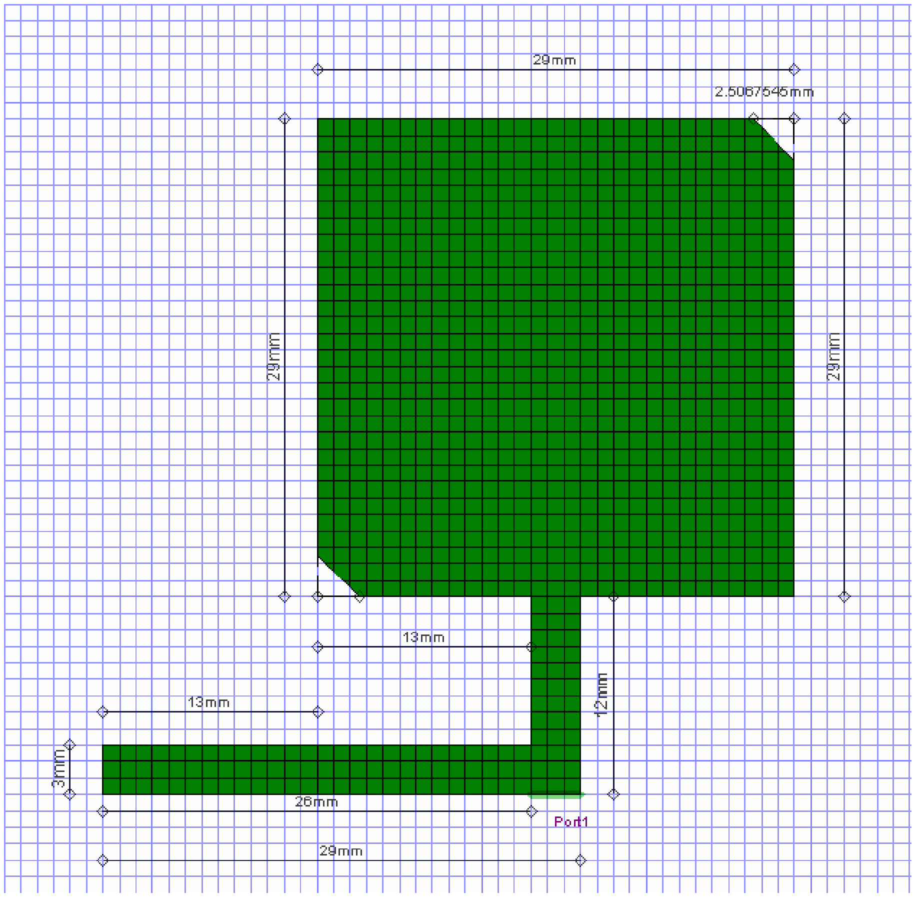


Figure 2-12. Square patch antenna using Ansoft Designer, with given dimensions, and output matched to standard 50Ω using stub stripline of length 12mm by 29mm.

Seen in figure 2-13 is the return loss S11 (dB) in terms of the swept frequency F(GHz). Return loss basically shows at what frequency the 50Ω is happening. The lower the return loss in dB, the better the match is. We notice that the return loss at 2.45GHz (pointer 1) is about -24.7dB, and the -10 dB bandwidth extends from about 2.4GHz to 2.48GHz, which is really good match for the 2.4GHz ISM band. One would try to match at the center of the 2,4GHz ISM band because after fabrication of the patch antenna, there will definitely be process variations, such that the dielectric material would probably be different than 4.4, or thickness would be different, and so on.

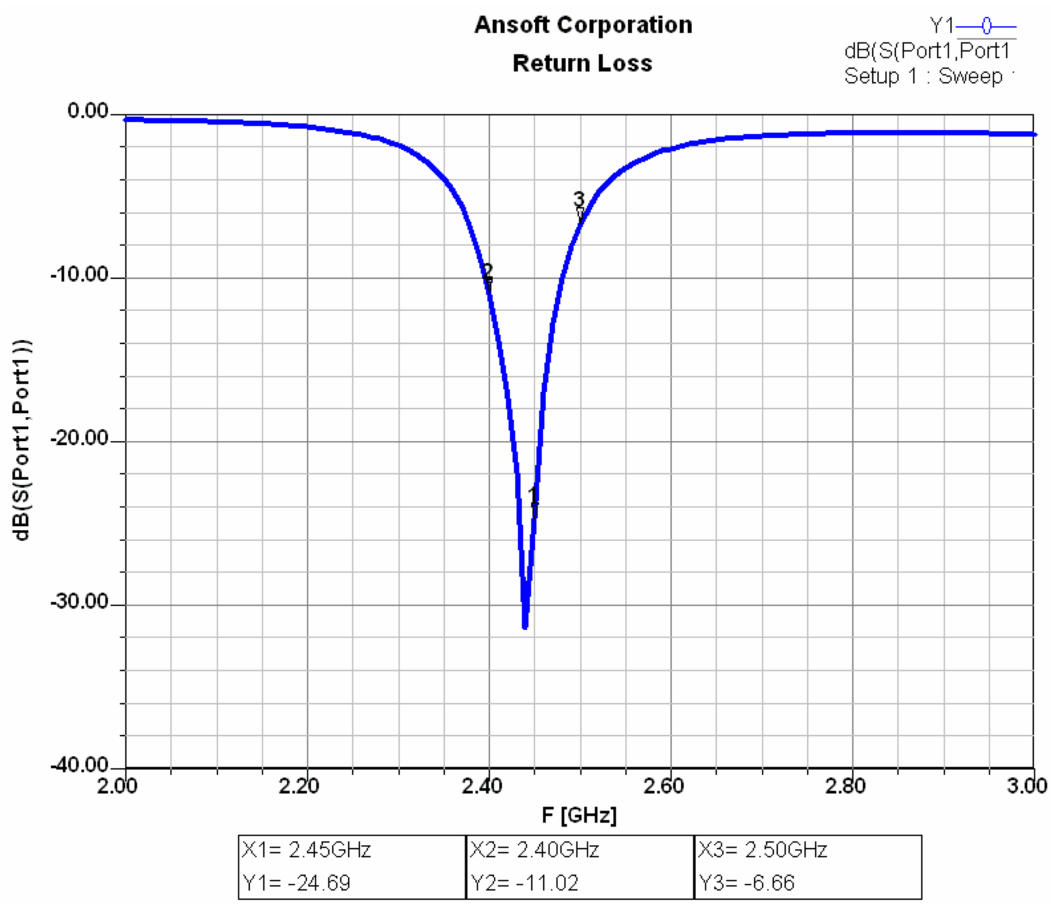


Figure 2-13. Return loss S11 (dB) in terms of the swept frequency F(GHz), matched at 2.45GHz.

The gain of this antenna is shown in Figure 2-14, which has good distribution of gain centered at the operating frequency 2.45GHz. As discussed previously, the gain of the antenna is a really important feature of wireless power transfer and self powered wireless sensor nodes. The gain obtained from the antenna at the cost of directivity is almost considered free power, since you are not paying for it with current consumption as the case with the power amplifier. Therefore, one could cascade an array of antennas to increase the gain of the system. However, the main disadvantage of antenna arrays is the larger size, which doubles for every 3 dB of gain.

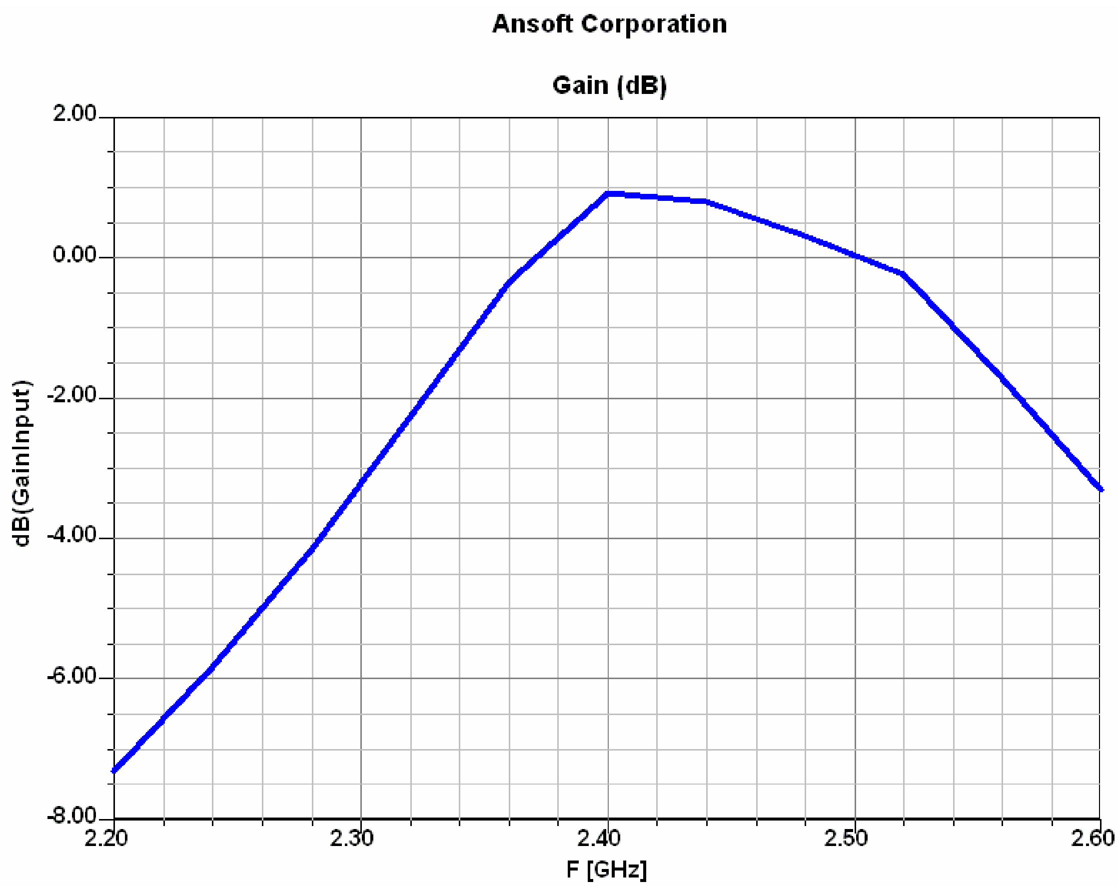


Figure 2-14. Antenna gain of patch antenna (dB) in terms of the swept frequency F(GHz).

The patch antenna was fabricated using a home-made etching technique using ferric chloride and blue press-n-peel sheets as seen in figure 2-15. The dimensions of the edges were not as accurate as simulated, and the antenna went through corrosion by time. Therefore, the performance of the antenna was not satisfactory, especially for a sensitive application as remotely powered wireless sensors. The matching greatly affects efficiency and gain, home-brewed antennas for this project produce unacceptable results.

Figure 2-15. Fabricated 2.45GHz antenna using homebrewed etching technique.

Another antenna was simulated with a different matching technique, and was sent to a professional fabrication company PCBexpress© for accurate fabrication results. The antenna was also simulated using Ansoft Designer and optimized to match at 2.45GHz, as seen in figure 2-16.

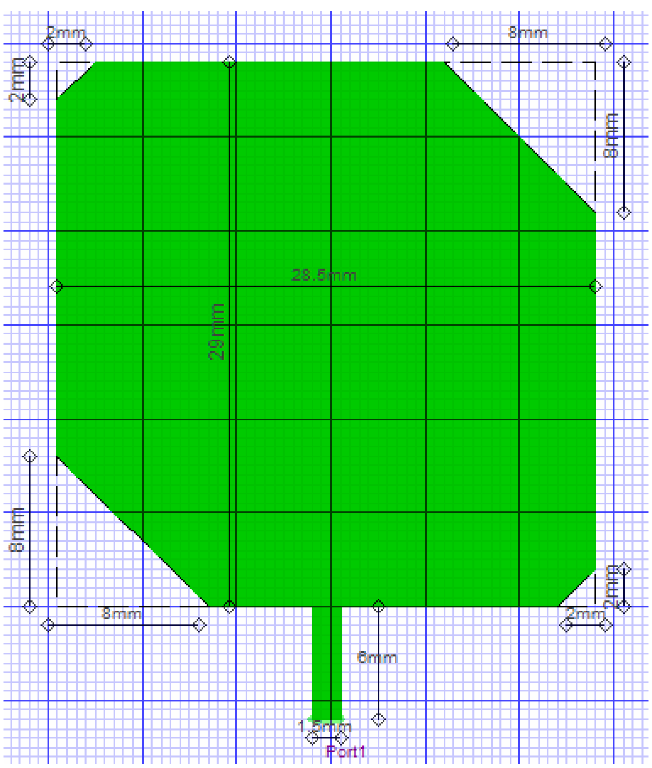


Figure 2-16. Square patch antenna using Ansoft Designer matched to 50Ω at 2.45GHz.

Seen in figure 2-17 is the return loss S11 (dB) in terms of the swept frequency F(GHz). We notice that the return loss at 2.45GHz (pointer 1) is -25.2dB, which is better than the previous version, and the -10 dB bandwidth extends from about 2.42GHz to 2.48GHz.

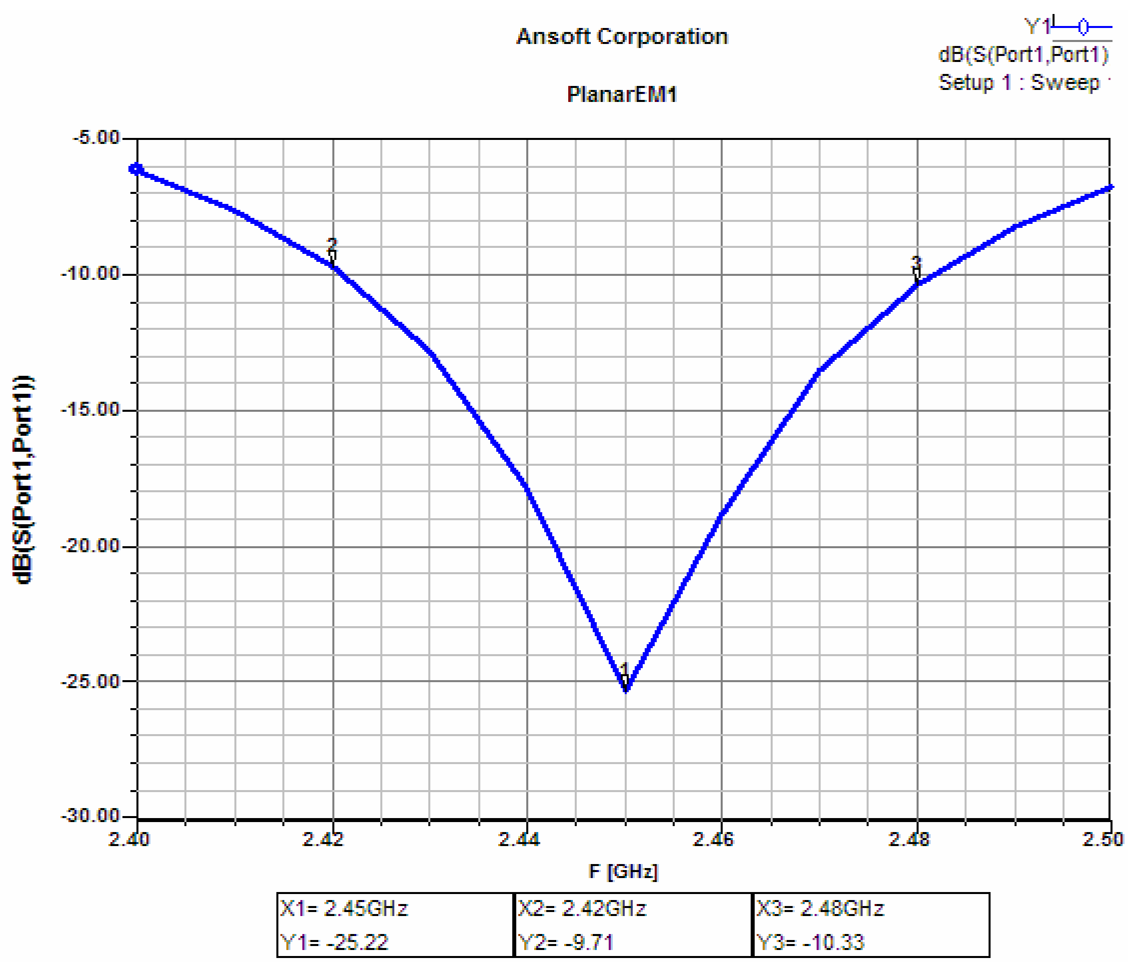


Figure 2-17. Return loss S11 (dB) in terms of the swept frequency F(GHz), matched at 2.45GHz.

The gain of this antenna is shown in Figure 2-18, and has a better gain distribution centered at 2.45GHz than the previous antenna.

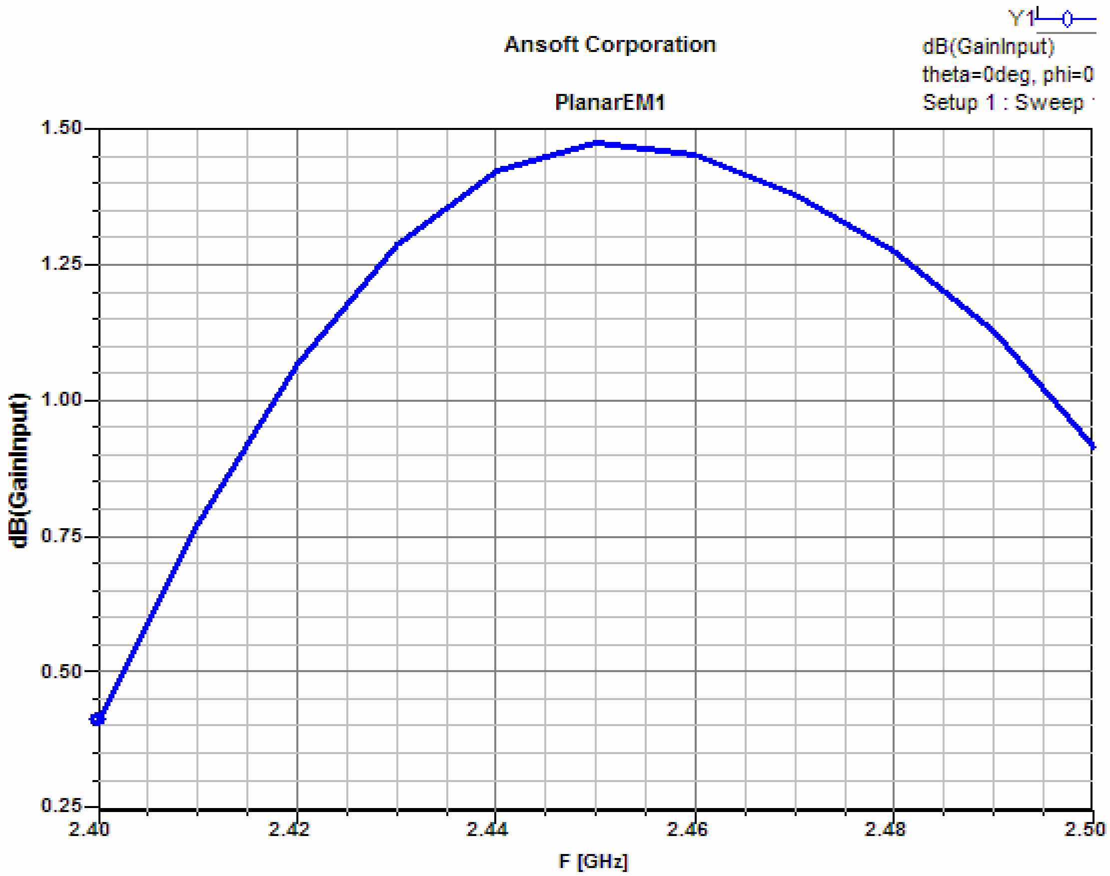


Figure 2-18. Antenna gain of patch antenna (dB) in terms of the swept frequency F(GHz). Gain is about 1.4dB or 3.5dBi.

This patch antenna was sent to a professional PCB fabrication company PCBexpress© as opposed to the previous antenna which fabricated in lab. The dimensions of the edges were precisely as designed and very close simulation results. In addition, the antenna has a green silkscreen which prevents the copper from corrosion.

Figure 2-19. Patch antenna for 2.45GHz ISM band, with 3.5dBi gain. Fabricated at PCBexpress.

This patch antenna can be used for both the remotely powered sensor node, and the RF signal generator. However, one might consider using a higher antenna gain on the RF generator since size constraint would not be an issue. Therefore, for the 2.45GHz RF generator, an array antenna was developed similar to the previous antenna, but has twice the gain. The antenna is composed of two cascaded patches as seen in Figure 2-20.

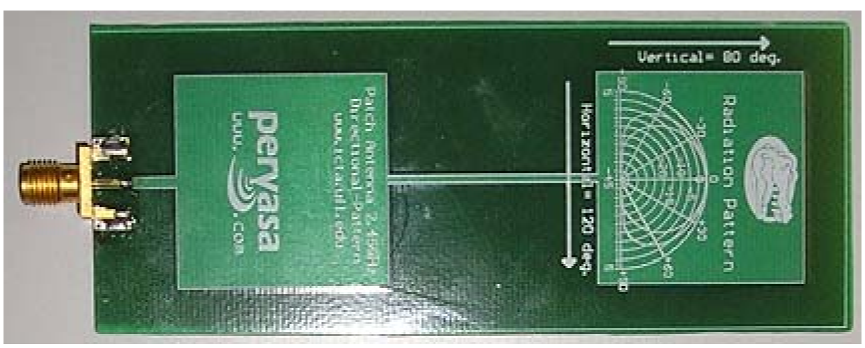


Figure 2-20. Patch antenna array, matched at 2.45GHz, with gain equal to 6dBi.

The higher the gain the RF generator has, the more power is delivered to the wireless node. Therefore, one can purchase an already made antenna array that has a larger bandwidth, and higher gain than a patch antenna fabricated on a FR4 board.

Power Delivery

Using the fabricated 3.5dBi 2.45GHz patch antenna in figure 2-19 on the wireless sensor node, and the 6dBi 2.45GHz antenna at the RF generator, with transmitter output power equal to that of the amplifier in figure 2-3 A, we revisit equation (3) and figure 2-2. In equation (3), P_t is set equal to +21dBm, which is the maximum output power of the ZRL-3500. G_t is set equal to 4dB (not dBi), which is the directivity gain of the patch antenna array located on the RF generator seen in figure 2-20. Gr is set equal to 1.5dB, which is the directivity gain of the patch antenna located on self powered wireless sensor node. Therefore, we obtain the equation below.

$$P_r(R,f) := 20\cdot\log\left(\frac{c}{f}\right) - 20\cdot\log(4\cdot\pi\cdot R) + 26.5 \tag{2-9}$$

In equation (2-9), P_t, G_t, and G_r add up to 26.5dB. Therefore, the received power is 26.5dB higher than that of figure 2-2. Notice in figure 2-21 how all the graphs have shifted up 26.5dB.

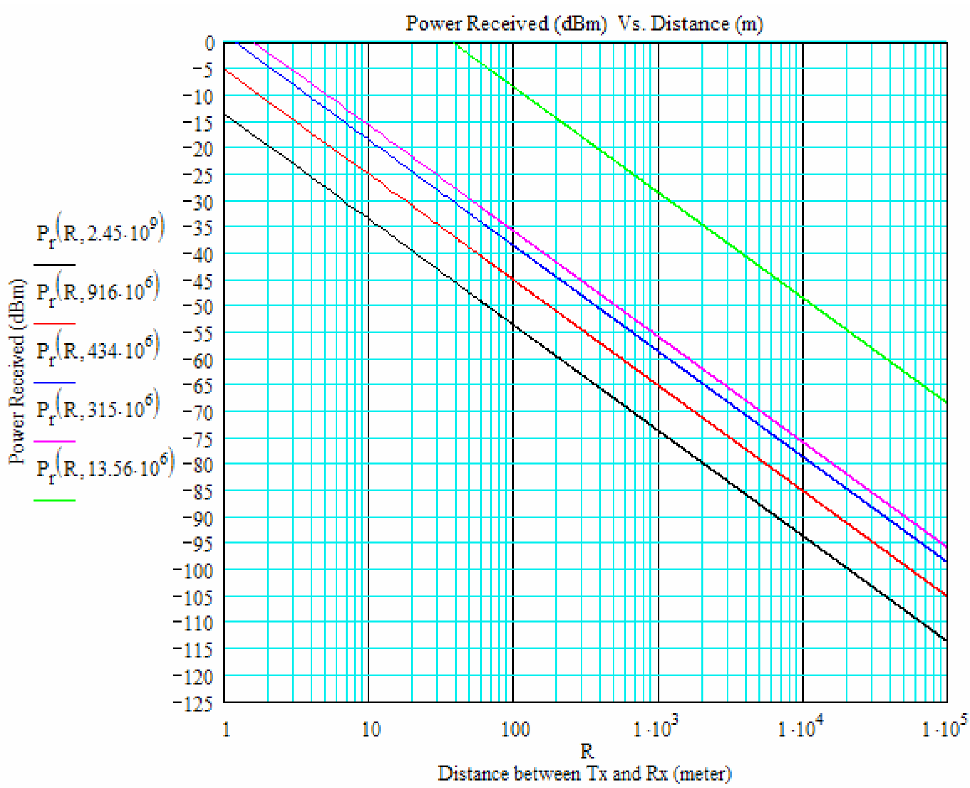


Figure 2-21. Improved wireless power received with additional 26.5dB gain.

Commercially Available Antennas for WPT

Even though we have made a significant 26.5dB improvement, the theoretical received power at one meter is only -15dBm, which is not enough power for wireless power delivery. Therefore, we would need to increase the power delivered in any means possible. This means that a higher antenna gain at the transmitter is required. HyperLinkTech sell HG2414P patch antenna array for WLAN use with high antenna gain equal to 14 dBi. This antenna would be used on the RF generator due to its large size. HyperLinkTech also offers Yaggi antennas and patch antenna arrays that have gains > 10dBi, and are readily available for customer purchase, seen in Figure 2-21 A through E.

Figure 2-22. High gain commercially available antennas suitable for remote power transfer

Unfortunately, for the remotely powered wireless sensors, it is difficult to increase antenna size due to size constraint. However, by using recent technology as chip antennas, one can cascade high gain chip antennas while maintaining similar node dimensions. Therefore, the author had found the following chip antenna 2450AT45A100 suitable for the purpose of reducing the size of remotely powered wireless sensors, as seen in figure 2-22 A.

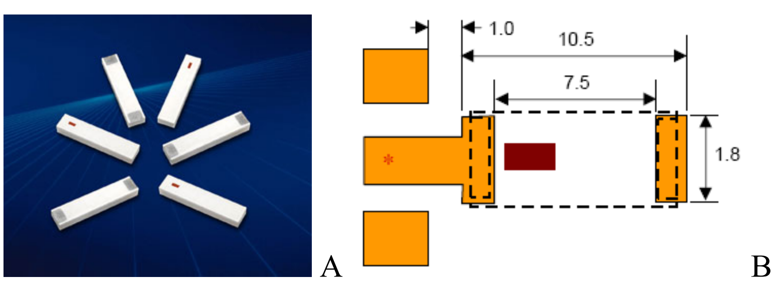


Figure 2-23. Commercial chip antenna. A) Chip Antenna B) Dimensions of Chip antenna. Borrowed from JohansonTechnology website.

The chip antenna is manufactured by JohansonTechnology© with average gain equal to 1dBi, and maximum gain equal to 3dBi. The chip antenna is weakly matched to 50Ω at 2.45GHz, with a return loss equal to -14dB. However, the company also offers a matching circuit for better bandwidth(BW), gain, and return loss seen in figure 2-24 A, return loss figure 2-24 B.

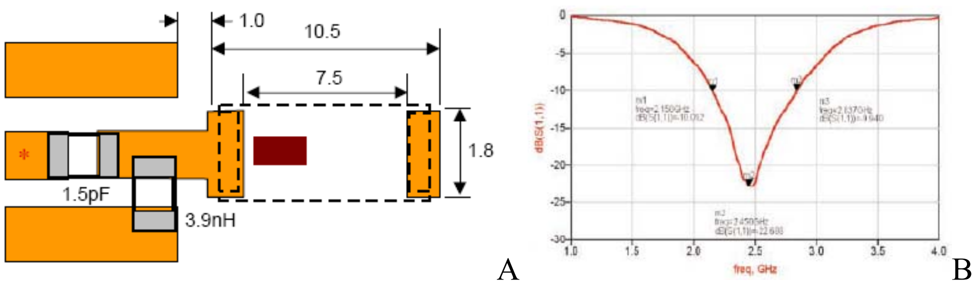


Figure 2-23. A) Matching network B) Return loss S11(-22.6dB), and BW (600MHz)

Attenuation

The main reason for the attenuation of the wireless signal in air is due to the atmospheric absorption due to the presence of water particles in the air. As seen in figure 2-24, the atmospheric absorption is very high for 2.4GHz signal. This is the main disadvantage of selecting a 2.4GHz frequency for wireless power transfer. However, it is a great advantage for microwave ovens. As a matter of fact, it is the only reason why microwave ovens operate at 2.4GHz because water absorption is very high at that frequency, which means that food containing water would cook very fast. However, one must not think that WPT is harmful for humans, for two simple reasons. First, the ouput power in its best is limited to 4 watts EIRP, which is well below that of a microwave oven 1000watts. Second, in order to cause any kind of severe harm to humans the wavelength would have to be small enough to resonate with the length of human cells and DNAs such as that of X-rays. A quick note to mention is that the radio signal produced by the microwave oven (2.4GHz) is not even a microwave scale wave. The wavelength of a 2.4GHz frequency is actually about 12.2 cm. However, it is called microwave because looking at table 2-1, you can see that it lies in the broad microwave spectrum.

Multipath fading is also another reason for signal attenuation especially if the wireless power transfer is being done indoors. Multipath fading could either by constructive or destructive. However, in most case it is usually destructive due to the signal bouncing off multiple walls back and forth. Multipath fading will reduce the amount of power transferred to the remotely powered wireless sensor and also cause communication errors in the channel. An open space would be a better environment for wireless power transfer. As a matter of fact, the best place for WPT is actually outer space where there is no water or oxygen absorption to attenuate the radio signal transmitted, but perhaps more interference and noise is the side effect. In addition, Friis equation mostly represents a theoretical received power, in reality one should only consider about ¼ of the theoretical distance calculated, and this is being optimistic.

Feasibility

WPT would be feasible and useful with the availability of high power amplifiers starting with at least a one watt output power, and a high gain antenna in the order of 14dBi and higher. Also, areas with less humidity would be better environment for deploying remotely powered wireless sensors. This is the reason why Nicolas Tesla decided to build his Tesla coil tower high above sea level where humidity is much less. The author's best case scenario is the available +21dBm power amplifier, 14dBi Antenna and 3dBi chip antenna. This gives a total system gain of about 34dB, which is about -7dBm theoretical received power according to equation (3). In the worse case scenario, the antenna would only have about 8dB gain, transmitter would transmit about 18dBm, and receiver chip antenna would be 0dB, such that the total system gain is now +26dBm instead, which is more of an expected gain rather than a worse case. Referring back to equation (3) a +26dBm system gain is equivalent to about -15dBm received power. However, according to the author, in order to receive a decent amount of power to work with, one would need a minimum of 0dBm, and preferably greater than +10dBm. Assuming a high power amplifier such as a 1Watt or a +30dBm, with a high gain antenna about +22dBi on the transmitter and a 2 dBi chip antenna on the wireless sensor node, one can achieve about +50dBm of system gain from transmitter to receiver. This much power would transfer a theoretical +10dBm power to the wireless sensor node. However, a more practical received power would be to subtract 6dB, which is equivalent to dividing the distance by 4, giving a +4dBm of received power, which is still a good amount of power to work with. This would allow a wireless sensor node to receive wireless power and operate comfortably about 2 meters away from transmitter. Two meters does not sound like much of a distance, however, it’s a good starting point for remotely powered wireless sensors.

CHAPTER 3
WIRELESS POWER TRANSFER SYSTEM DESIGN

System Level Design

The system level of remotely powered wireless sensors is mainly divided into two parts. The first part is the RF generator and the second is the self powered wireless sensor. The RF generator is responsible to generate the high power radio signal and radiate it towards the wireless sensor. Power for the RF generator is considered to be abundant and constantly available. ON the other hand, the wireless sensor maintains a low power state and energy conservation via energy management system and low power software selectable states. The wireless sensor has the responsibility to detect the high power signal and rectify it into usable DC energy, stored locally for future use. Figure 3-1 shows the system level design of the system.

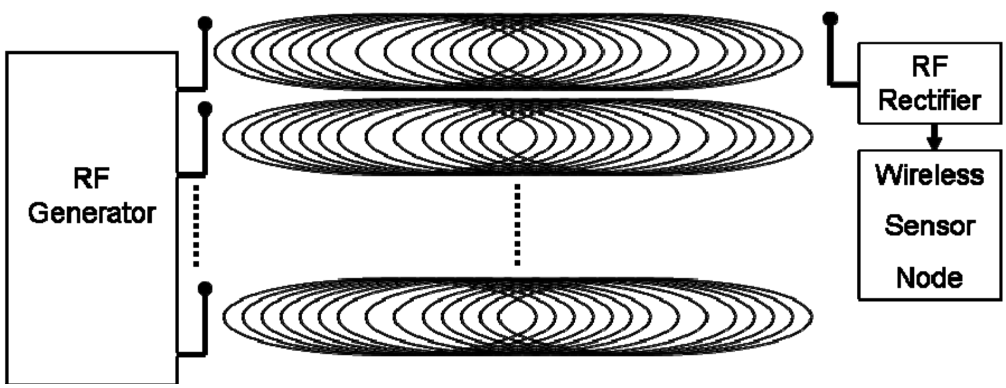


Figure 3-1. Top level system design.

In figure 3-1, the RF generator shown to the left generates the high power RF signal and propagates it in the direction of the wireless sensor. Multiple antenna arrays can be used to propagate a concentrated RF signal in the general direction of sensors in the vicinity of the RF generator. A splitter can be used to split the RF signal into multiple sources at the cost of less signal power. The middle part of figure 3-1 is the concentrated RF signal propagating in air, and on the right is the remotely powered wireless sensor detecting and rectifying the RF signal.

System Design Constraints

The system constraints of the RF generator are far more flexible than that of the remotely powered wireless sensor. The RF generator is considered to have infinite amount of available power, yet it would also have the capability to operate with a large battery if required. The current consumption of the RF generator is highly dominated by the RF power amplifier. The ZRL-3500 consumes about 575mA at +12volts DC input.

The remotely powered wireless sensor has far more constraints than the RF generator. First of all the wireless sensor has to be optimized for lowest power consumption possible. The author recommends a total power consumption less than 1mWatt in active wireless transmission state, and less than 1uWatts in sleep mode. The remotely powered sensor has to be as small as possible in order to be adopted in any application and in any size limited environment. Therefore, the wireless sensor node would use a chip antenna instead of a patch to further reduce dimensions. Ultra capacitors can also be used on the wireless sensor nodes due to their smaller size and larger capacity. However, ultra capacitors have longer charging time due to their large capacity, which would be a problem for charging. Surface mount components are advisable for the wireless sensor node, and perhaps a final integrated ASIC would even further drop power consumption and size.

Range Constraints

Due to the main size constraint of the remotely powered wireless sensor, the patch antenna would have to be replaced with the chip antenna. This drops efficiency due to impedance mismatch between chip antenna and RF to DC sensor. For this reason, the total power received would be less, and thus the range would be reduced. For a typical scenario, the RF generator is capable of outputting a typical +19dBm to +21dBm of output power, transmitter antenna has a gain of about +8dBi to +12 dBi, and wireless sensor node has about -1dBi to +1dBi gain. Therefore, the total system gain ranges from +26dB to +32dB. According to equation (3), an average of +30dB system gain gives about -10dB of received power at one meter, and about +0dBm at 20cm away. As mentioned in previous sections, usable power would have to be at least +0dBm. Therefore, the range at the given constraints is limited to about 20cm. However, with a higher power amplifier, this could be easily extended.

Cost Constraints

The RF generator is perhaps the most expensive unit in the design. However, there is only one RF generator in the system, so it is not a major issue in the system. The author's RF generator cost was about $400 in parts. However, this cost can easily increase with the replacement of the RF amplifier with a higher gain one. Amplifiers in the 1Watt range can easily start about $1,000 and up to couple thousand dollars for military RF amplifiers. The wireless sensor cost is much less than the RF generator, costing about $25 dollars with quantities greater than a hundred. The author did not address issues with reducing cost, but monitored the increase in cost as the project developed. In general, since wireless power transfer and remotely powered wireless sensors is not as popular yet, components such as power amplifiers are still expensive and range in thousands of dollars. However, in the future, the author believes as the concept picks up in the future, special designed high power amplifiers could be produced for cheaper prices.

Radio Frequency Generator

The RF generator is one of the two legs of the system. The RF generator design would either make or break the system. The system is mainly composed of a signal generator block, a high power amplifier, and a baseband processor. In addition, a large graphical LCD display is located on top of the RF generator for visual feedback. Figure 3-2 shows the back side of the RF generator.

Figure 3-2. Back-side view of RF generator.

Seen in figure 3-2 is the backside of the RF generator. Displayed are two fans mounted on top of a heat-sink. A temperature sensor monitors the amplifier’s temperature and turns on the two fans when the temperature goes over a preset limit. The fans are tied down with tie-straps to reduce vibration. Also see in figure 3-2 are 5 LEDs on the top left side. Four in which are yellow and correspond to up, down, left, and right, and one LED is green and displays a green color. These buttons are used for user input to navigate the menu on the LCD display. In figure 3-3, the front of the RF generator is displayed.

Figure 3-3. Front-side view of RF generator.

Seen in figure 3-3 is the frontside view of the RF generator. First, there are two DC input power supplies with labels “uC-DC +12-6V” for the microcontroller power supply, and “RF-DC +12V” is used for for the RF power supplied to amplifier and signal generator. Second, there is a RS232 serial port, that would communicate locally with the microcontroller. Third, there is a microcontroller programmer “uC Prog” used to flash the microcontroller program memory. Finally, there is the high power RF output port seen in the top right corner with an SMA extended cable.

Seen in figure 3-4 is the right side view of the RF generator. There are two turn knobs which are the RF tuner, and the LCD contrast tuner. The RF tuner when turned will adjust the the RF frequency. The frequency can be adjusted from 2165MHz to 2650MHz, which in terms covers the required 2.45GHz range. The other knob adjusts the contrast of the display for better user view.

Figure 3-4. Side view of RF generator, displaying tuning knobs.

Radio Frequency Signal Source

The main source of the RF generator is the local oscillator purchased from MiniCircuits© with model number ZX95-2650 with tuning frequencies from 2165MHz to 2650MHz. The frequency is adjusted with the right knob seen in figure 3-4. The maximum output power of the oscillator is about +5dBm. Voltage supply ranges from +12 to +13 volts and current consumption is about 25mA. Seen in figure 3-5 is the oscillator ZX95-2650 from MiniCircuits.

Figure 3-5. Signal generator local oscillator from MiniCircuits.

High Power Signal Amplifier

The power amplifier was also purchased from MiniCircuits with model number ZRL-3500. The amplifier is powered from a +12 volts source and has an internal regulator at +5 volts. The maximum output power of the amplifier is about +21dBm at best. This is considered to be a medium power amplifier. However, for wireless power transfer, this amplifier is considered to be a low power amplifier. Amplifiers with minimum output power of 1watt should be considered for remote powered wireless sensors. The power amplifier is the most power hungry device in the system consuming about 575mA of current. Seen in figure 3-6 is the power amplifier ZRL-3500 from MiniCircuits.

Figure 3-6. RF amplifier ZRL-3500 from MiniCircuits.

Antenna of Choice

Antenna choice is a very important factor in WPT systems. Since the RF generator has less size constraints than the wireless nodes, the antenna size would not be a major concern. Therefore, the antenna size can be relatively large with high gain. The author recommends antennas with gain greater than 10dB, and preferably as high as possible. Antenna gain could make the wireless power transfer an easier task. However, the higher the antenna gain, the narrower the radiation beam, or directivity, which means that the antenna would have to be directed towards the wireless sensor. The author chose the patch antenna array from HyperTech with model number HG2414P with directivity gain of +14dBi, seen in figure 3-7 A. In addition, the antenna has a 30 x 30 degrees vertical and horizontal radiation beam seen in figure 3-7 B and 3-6 C respectively.

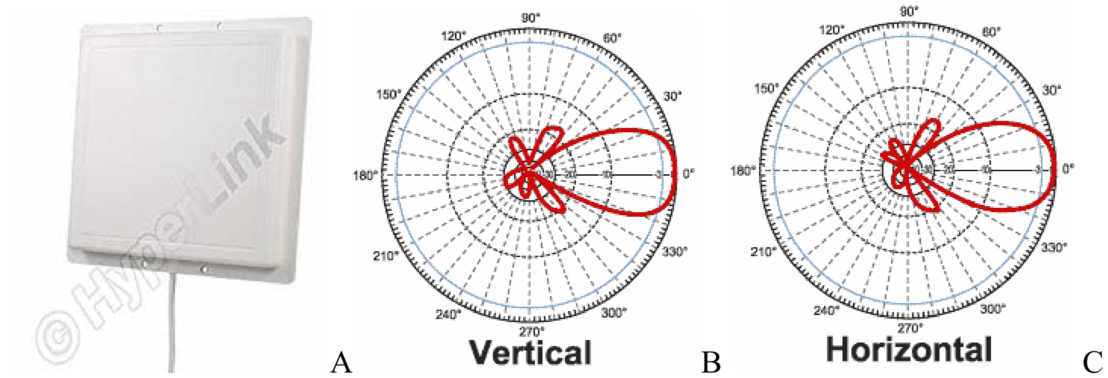


Figure 3-7. Commercial patch antenna. A) Patch antenna HG2414P B) Vertical radiation pattern C) Horizontal radiation pattern

RF to DC Wireless Sensor Node

The RF to DC remotely powered wireless sensor is the other leg that makes this project walk. The RF to DC sensor is responsible for harvesting the radiated power from the RF generator and turning it into DC energy. The system design can be seen in figure 3-7.

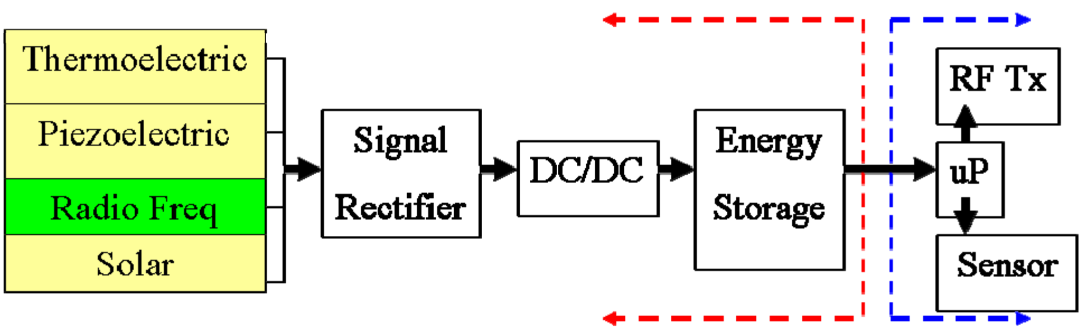


Figure 3-8. RF to DC wireless sensor node system design.

Seen in figure 3-8 is the system level design of the RF to DC remote powered wireless sensor. Starting from left to right, the first stage is the source of energy harvested. There are many sources of clean ambient energy that can be scavenged. We have discussed these sources in the introduction. Therefore, we will only discuss the RF source in the green colored block. When the RF signal is received via matched chip antenna, the signal is fed into the signal rectifier. In this case, the signal rectifier is the voltage doubling schottky diodes. The schottcky diode, also know as zero biased diodes (ZBD), have to have minimum forward voltage drop. When the signal is detected and turned into DC voltage, the voltage enters the DC to DC regulator, turning the received DC source into stable usable voltage such as 2.5volts or 2.0volts. The lower the required voltage is the less power is consumed, which is a concept we also discussed in the introduction. The regulated voltage is stored on a local capacitor, such as a supercapacitor. One should be careful with the capacitor capacity, too high of capacitance would take too long to charge. The author recommends a one mFarad value capacitor for a fast charging response. The choice of capacitor is of course dependant on the application. The author uses a regular 1mFarad capacitor for storage. When the energy is successfully stored on a capacitor, the baseband section, seen in blue, can use this energy to monitor a sensor and send back a reading value.

Antenna Matching

The path antenna used is the 2450AT45A100. The chip antenna is manufactured by JohansonTechnology© with average gain equal to 1dBi, and maximum gain equal to 3dBi. The chip antenna is weakly matched to 50Ω at 2.45GHz, with a return loss equal to -14dB. However, the company also offers a matching circuit for better bandwidth(BW), gain, and return loss seen in figure 2-24 A, return loss figure 2-24 B. By using the provided matching network, a better 50Ω match is possible with a wide bandwidth of 600MHz. A 1.5p Farad and a 3.9n Henry is required for matching. Impedance matching is important to achieve maximum power transfer with minimum power loss and reflection.

RF to DC Matching Network

It is important to match the RF to DC stage of the sensor. This will determine how efficient the wireless sensor is with converting RF energy to DC energy. Seen in figure 3-9 is the matching for the RF to DC sensor using smith chart technique. To match the input of the voltage doubler to the antenna a 13nHenry inductor is required.

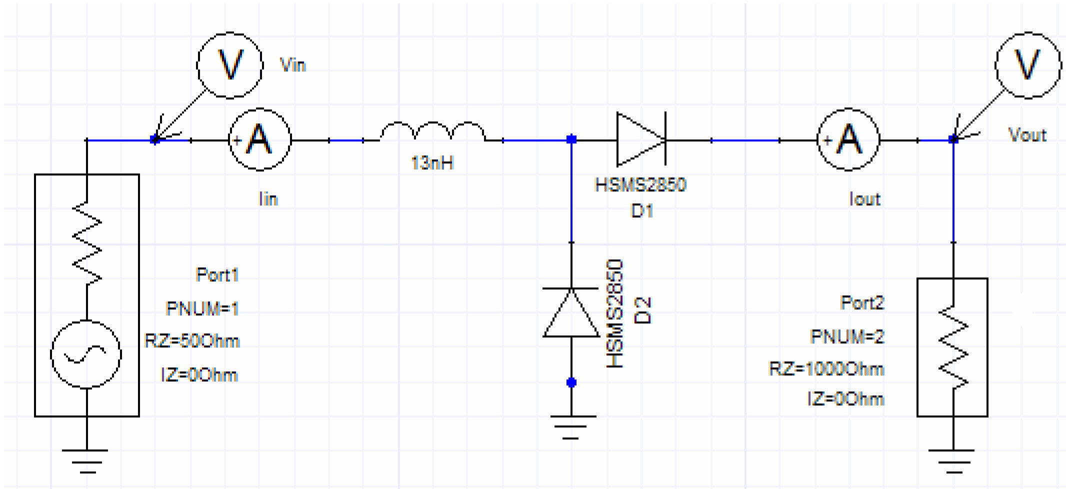


Figure 3-9. RF to DC matching network.

Seen in figure 3-9 is the voltage doubler RF to DC conversion with input matching to 50Ω. The schottky diodes used are the ZBD HSMS-2850 from Agilent©. The output voltage is as function of frequency is seen in figure 3-10, such that input power is 0dBm.

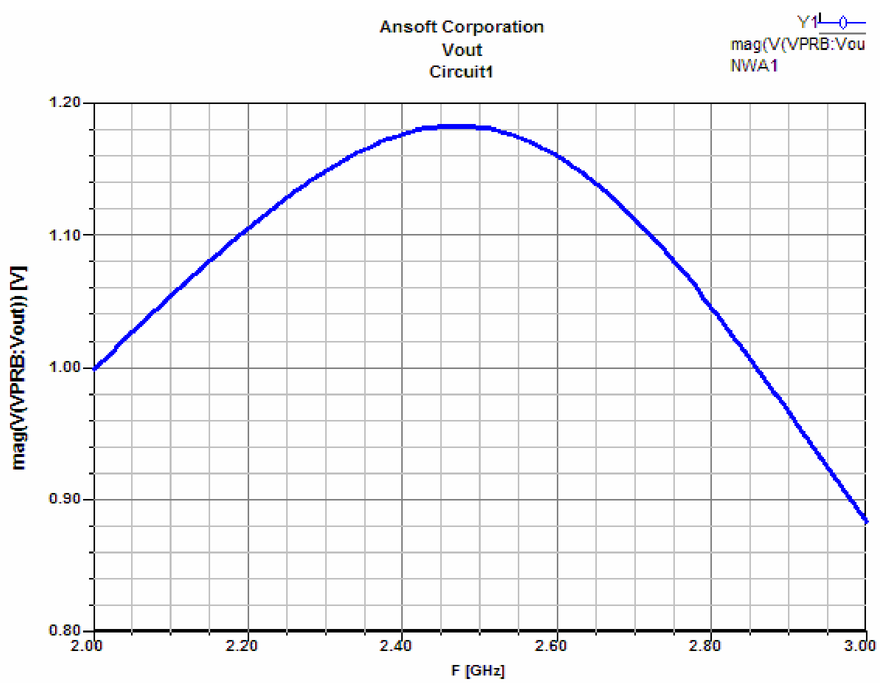


Figure 3-10. RF to DC output voltage about 1.2 volts.

Also the simulated current is shown in figure 3-11, such that the input power is also 0dBm.

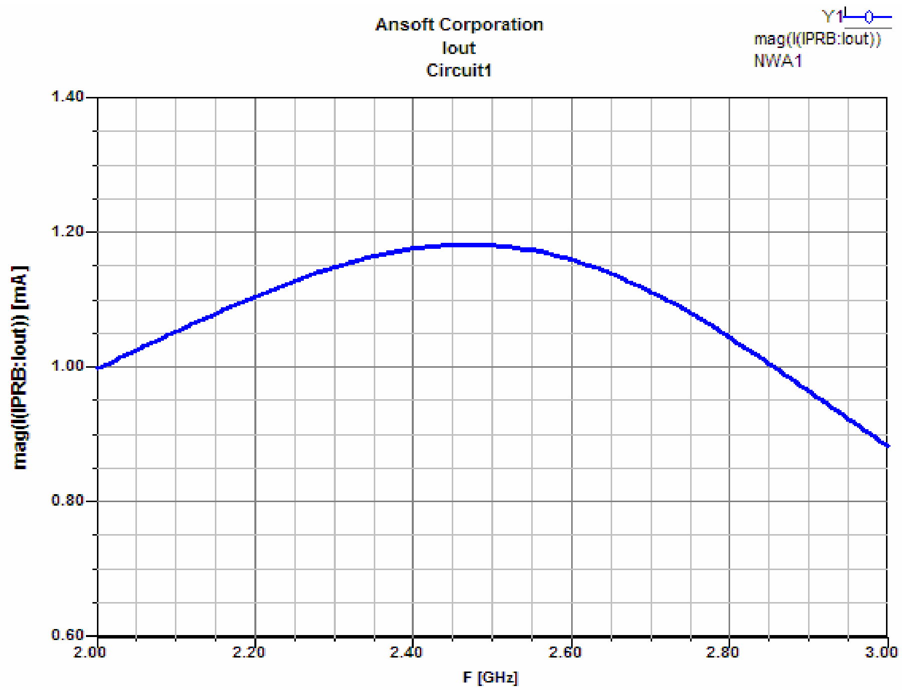


Figure 3-11. RF to DC output current about 1.2 mA.

The simulation shows that since the voltage and the current are of equal values, then the power is maximum, which means we have impedance matching at 2.45GHz.

Low Power BaseBand Processor

The baseband system is composed mainly of three blocks the PIC16F686 microcontroller from Microchip, the low power RF transmitter, and the piezoelectric sensor. When the microcontroller receives enough energy to power up, it will go directly into sleep mode to conserve the energy stored. The system is interrupt driven, meaning that when the piezoelectric sensor is actuated, the microcontroller wakes up from sleep and transmits its unique ID to the receiver base station at a frequency equal to 916MHz. Most of the energy management is done by the microcontroller. The C code for the wireless sensor node is shown in appendix A.

Low Power Sensors

A unique sensor is used with the wireless sensor node. The sensor is made from a piezo electric material that produces high voltage when stroke. This voltage has very low current, however, it is enough for CMOS technology to be triggered. When the microcontroller is in sleep mode and the piezoelectric sensor is moved, it produces a voltage burst that interrupts the PIC from sleep mode. The importance of this kind of sensor is that it does not consume power to operate, it actually produces it.

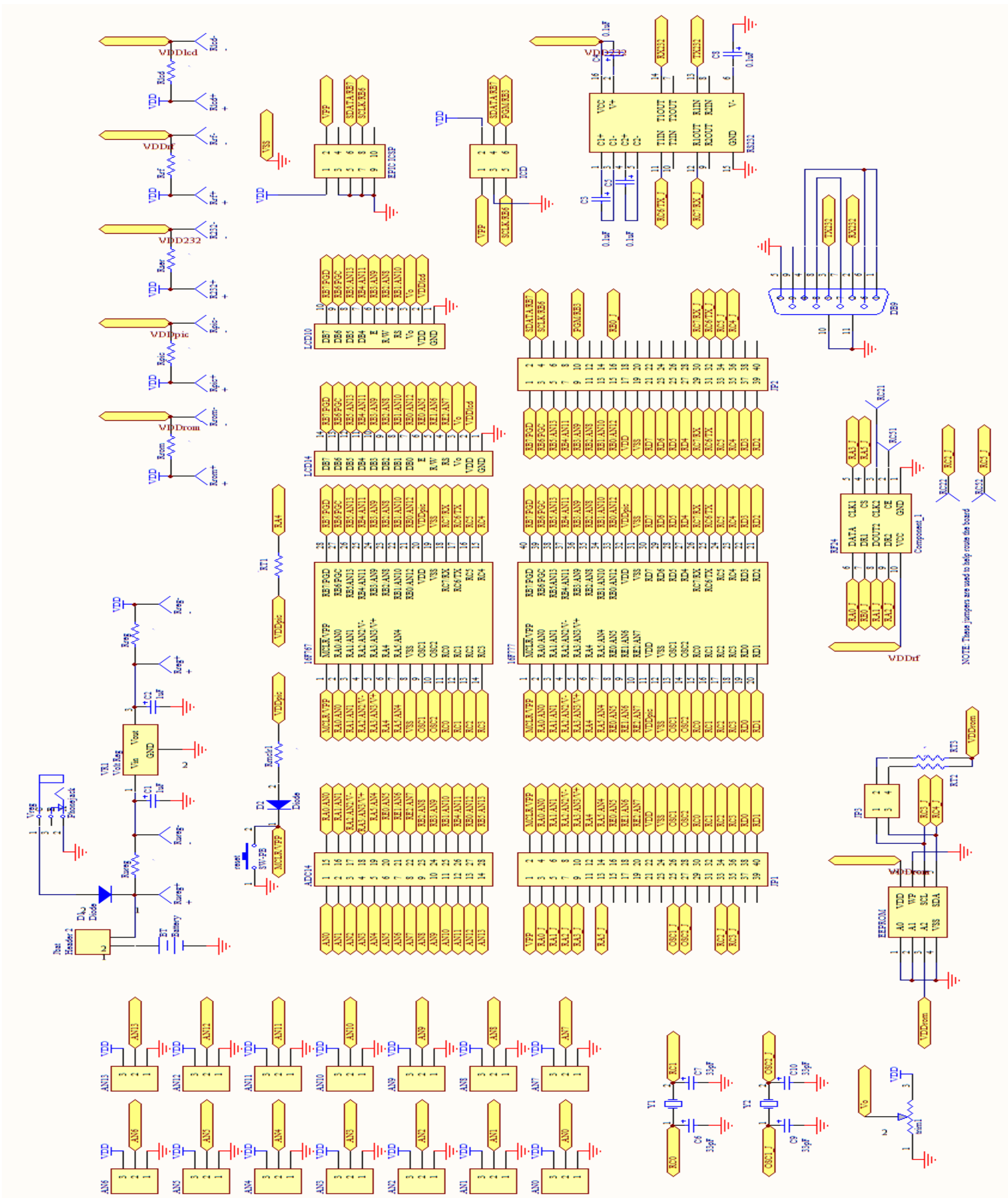
Low Power Wireless Transmitter

The transmitter is a SAW based low power transmitter. It operates at 916MHz frequency, which is different than the frequency supplying the power, so they don’t interfere. The transmitter can operate on a low supply voltage as 1.2 volts and current of 1.2 mA which is much less than what a Zigbee node consume (50mA). Therefore, with minimum duty cycles, the sensor can last forever, as long as there is a wireless power supply supplying power.

APPENDIX A

ELECTRONIC SCHEMATIC OF RF BASEBAD CONTROLLER

This schematic was designed and implemented by the author. The schematic was designed you Protel DXP.



APPENDIX B
REMOTE POWERED WIRELESS SENSOR C CODE

This is the C code implemented for the remote powered wireless sensor node. The code was written using CCS compiler.

```
#include <16F688.h>
#device adc=8

#FUSES NOFCMEN                    //Fail-safe clock monitor disabled, switches to internal if
external fails, page 33 for more details
#FUSES IESO                   //Internal External Switch Over mode enabled
//#FUSES NOIESO                  //Internal External Switch Over mode disabled, page 33 for
more details
//#FUSES BROWNOUT                 //Reset when brownout detected
#FUSES NOBROWNOUT                 //No brownout reset
#FUSES NOCPD                  //No EE protection
#FUSES NOPROTECT                  //Code not protected from reading
#FUSES MCLR                   //Master Clear pin enabled
#FUSES NOPUT                  //No Power Up Timer, page 33 for more details
#FUSES NOWDT                  //No Watch Dog Timer
//#FUSES HS                   //High speed Osc (> 4mhz)
#FUSES XT                     //High speed Osc (<= 4mhz)
//#FUSES INTRC_IO                 //Internal RC Osc, no clkout
//#FUSES INTRC                //Internal RC Osc
//#FUSES LP                 //Low power osc < 200 khz

#use delay(clock=4000000) // 200K osc
#use rs232(baud=38400,parity=N,xmit=PIN_C4,rcv=PIN_C5,bits=8) // Baud=2.5% Fosc ,
%3.125

// assume Tx_bits= 32bits to be transmitted
// time to transmit = Tx_bits * 1/Baud = 32bits * 1sec/3K bits = 11 msec
// Power Consumed = 1.5v * 1.5mA = 2.25mW for the transmitter
// E = P* time = 2.25mW * 11ms sec = 25uJ <<<<<<<<< Transmitter
// will need 3 diodes in series, or half voltage divider 3.3v/2 = 1.6v
// 1*Tao= 0.63*V=0.63*6.3v=4v
// E = 0.5(C)(V)^2 = 0.5(C)(4)^2=25uJ => C=50uJ/16=3uF
// E = 0.5(100uF)(4)^2=800uJ
// Tao = R*C =10K*100uF = 1 sec to charge cap
// P = 200uA*3.3v = 0.66mW (pic power consumed)
// E = 0.66mW*11ms = 7uJ <<<<<<<<< PIC energy

int i=0;
```

```
//Baud Rates:
// 110, 300, 1.2K, 2.4K, 4.8K, 9.6K, 19.2K , 38.4K, 57.6K, 115.2K, 230.4K, 460.8K, 921.6K


//#byte OSCCON = 0x8F
//#byte OSCTUNE = 0x90
//#byte OSCTUNE = 0x90

//#byte TXSTA = 0x16
//#byte RCSTA = 0x17

#int_EXT
EXT_isr()
{
    //setup_oscillator(OSC_EXTERNAL); //OSC_31KHZ, OSC_125KHZ ,OSC_250KHZ,
OSC_500KHZ
    //#use delay(clock=4000000) // 200K osc
    //#use rs232(baud=38400,parity=N,xmit=PIN_C4,rcv=PIN_C5,bits=8) // Baud=2.5% Fosc ,
%3.125
    delay_ms(10); //allow ascillator stability

    SETUP_UART(TRUE);
    printf("%cAA%C",0xFF,i);
    SETUP_UART(FALSE);
    output_low(pin_c4);
    i++;
}

void main()

{
  char start_byte='A', device_id='B', adc_data='C', crc_data='D', i;
  unsigned int int_counter=0;

  output_low(pin_c4);

  setup_adc_ports(NO_ANALOGS|VSS_VDD);
  setup_adc(ADC_OFF);

  setup_timer_0(RTCC_INTERNAL|RTCC_DIV_1);
  setup_timer_1(T1_DISABLED);
  //setup_timer_2(T2_DISABLED,0,1); //for PIC16F684

  setup_comparator(NC_NC);
  setup_vref(FALSE);
```

```
  ext_int_edge(L_TO_H);
  enable_interrupts(INT_EXT);
                              //clear_interrupt(INT_EXT);
  enable_interrupts(GLOBAL);

//#use delay(clock=4000000) // 200K osc
  //OSCCON = 0x21;


while (1)
  {
    sleep();
  }

}
```

APPENDIX C
RF BASEBAD CONTROLLER C CODE

This is the C code implemented for the RF generator baseband processor. The code was written using CCS compiler.

```
#include <16F777.h>
#device *=16
#device adc=8
#fuses HS,NOWDT,NOBROWNOUT
#use delay(clock=20000000)
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#use rs232(baud=19200,parity=N,xmit=PIN_C6,rcv=PIN_C7,bits=8,stream = pc)

//#use rs232(DEBUGGER)
#use fast_io(B)
//#use fast_io(D)
#include <input.c>

//LCD port definition -Done!
#define gl_dat portb
#define gl_a0  pin_d7 //output pin
#define gl_cs  pin_d6 //output pin
#define gl_wr  pin_d5 //output pin
#define gl_rst pin_d4 //output pin
//#define gl_rd  pin_d4 // hard wired to VDD=+5V

//Bump switches
#define right_bump  !input(pin_e0) //input bump switch
#define left_bump   !input(pin_e1) //input bump switch
#define RF_ON       output_high(pin_d1)
#define RF_OFF      output_low(pin_d1)
//#define more_bump   !input(pin_e2) //input bump switch

#define pyro_an0 0
#define temp_an1 1

//IR port definitions
#define GP2D02_VIN   pin_d2 //green
#define GP2D02_VOUT  pin_d3 //yellow
```

```
// servo constatnts
//#define start_byte 0x80
//#define device_id 0x01

//LCD Constants used -Done!
#define SYS_SET         0x40
#define SYS_SLEEP       0x53
#define SYS_CGRAM_ADDR  0x5C
#define SYS_SCROLL      0x44
#define SYS_SCROLL_HDOT 0x5a
#define SYS_SCROLL_RATE 0x5a
#define SYS_CUR_FORM    0x5d
#define SYS_CUR_ADDR    0x46
#define SYS_CUR_READ    0x47
#define SYS_CUR_DIR_RT  0x4c
#define SYS_CUR_DIR_LT  0x4d
#define SYS_CUR_DIR_UP  0x4e
#define SYS_CUR_DIR_DN  0x4f
#define SYS_OVER_LAY    0x5b
#define SYS_MWRITE      0x42
#define SYS_MREAD       0x43

#define LCD_DISP_OFF    0x58
#define LCD_DISP_ON     0x59
#define LCD_INVERSE     0xff
#define LCD_NORMAL      0x00
#define LCD_CR          0x20    //32 Chars/bytes per line
#define LCD_W           0x100   //256 pixels wide
#define LCD_H           0x80    //128 pixels high
#define LCD_Lh          0x08    //Height of line (8x8 characters)
#define LCD_L1          0x00    //Line 1
#define LCD_L2          0x20    //Line 2
#define LCD_L3          0x40    //Line 3
#define LCD_L4          0x60    //Line 4
#define LCD_L5          0x80    //Line 5
#define LCD_L6          0xA0    //Line 6
#define LCD_L7          0xC0    //Line 7
#define LCD_L8          0xE0    //Line 8
#define LCD_L9          0x100   //Line 9
#define LCD_L10         0x120           //Line 10
#define LCD_L11         0x140           //Line 11
#define LCD_L12         0x160           //Line 12
#define LCD_L13         0x180           //Line 13
#define LCD_L14         0x1A0           //Line 14
#define LCD_L15         0x1C0           //Line 15
#define LCD_L16         0x1E0           //Line 16
```

```
#define LCD_GRH         0x1000   //Graphic home position



// graphic LCD
char line_string [33];
void gl_init();
void gl_grfclr();
void gl_grfhome();
void gl_strobe();
void gl_txtclr();
void gl_setaddr   (int gl_cur, long gl_addr);
void send_data    (int gl_byte);
void send_command (int gl_cmd);
#separate
void g_printf     (char string[],long Line_num);
void g_clear_line (long Line_num);

void load_image();


void load_image()
{

  int i,j;
  gl_txtclr();
  send_command(SYS_CUR_ADDR);         //CSRW command
        send_data(0x00);
        send_data(0x10);
        send_command(SYS_CUR_DIR_RT);         //Cur movement right
        send_command(SYS_MWRITE);

  while(fgetc(pc)!=']')
  // after the ']' microcontroller will lose 31 characters (because of software rs232) to initiate i
and j
again1:
  for(i=0;i<128;i++)   //128/8=16
    {
      for(j=0;j<32;j++) //256/8=32
      {
        send_data(fgetc(pc));
      }
    }
    goto again1;
}
```

```
int get_temp()
{
  set_adc_channel(temp_an1);
  delay_ms(1);
  return (read_adc()<<1);
}


#include <graphical_LCD.h>


//////////////////////////MAIN()///////////////////////////////////////////
void main() {

//LCD Global Variables used -Done!
int  gl_cmd;
int  gl_cur;
int  gl_byte;
int  gl_i;
int  gl_j;
int  gl_k;
long gl_x;
long gl_y;
long gl_addr;
long gl_w;
int  gl_read;
int  gl_old;
long pix_x;
long pix_y;
long gl_addrlo;
long gl_addrhi;
int  gl_nib;

// servo control variables
int servo_num;
int right_arm_angle;
int left_arm_angle;

//general variables
int i=0,j=0,k=0;

//variables used for UltraSound
long returned_distance;
float distance;
```

```
//variables used for ADC
int pyro_adc;      //16-bit integers
float pyro_volts;
int temp_cel; //should be long, but doubt temperature would be that high
float temp_volts;

// CMUcam variables
char cmu_char[10];
long cmu_param[8];

int ir_reading;
int speed;
//char bt_rx[33];
char bt_rx[3];
char rx_data[5];
int menu_option;

//pwm variables:
unsigned long pwm_freq;
unsigned int t2p;
unsigned int value;

   //some stuff
   setup_spi(FALSE);
   //setup_counters(RTCC_INTERNAL,RTCC_DIV_2);
   //setup_timer_0(RTCC_INTERNAL| RTCC_DIV_8);
   //setup_timer_0(RTCC_INTERNAL| RTCC_DIV_64);   //timer_0 will overflow every 16.32
msec
   setup_timer_0(RTCC_INTERNAL|RTCC_DIV_128);   //timer_0 will overflow every 32.7
msec, resolution = 128us (increments every 128us)
   //setup_timer_1(T1_DISABLED);
   setup_timer_1(T1_INTERNAL|T1_DIV_BY_1);      //overflows every 65.5ms
   //setup_timer_2(T2_DIV_BY_16,255,16);          //overflows every 65.5ms


   //setup_timer_2(T2_DISABLED,0,1);
   setup_comparator(NC_NC_NC_NC);
   setup_vref(FALSE);

   //set_timer0(0);                    //reset timer
   //set_timer1(0);                    //reset timer
   //set_timer2(0);                    //reset timer

   //counter0_overflow = 0;
   //counter1_overflow = 0;
```

```
  //counter2_overflow = 0;

  set_tris_b(0x00);
  //set_tris_d(0x00);

  //enable_interrupts(INT_TIMER0);          //activate timer
  //enable_interrupts(INT_TIMER1);          //activate timer
  //enable_interrupts(INT_TIMER2);          //activate timer

  disable_interrupts(INT_TIMER0);          //dectivate timer
  disable_interrupts(INT_TIMER1);          //dectivate timer
  disable_interrupts(INT_TIMER2);          //dectivate timer

  //enable_interrupts(GLOBAL);              //activate global interrupt flag
  t2p = 255;
  setup_timer_2(T2_DIV_BY_16,t2p,1);       //pwm_freq = 98KHz

  //setup_ccp1(CCP_PWM);   // Configure CCP1 as a PWM
  setup_ccp2(CCP_PWM);


  //setup_ccp3(CCP_PWM);

  value = t2p>>1;

  //set_pwm1_duty(value);
  set_pwm2_duty(value);


  //LCD
  fprintf(pc,"\r\nInitializing Graphical LCD...");
  output_low(gl_rst);
  delay_ms(100);

  output_high(gl_rst); //Make sure reset is high
  delay_ms(100);

  output_low(gl_cs); //Chip select active
  delay_ms(10);

  gl_init();                 //Initialize display

  fprintf(pc,"Done!\r\n");
////////////////////////////////////////////////////////////////////////////////
```

```
    strcpy(line_string, "Welcome to Wireless Power Trasfer!");
    g_printf(line_string,LCD_L1);

    sprintf(line_string, "t2p=%u, value=%u",t2p,value);
    g_printf(line_string,LCD_L2);

    output_low(pin_c2);

    delay_ms(5000);
    //t2p=255;
    while (1)
    {

      //setup_timer_2(T2_DIV_BY_16,t2p,1);
      value = t2p>>1; //divide by 2
      sprintf(line_string, "t2p=%u, value=%u",t2p,value);
      g_printf(line_string,LCD_L2);
      delay_ms(1000);
      t2p = t2p +1;

    }

  }
```

APPENDIX D
RECEIVER INTERFACE TO ATLAS C CODE

This is the C code implemented for the receiver interfaced to Atlas. The code was written using CCS compiler.

```
#include <16F688.h>

#device adc=8

#FUSES NOFCMEN                    //Fail-safe clock monitor disabled, switches to internal if
external fails, page 33 for more details
#FUSES IESO                    //Internal External Switch Over mode enabled
//#FUSES NOIESO                    //Internal External Switch Over mode disabled, page 33 for
more details
//#FUSES BROWNOUT                    //Reset when brownout detected
#FUSES NOBROWNOUT                    //No brownout reset
#FUSES NOCPD                    //No EE protection
#FUSES NOPROTECT                    //Code not protected from reading
#FUSES MCLR                    //Master Clear pin enabled
#FUSES NOPUT                    //No Power Up Timer, page 33 for more details
#FUSES NOWDT                    //No Watch Dog Timer
#FUSES HS                    //High speed Osc (> 4mhz)
//#FUSES INTRC_IO                    //Internal RC Osc, no clkout
//#FUSES INTRC                    //Internal RC Osc
//#FUSES LP                    //Low power osc < 200 khz

#use delay(clock=4000000) // 200K osc
//#use rs232(baud=19200,parity=N,xmit=PIN_C4,rcv=PIN_C5,bits=8,DISABLE_INTS) //
Baud=1.5% Fosc
  #use rs232(baud=38400,parity=N,xmit=PIN_C4,rcv=PIN_C5,bits=8) // Baud=1.5% Fosc

// assume Tx_bits= 32bits to be transmitted
// time to transmit = Tx_bits * 1/Baud = 32bits * 1sec/3K bits = 11 msec
// Power Consumed = 1.5v * 1.5mA = 2.25mW for the transmitter
// E = P* time = 2.25mW * 11ms sec = 25uJ <<<<<<<<< Transmitter
// will need 3 diodes in series, or half voltage divider 3.3v/2 = 1.6v
// 1*Tao= 0.63*V=0.63*6.3v=4v
// E = 0.5(C)(V)^2 = 0.5(C)(4)^2=25uJ => C=50uJ/16=3uF
// E = 0.5(100uF)(4)^2=800uJ
// Tao = R*C =10K*100uF = 1 sec to charge cap
// P = 200uA*3.3v = 0.66mW (pic power consumed)
// E = 0.66mW*11ms = 7uJ <<<<<<<<< PIC energy
int rx_char, valid_data,j;
unsigned int rx_buffer;
char byte1,byte2,byte3,byte4,byte5,byte6,byte7,byte8;
```

```
//Baud Rates:
// 110, 300, 1.2K, 2.4K, 4.8K, 9.6K, 19.2K , 38.4K, 57.6K, 115.2K, 230.4K, 460.8K, 921.6K

#int_RDA
RDA_isr() //lots of work to be done here !!!
{

   rx_char=getc();
   printf("%c",rx_char);

}




void main()

{
  //char start_byte='A', device_id='B', adc_data='C', crc_data='D', i;
  //char rx_string;
  char byte1,byte2,byte3,byte4,byte5,byte6,byte7,byte8;
rx_buffer=0;
   //setup_vref(VREF_LOW|2);
   //setup_comparator(A1_VR);

  //setup_adc_ports(sAN0|sAN1|VSS_VDD);
  setup_adc_ports(NO_ANALOGS|VSS_VDD);
  setup_adc(ADC_OFF);

  setup_timer_0(RTCC_INTERNAL|RTCC_DIV_1);
  setup_timer_1(T1_DISABLED);
  //setup_timer_2(T2_DISABLED,0,1); //for PIC16F684

  setup_comparator(NC_NC);
  setup_vref(FALSE);
//SET_TRIS_C(0x00);
//SET_TRIS_A(TRISA|00000011);

   printf("hello world");

   //enable_interrupts(INT_COMP);
   enable_interrupts(INT_RDA);
   enable_interrupts(GLOBAL);
  //OSCCON = 0x21;

//SET_TRIS_C(0x00);
```

```
while (1)
  {
          //wait for interrupt
  }

}
```

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BIOGRAPHICAL SKETCH

I received my bachelor's degree in electrical engineering from the University of Florida. My special undergraduate interest was radio frequency system level design. I did about two years of research in the ECE department and had two major publications in which I was the first author. I then joined a local company in Gainesville, Florida, in which I worked with high profile companies such as DoCoMo, Intel, and Advanced Micro Devices (AMD) on a very specialized and detailed analysis, in which mobile handsets' power usage is measured and benchmarked, and design refinements and changes are recommended. I was the chief RF engineer who was running and managing all work related to power benchmarking. At a young age, I was managing two people, and delivering high quality results to customers. I flew to business meetings with Intel, DoCoMo, and AMD, and I met several of their VPs. This line of business generated significant revenues to the company.

In the Fall of 2005, I joined the CISE department at the University of Florida to pursue the Master of Science degree in computer engineering under the supervision of Dr. Abdelsalam (Sumi) Helal. I have known Dr. Helal for more than three years. I am honor to know him and work for him. It has always been a pleasure to work with him on various projects and I am fortunate enough to have learned a lot from him. In the first semester of graduate school, I established myself as a research assistant for the pervasive mobile computing laboratory. I designed an RF system that allows sensor network nodes to be power charged wirelessly and from a distance as my thesis, which is currently prototyping the Pervasive and Mobile Computing Laboratory, and has been disclosed to the University of Florida, which has accepted the disclosure and filed for a patent application. The docket number of this patent is PCT02/22/06. Currently, I am applying wireless power transfer to the ATLAS Sensor Platform, which is being commercialized by Pervasa, Inc, a University of Florida startup.