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A Capstone Project on the Development of an Environmental Monitoring Wireless Sensor Network Powered by Harvested RF Energy

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Introduction

In today's wirelessly connected world, radio frequency energy surrounds us. Radio frequency energy is currently broadcasted from billions of transmitters such as cellphones, computers, Wi-Fi routers, radio base stations, broadcasting towers etc. The ability to harvest RF energy either from the ambient or from specialized sources leads to the possibility of creating new devices with wireless charging capabilities; this means that no batteries are needed. Battery based systems generate maintenance costs because batteries need to be replaced over time. This is not the case with wireless charging devices where the device can be used in demand or when enough charge has been accumulated.

RF energy receivers are currently available in the market. An example is the Powercast Power harvester [1], that delivers renewable energy by converting radio waves to DC power. This RF power harvester could be added to a circuit with a 50Ω antenna in order to power a low power circuit. The device will always need to have a source for RF energy to harvest from which could be a Wi-Fi router, a cellphone tower placed in the proximity of the RF energy harvester, or simply a place with high RF traffic.

The main idea of this project is to create an environmental wireless sensor network (WSN), which is powered by an RF energy receiver. While the use of renewable energy, such as solar power, for powering wireless sensor networks has been studied in the past [2]-[6], the use of RF energy harvesting as the sole source of energy in wireless sensor networks is relatively new. For example, the authors in [7] give details of using TV broadcast airwaves as a source of energy to power wireless sensor nodes. In this paper, we provide the design, implementation and experimental results of an environmental monitoring wireless sensor network (measuring temperature and pressure) which is powered by an RF energy harvester and which can operate without the use of batteries. As will be shown in the paper, the RF energy harvester can generate a limited, yet sufficient, amount of power, for the successful operation of a wireless sensor network in periodic intervals, which makes it suitable for environmental monitoring applications, where the sensors need to be on for a small period of time and will allow the system to recharge in between sensing intervals. The project is targeted to areas with high traffic of radio signals such as big cities with communication towers, working environments, etc. This kind of wireless sensor network will not be viable for rural areas, or areas that do not have a lot of radio frequency transmitters.

This paper summarizes a one-semester capstone design project that was implemented at the Department of Electrical and Computer Engineering at … . The students, in consultation with a faculty advisor selected the topic of the project. The design and implementation of the project was carried out by two senior students as part of their capstone design class. The students met with their faculty advisor on a weekly basis to discuss the project's progress.

The results presented in this paper are the outcomes of this one-semester Senior Capstone Electrical Engineering project. Senior Capstone Projects represent the culmination of the educational experience, where real world problems are integrated into the classroom. The students handle open ended engineering problems whose solutions require a synthesis of engineering knowledge, analysis, creativity, market needs, safety and esthetics. Projects are carried out by students and supervised by instructors and industry mentors. Two electrical engineering students were assigned to the RF Energy harvester project.

The objectives of this project were:

- ❖ To expose students to one of the emerging technologies that are not normally covered in undergraduate engineering courses.
- ❖ To provide students with a culminating interdisciplinary design experience that allows student to utilize and adapt knowledge gained from a variety of undergraduate courses including electronics, digital design, computer architecture, computer science, and wireless communication in the design and implementation of a useful and eco-friendly application under realistic constraints such as low cost and low power consumption.

- ❖ To design and implement an environmental wireless sensor network capable of measuring temperature and pressure, powered exclusively with RF energy.
- ❖ To optimize the sensing node for minimum power consumption.

The rest of the paper is organized as follows. In Section II, a review of RF energy harvesting is provided and background material on the topology used for the implementation of the wireless sensor network is given. In Section III, the details of hardware and software implementation are provided. The experimental results are given in Section IV. The project assessment and cost associated with this project is given in Section V. Finally, the conclusions and lessons learned are provided in Section VI.

II. Background

<u>Relevance to Previous Work</u>

In this project the Arduino platform was extensively used. Our work builds on previous studies that show the use of the Arduino platform in teaching embedded systems and its use in Senior Capstone Projects [7]-[10]. For example, a study on the use of Arduino for teaching embedded system was presented in [7]. The study outlined a large group of applications created using the Arduino microcontroller. The study concluded that the Arduino platform can be used to teach many aspects of embedded system design. A series of mechatronics laboratory exercises utilizing sensors, actuators, electronics and the Arduino® microcontroller was presented in [8]. The laboratory teaches students how to shield the Arduino board, how to use the Arduino development environment and its code library to develop C code for a variety of applications. A capstone design utilizing Wireless 820.11 Wi-Fi technology and Arduino microcontroller in an application aimed at securing the delivery of controlled substance in medical centers was published in [9]. A hands-on project course in networking and security employing Arduino microcontroller and open source software, and MySQL database was presented in [10]. The main aim of the project was to design and implement a prototype of web, mobile, and network based applications.

<u>RF Energy Harvesting</u>

The general system architecture of the RF energy harvesting should be designed such that it consumes low power, while providing the highest conceivable efficiency. Therefore, low power circuit techniques must be used through all stages of the design. A typical RF to DC converter, as shown in Figure 1, consists of 5 stages: power source, impedance matching, rectifier, regulator circuit, and the load [11]. The power source stage typically includes an antenna that is accommodated to a specific frequency range. The antenna has the task of transforming the RF energy into a sinusoidal voltage. The most efficient band for this kind of conversion is the 915 MHz band, where the output of around 300 mV is achieved after the antenna.

The next stage is the impedance matching stage. To obtain the maximum power transfer between the power source and the rectifier, their impedances need to be matched. The impedance of the antenna (about 50 ohms) is typically much lower than the impedance of the rectifier; since the impedance of the rectifier is going to depend on the impedance of multiple internal stages. The next stage is the rectifier. The rectifier has the task to amplify and convert a sinusoidal voltage into a DC voltage. The efficiency of the rectifier will play a big role in the quality of the RF to DC converter, as rectifiers with higher efficiency will help the circuit to be less power consuming. Next, is the regulator circuit. The RF energy does not provide constant power and this will make the DC output not be constant, potentially damaging the load. For this reason, a regulator circuit can be used in order to regulate the output voltage and to make it have a constant voltage level. The last stage is the load stage. The load can be resistive, capacitive, or inductive. For WSNs a microcontroller attached with sensors is used as the load. All the preceding stages have to be adapted in order to meet the requirements of the load stage, such as: input voltage, input current, and operating time. To have an efficient RF to DC converter, the following performance criteria have to be met: high power conversion efficiency, small dimension, shorter rise time or startup time, low input power threshold, low ripple or noise, and high voltage conversion efficiency.

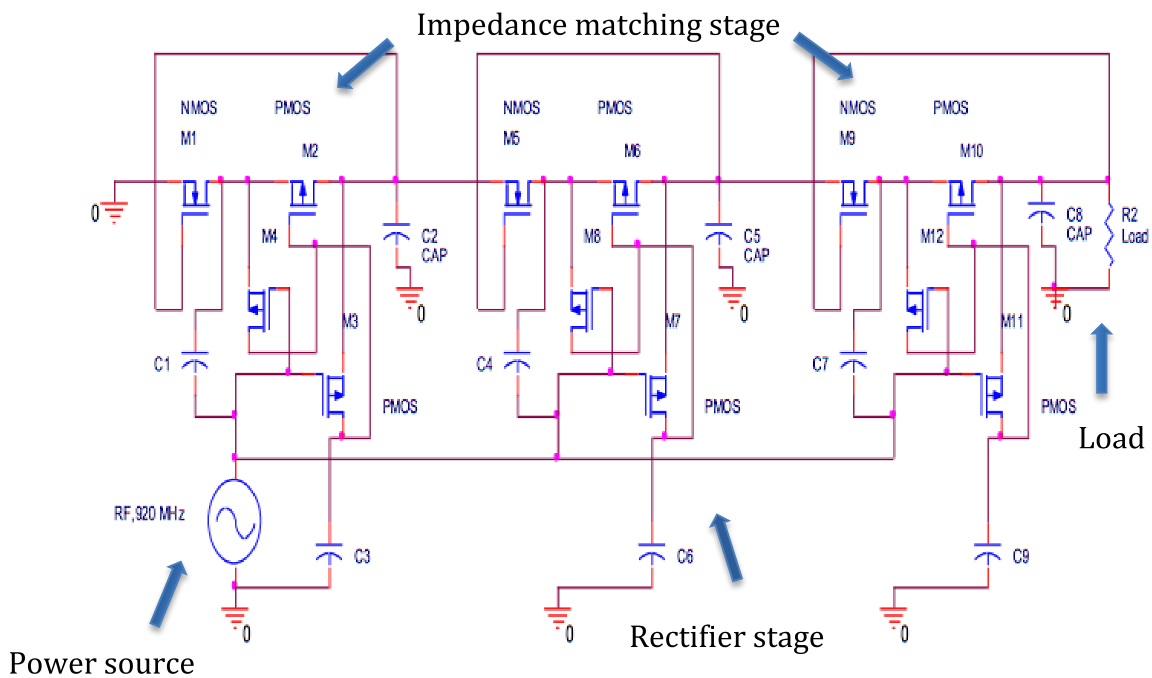


Figure 1- RF to DC conversion circuit (after [8])

The RF-DC rectifier consumes the largest percentage of power and hence its efficiency heavily affects the overall performance of the entire system. The rectifier is also responsible for relaying the harvested power to the other parts of the system, so if the power is not handled properly at this first stage the entire system will be negatively affected. With the proper design of the RF-DC rectifier and optimization of other circuit parameters such as antenna matching the performance of the system can be greatly improved.

<u>Topology of the Designed Wireless Sensors Network:</u>

A tree-topology WSN consisting of two sensor nodes, and a sink base station was successfully built and tested using open source and inexpensive hardware to measure various environmental factors such as pressure and temperature. The sensor nodes consisted of pressure and temperature sensor, and a radio module (transmitter) packaged together. The base stations consisted of Arduino Uno and Launchpad MSP430 micro-controller and a radio module (receiver) that can collect data from the various sensors and submit to a sink base station where data can be stored and processed. Finally a website was developed where the captured data can be continuously stored and displayed in real time. This project uses a tree-topology hierarchy for the WSN design layout, which consists of two sensor nodes and a sink node. These sensor nodes are divided into clusters, in which one router takes the role for communication with these sensors. Routers form a virtual hierarchical tree, which is the topology of the sub WSN. The advantages of tree-topology are 1) wide area coverage and 2) Low sensor node power consumption

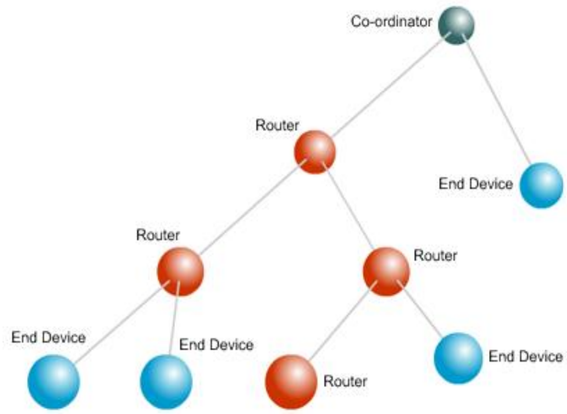


Figure 2- Tree Topology

III. Hardware and Software Implementation

In this Section, we first give a brief description of the parts used for the design of the hardware. Then the hardware and software implementation is discussed in detail.

Hardware Parts:

A. Launchpad MSP430G2553 microcontroller

The MSP430G2553 microcontroller, shown in Figure 3, is developed by Texas instruments. It is an Arduino type microcontroller based on the MSP430 low-power microprocessor series and has been optimized for ultra-low power consumption (about 6mA) and general-purpose low power applications such as battery free applications. It can be programmed in either C or assembly. The MSP430G2553 Key features are: 3.3V of supply, 16 MHz oscillators, 512B RAM, 8ch 10-bit ADC, 2 16-bit timers, up to 1 I2C, 1SPi, 1 UART ports.

Figure 3- Launchpad MSP430G2553 microcontroller

B. <u>CC110L RF booster pack</u>

The CC110L RF BoosterPack, shown in Figure 4, is a low-power wireless transceiver extension kit for use with the Texas Instruments MSP-EXP430G2 LaunchPad development kit. Based on the CC110L device, the on-board Anaren Integrated Radio (AIR) A110LR09A radio module with integrated antenna operates in the European 868-870MHz and US 902-928MHz ISM bands.

Figure 4- CC110L RF booster pack

C. BMP180 temperature and pressure sensor

The BMP180 is a low power consuming, low cost, and high precision barometric sensor. It measures barometric pressure and temperature and is shown in Figure 5.. It is a 5V compliant sensor that works using the I2C interface (SDA SCL). The sensor has a very fast response time, which make it ideal for fast sensing systems.

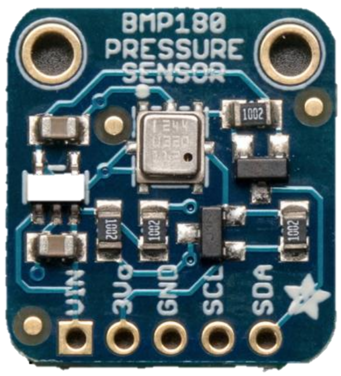


Figure 5- BMP180 Temperature and Pressure sensor

D. ASX210A03 DPDT relay

The ASX210A03 DPDT relay is a signal relay used to interchange between two common pins. It is a low signal relays and operates using a 3V power supply and the coil current is 10mA, making it viable candidate for low power consumption applications.

Figure 6- ASX210A03 DPDT relay

E. P2110 RF energy harvester evaluation board

The P2110 is the radio frequency energy harvester and is used to power the circuit. It can provide up to 5.5 volts and a current of 50mA. The chip works with 50-ohm antenna, which will collect the RF energy; The harvester can work from a frequency range of 600MHz to 1000MHz. In order to store the energy produced by the chip, a storage capacitor has to be connected to the output of the chip. The size of the capacitor will be determined based on the amount of current that the circuit will consume and the amount of time it will be turned on.

Figure 7- P2110 RF energy harvester evaluation board

F. <u>Arduino Uno microcontroller</u>

The Arduino Uno is open software, preassembled, 32-bit microcontroller based on the ATMEGA328 microprocessor. It comes with Arduino Boot loader that allows the user to program the microcontroller in C. This microcontroller works with a supply voltage of 5 volts and comes with 10 digital pins and 5 analog pins with a maximum current of 250 mA. The Arduino Uno allows the use of UART, SPI, and I2C protocols for easy connection with external devices and sensors.

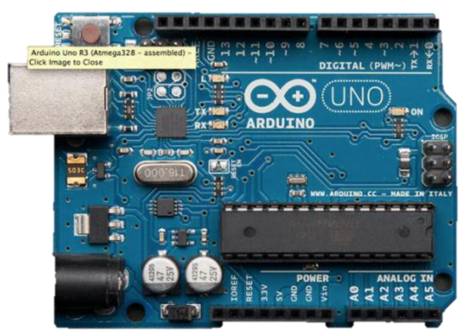


Figure 8- Arduino Uno microcontroller

G. <u>Adafruit CC3000 Wi-Fi shield</u>

The Adafruit CC3000 Wi-Fi shield is a 802.11 compliant device with open WEP/WPA/WPA2. It works with the SPI protocol meaning that the data can be pushed as fast or as slow as wanted. It works with 3.3 volts of power supply. The Wi-Fi shield will be used for uploading the data gathered from the based station to the Internet via Wi-Fi.

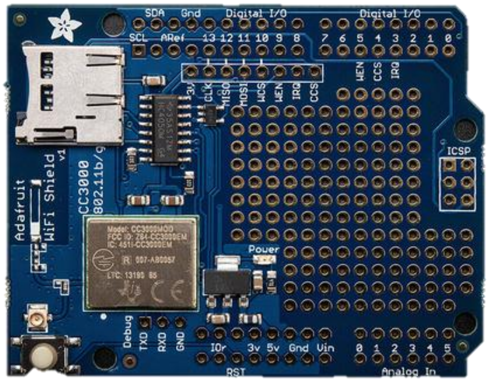


Figure 9- CC3000 Wi-Fi shield

Design Specifications:

The main objective of the project is to design an environmental radio frequency powered wireless sensor network. This objective will be accomplished using the P2110 as the power source for the transmitter node. Since a storage capacitor will be placed at the output of the P2110 chip, the power will not be supplied to the microcontroller constantly. This means that the microcontroller will be programmed to turn on when the storage capacitor is fully charged. When on the microcontroller will measure all sensor values and transmit them wirelessly to a base station; after this process is done, the microcontroller will send a signal to the P2110 to stop the supply of voltage to save the energy, hence preventing the capacitor to be fully discharged.

The receiver (base station) will be on at all times checking for data from the transmitter. After receiving the data from the transmitter, the receiver will send the information to a specific website. The sensor data will then be stored in a MySQL database where all the analysis and graphing of the data will take place. An overview of the system, the transmitter, the receiver and a block diagram of the system are shown in Figures 10 to 14, respectively.

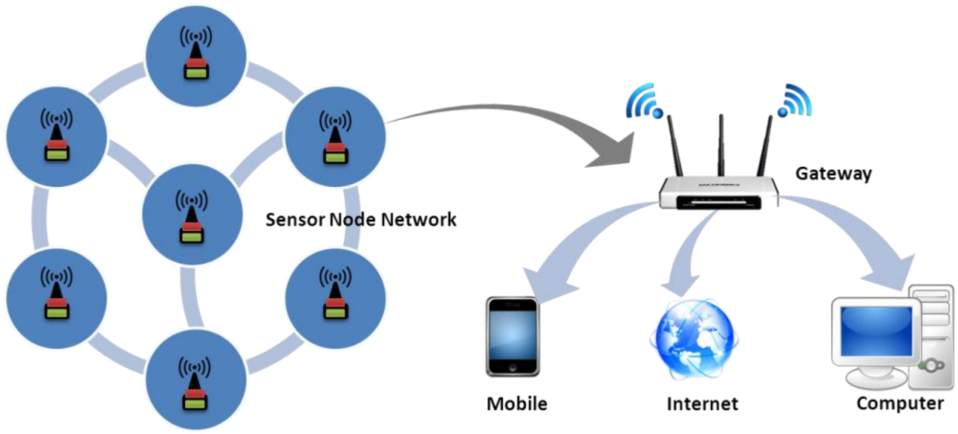


Figure 10- System Overview

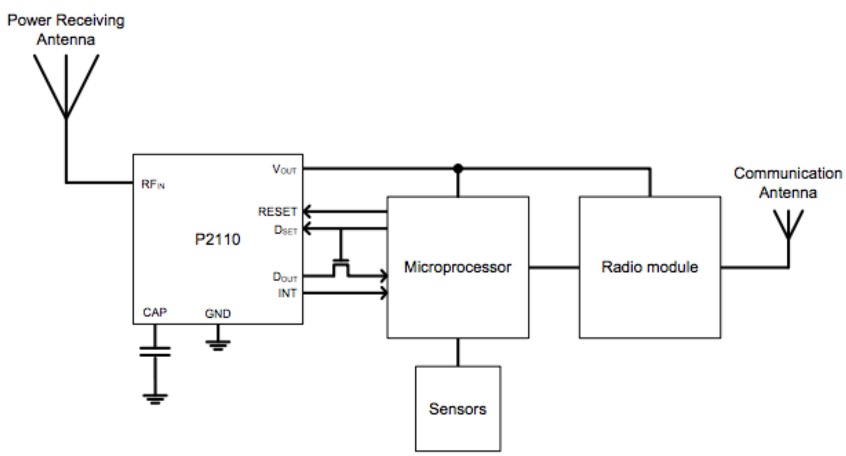


Figure 11- Transmitter node

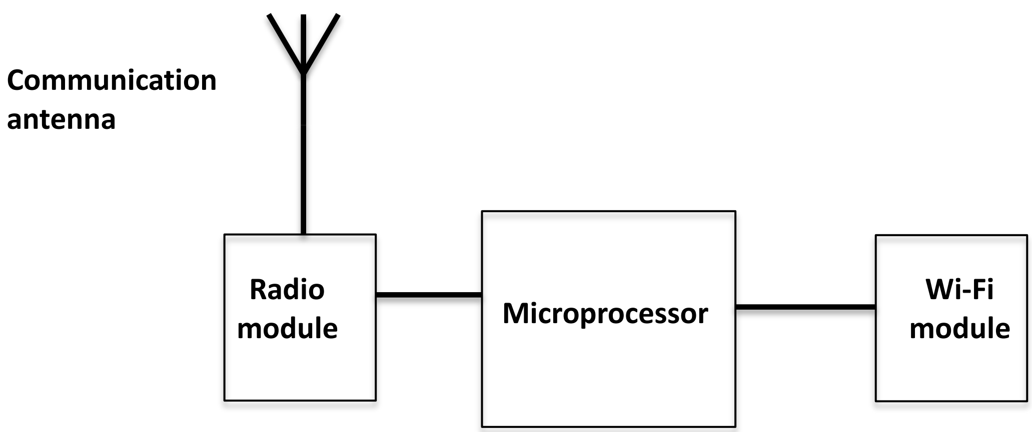


Figure 12- Receiver (base station) node

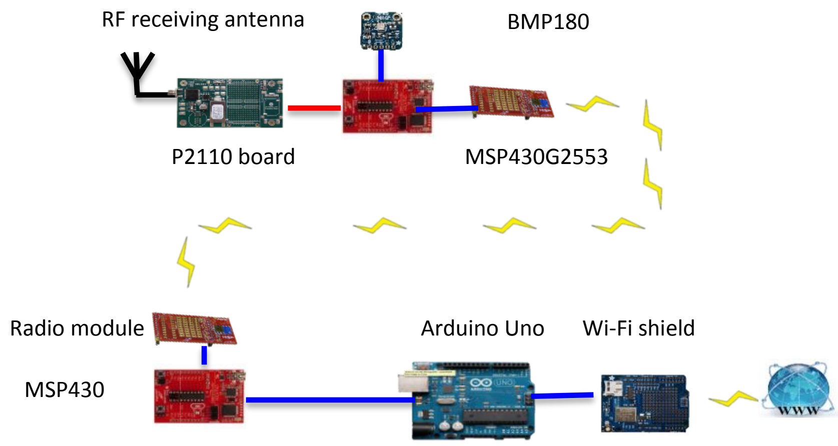


Figure 13- Block diagram of the whole system

Hardware Implementation.

A. Sensing node:

The sensing node is where the temperature and pressure are being measured. As stated in the project it has to work exclusively with RF energy. The P2110 board was used in order to provide the RF energy to DC current capabilities; it is connected using in the same way as shown in Figure 11. The microcontroller used for the sensing node is the MSP430G2553, which has very low power consumption. The sensor used was the BMP180 to add the pressure and temperature sensing capabilities. The CC110L radio module was connected in order to send the data to the base station. The sensor uses the I2C interface of the microcontroller, and the radio module works with SPI; unfortunately, in the MSP430 uses the same two pins for the two different protocols, which are (SDA and SCL). In order to solve this problem the implementation of a DPDT relay was needed. This was solved by connecting the common two pins of the MSP430G2553 to the common two pins of the DPDT relay, the sensor pins to the NC pins of the DPDT relay, and the two pins of the radio module into the NO of the DPDT relay. The main idea is to have one component isolated from the two pins while the other does its task and then switch to the second component. This idea can be implemented by implementing the connections stated above and by sending a digital signal to the coil of the DPDT relay.

The frequency used to charge the capacitor using the P2110 was from 902MHz to 928MHz; nevertheless, the frequency that the RF board will capture will depend solely on the antenna used. A better antenna that can capture a broader range of frequencies could be used in order to charge the device faster. The size of the capacitor will be proportional to the voltage and current used by the microcontroller, the sensors and the radio module, as well as its operating time. The size of the capacitor, according to the data sheets, can be determined as follows:

$$C = 15V_{out}I_{out}t \qquad (1)$$

A detailed picture of the schematic of the sensing node, and the implemented systems can be seen in Figures 14 and 15, respectively.

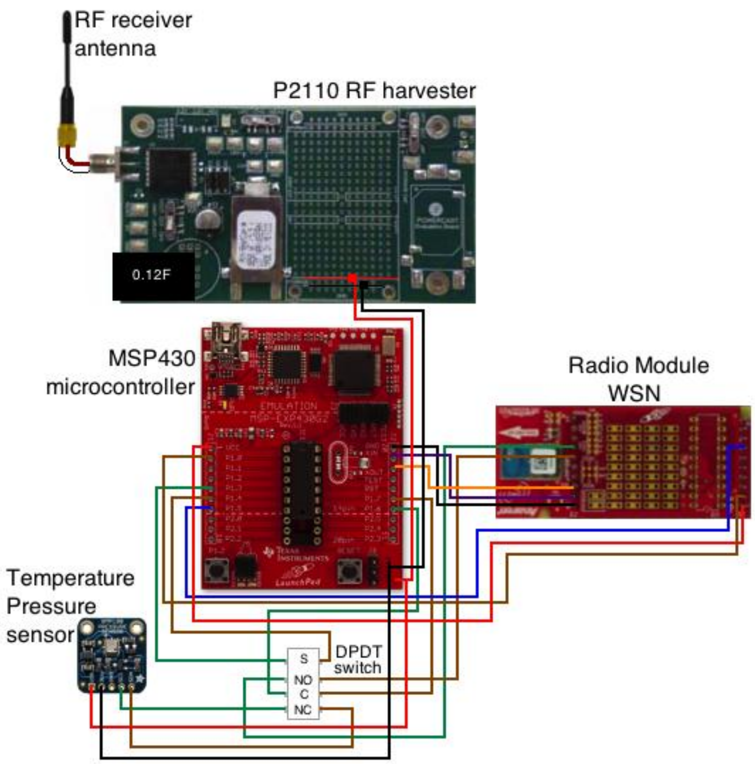


Figure 14- Schematic of the sensing node

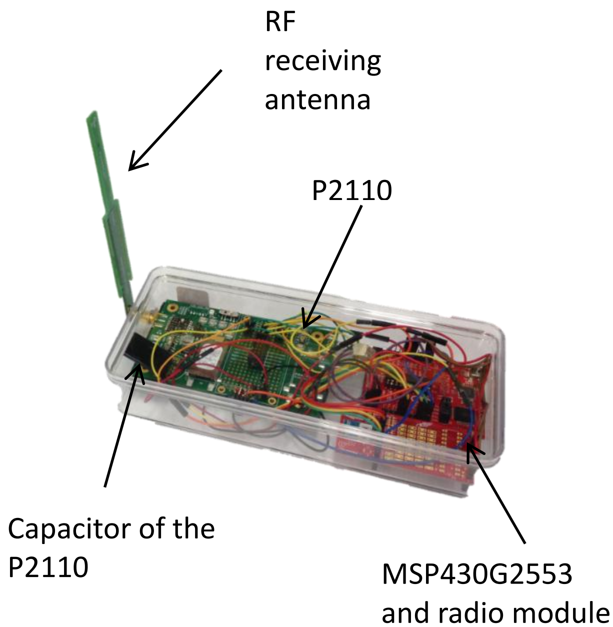


Figure 15- Sensing node packaging

B. Base Station

The base station is comprised of a MSP430 chip , radio module, Arduino Uno, and a Wi-Fi shield. The radio module and the MSP430 receive the information, check for package error, and transmit it to the Arduino Uno via UART. The Arduino Uno will then proceed and establish a connection to the Internet using the Wi-Fi shield. Finally a TCP connection will be established to a web server of preference, where it will send the data to a specific webpage. A detailed picture of the schematic of the base station can be seen in Figure 16. Figure 17 shows the implemented base station.

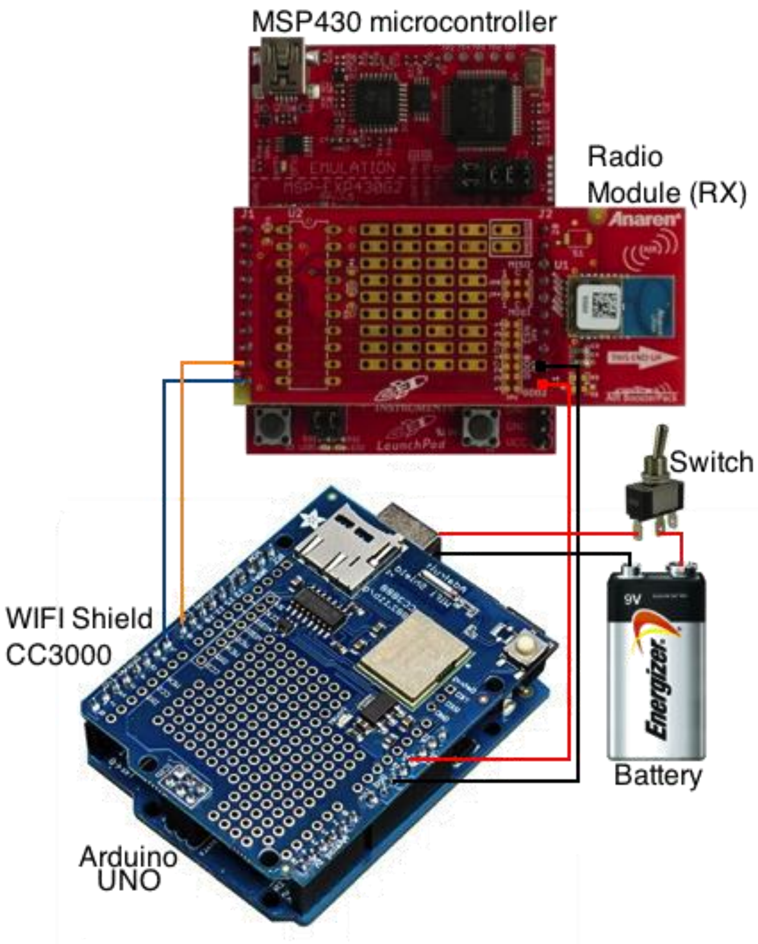


Figure 16- Schematic of the base station

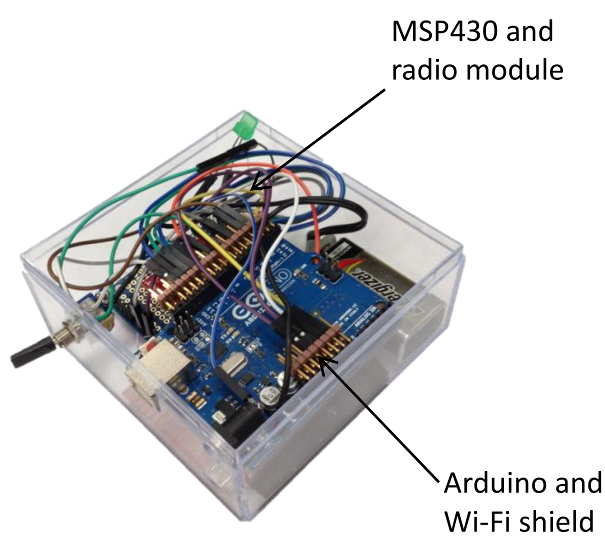


Figure 17- Base station packaging

Software implementation

The Arduino and Energia environment were used in order to program the microcontrollers, and implement the sensor and radio modules algorithms. Arduino and Energia are open software environments which allow the user to quickly program a microcontroller (Arduino and MSP series) using the C programming language. Figure 18 shows a snapshot of the Energia and Adruino environments.

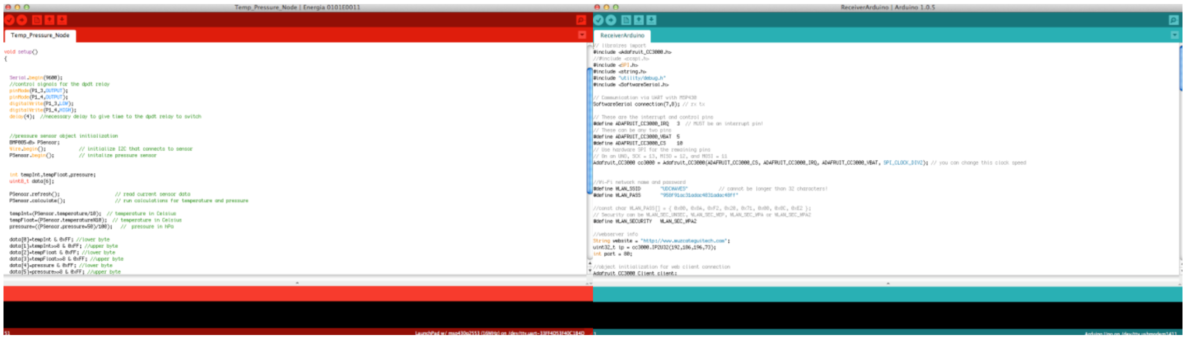
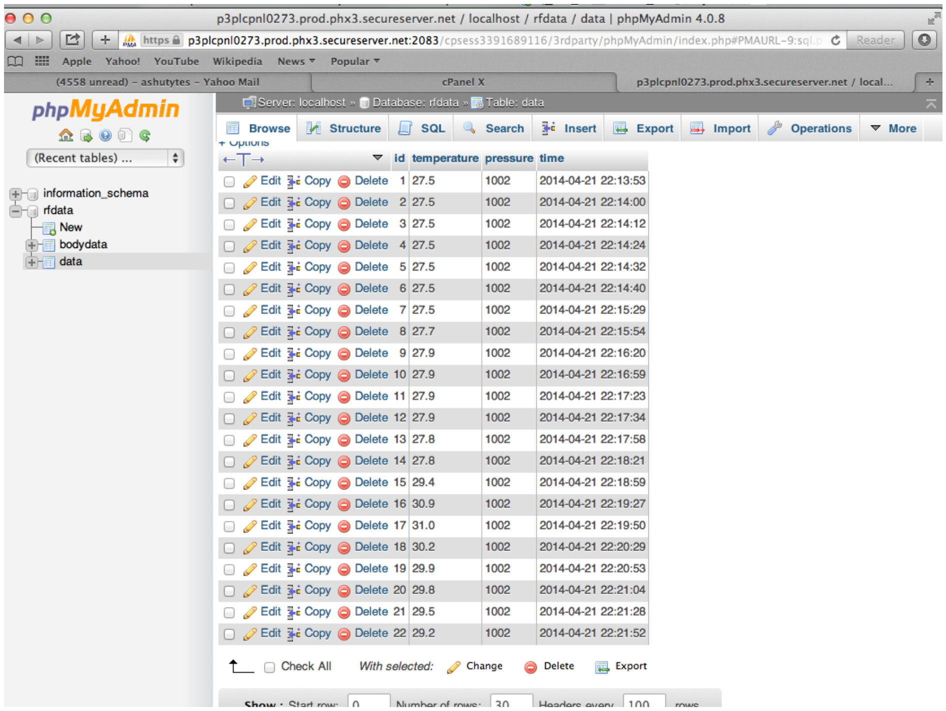


Figure 18- Energia and Arduino environment respectively

A webserver was created in order to introduce the data into the MySQL database. The webserver was programmed in PHP instead of HTML because of PHP's easy programming format and user support. The PHP program was uploaded using FileZila, which is a free File Transfer Protocol (FTP) application software that allows the user to establish an FTP connection with the server. The MySQL database is organized in a table form where each data field can be specified, numbered, and time stamped. It allows the user to easily tabulate data that can be exported into different file types (including excel). The following Figure was taken from the actual implemented MySQL database designed for this project. An ID number and a timestamp were incorporated in the table which lets the user know the number and time of measurements taken.



id	temperature	pressure	time
1	27.5	1002	2014-04-21 22:13:53
2	27.5	1002	2014-04-21 22:14:00
3	27.5	1002	2014-04-21 22:14:12
4	27.5	1002	2014-04-21 22:14:24
5	27.5	1002	2014-04-21 22:14:32
6	27.5	1002	2014-04-21 22:14:40
7	27.5	1002	2014-04-21 22:15:29
8	27.7	1002	2014-04-21 22:15:54
9	27.9	1002	2014-04-21 22:16:20
10	27.9	1002	2014-04-21 22:16:59
11	27.9	1002	2014-04-21 22:17:23
12	27.9	1002	2014-04-21 22:17:34
13	27.8	1002	2014-04-21 22:17:58
14	27.8	1002	2014-04-21 22:18:21
15	29.4	1002	2014-04-21 22:18:59
16	30.9	1002	2014-04-21 22:19:27
17	31.0	1002	2014-04-21 22:19:50
18	30.2	1002	2014-04-21 22:20:29
19	29.9	1002	2014-04-21 22:20:53
20	29.8	1002	2014-04-21 22:21:04
21	29.5	1002	2014-04-21 22:21:28
22	29.2	1002	2014-04-21 22:21:52

Figure 19- MySQL database table

In this project, 915MHz dipole antenna was used to harvest RF power for the environmental wireless sensor network. The 915MHz antenna can receive frequencies in a range of 902MHz to 928MHz. Although a 915MHz antenna was used, the P2110 RF harvester can operate in a range 600MHz to 1000MHz. Depending on the frequency availability of the area of implementation, the receiver antenna for the harvester can be modified for the most abundant frequency within the operating range. The other constraint is the distance between the sensor (RF harvester) and the transmitter. As this distance increase, the time needed to charge the capacitor using P2110 RF harvester increases due to EIRP of the transmitter. Therefore, location of the transmitter should be taken into account in placing the sensor node.

IV. Experimental Results

As discussed before, the P2110 RF harvester stores the energy that it gathers from the ambient RF energy into a capacitor. When the capacitor is full, it will discharge; therefore powering the circuit. When the capacitor reaches is threshold the P2110 board will start collecting RF energy again to charge the capacitor. The size of the capacitor will be dependent on the specifications of the circuit that will be powered. As shown in equation (1), the capacitor size is the function of the circuit voltage, average circuit current and the operating time of the circuit. For the designed circuit the following values were obtained:

Voltage of the circuit (V_{out}) $= 3.3V$

Average current of the circuit (I_{out}) $= 54$ mA

Operating time of the circuit (t) $= 34$ms

capacitor size $= 106$ mF

Measurements

A 3 watt transmitter was located around 2 meters away from the sensing node. This allowed the sensing node to turn on approximately every 45 seconds. The system was also tested at a distance of 5 meters from the transmitter. In this case, the sensing node turned on every 5-6 minutes and the value of the measurements was the same in both cases. This shows that distance will not affect the performance of the sensing node but will affect the time needed to charge the capacitor. This is as expected because as the distance between the RF transmitter and sensor node increases, the amount of RF energy at the sensor node will decrease requiring a longer time for the capacitor to charge. The designed sensor network was taken indoors and outdoors in order to gather real data. The results of the temperature and pressure nodes are shown in Figure 20. As visible in the temperature graph, the first part of the graph represents the indoor part of the experiment and the second part represents the outdoor part of the experiment. In the indoor part, the temperature is steady (around 25C). The spike in temperature was due the positioning of a lighter at the bottom of the sensor; this was done in order to check the sensor response to sudden changes in temperature. After this, the sensor was taken outside around 10:00 PM until 6:00 AM. As visible, the temperature drops as the night gets colder, and it starts rising again when the sun starts to come out. The pressure graph is really steady and varies from 1008 Pascal to 1002 Pascal, as expected, because pressure is not supposed to vary drastically for a given altitude.

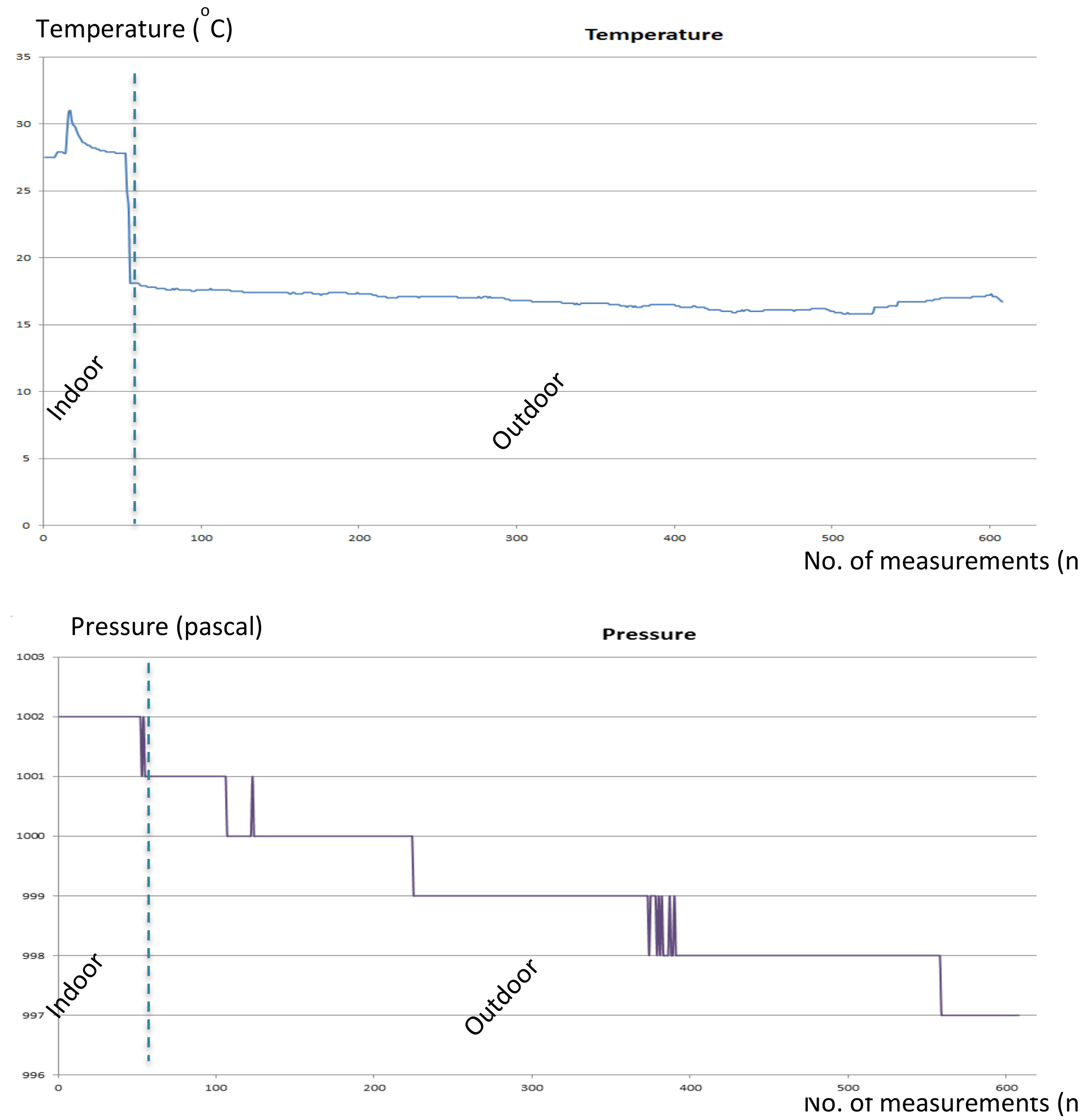


Figure 20- Temperature and pressure measurements

V. Project Assessment

The senior capstone design projects are assessed based on multiple realistic engineering design constraints and pertinent engineering standards. The followings are the considerations for the RF Energy Harvester project.

<u>Multiple Realistic Design Constraints:</u>

1. Low-cost, low-power, low maintenance Wireless Sensors Network system;
2. Choose RF converters with High power conversion efficiency, small circuit size,

shorter rise time or startup time, low input power threshold, low ripple or noise, and high voltage conversion efficiency;

3. Low sensor node power consumption;
4. Sub-system operational frequency range of 902MHz to 928MHz, for the receiving antenna not to interfere with any device in the area;
5. RF harvester, sensors, and transmitter proximity range;
6. RF harvester output Capacitance sized to provide adequate power for the Sensor node microcontroller over the data acquisition and transmission range.

Pertinent Engineering Standards:

1. IEEE STD 100-1984 data communication protocols;
2. Use IEEE 802.15 communication protocol standard in compliance with the Federal Communication Commission (FCC) rules.

Cost summary

The project was built using cost-efficient components and can be easily duplicated. A cost summary is provided in Table 1.

Table 1. Project Parts Price List

Component	**Cost($)**
2 x Mouser Powercast P2110-EVB	337.50
1 x COZIR Ambient 2/5/10K CO2 Sensor GC-0010 0-2000 ppm	109.00
4 x P2110 RF energy harvester chip	143.80
2 x XBee Module - Series 2 - 2mW with Wire Antenna - XB24-AWI-001	45.90
1 x Adafruit CC3000 Wi-Fi Shield with Onboard Ceramic Antenna	39.95
4 x Antenna M2M 0600-00029	58.56
Miscellaneous parts	100.00
Total	**$834.71**

VI. Conclusion and lessons Learned

This paper provided details of design, implementation, and experimental results of an environmental monitoring wireless sensor network powered by RF energy harvesting. For the optimized sensor node, the size of the capacitor was calculated to be 106 mF. This value of the capacitance was big enough to allow the microcontroller to turn on and make measurements of temperature and pressure in a reasonable and optimal period of time.

The RF harvested environmental WSN was designed, tested and implemented in real time, where data was measured, stored in the server, parsed to the MySQL database and finally displayed in graphs. Even though the dipole antenna used for this project allowed the WSN to work with a frequency range from 902 MHz to 928 MHz, a different antenna could be used for the WSN. As a future work for this project the viability of a different antenna can be researched in order to allow the WSN to have more versatility. As an example, an antenna that works from 800 MHz to 840 MHz can be used in order to give the WSN the capability of harvesting energy from GSM frequencies.

To successfully complete the implementation of this project, students had to read and digest a large volume of published literature, vendors' manuals, and to learn the regulation governing the use of RF bands. Designing and implementing such real-life application has helped students develop skills needed for long-life learning.

In addition, some aspects of this research project can be integrated in the teaching of undergraduate course. For example, experience gained in designing impedance matching circuits, and in programming the micro-controller and integrating it with the rest of the design components can help instructors design tutorials and laboratory exercises in designing multi-stage electronic circuits and muti-controller-based applications.

The successful implementation of the capstone project clearly indicated that the students were able to apply knowledge gained from almost all courses in their undergraduate education. They were also able to design and implement a useful application using modern engineering tools and a variety of computer languages such as C and MySQL database. The project implementation met both its constraints; low-cost and low power consumption. The project design and implementation also satisfied many of student learning outcomes, as defined by ABET, for capstone design projects.

VII. Acknowledgement

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References:

[1] http://www.powercastco.com/products/powerharvester-receivers/

[2] D. Dondi, S. Scorcioni, A. Bertacchini, L. Larcher, "An autonomous wireless sensor network device powered by a RF energy harvesting system" IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society, Montreal, QC, 25-28 Oct. 2012.

[3] F. Cuomo S. Della Luna, U. Monaco, U, and T. Melodia "Routing in ZigBee: Benefits from Exploiting the IEEE 802.15.4 Association Tree", *Proc. of IEEE International Conference on Communications,* Glasgow, Scotland, June 2007.

[4] K. Lu, Y. Qian, D. Rodriguez, W. Rivera, and M. Rodriguez "Wireless Sensor Networks for Environmental Monitoring Applications: A Design Framework", in Proc. IEEE Global Communications Conference, Washington, DC, November 2007.

[5] J. Yang and X. Li, "Design and implementation of low-power wireless sensor networks for environmental monitoring", *Proc. of IEEE International Conference on Wireless Communications, Networking and Information Security,* Beijing, China, June 2010.

[6] B. Pekoslawski, et. al. "Autonomous wireless sensor network for greenhouse environmental conditions monitoring", Proc. of the 20th International Conference on Mixed Design of Integrated Circuits and Systems, Gydnia, Poland, June 2013.

[7] H. Nishimoto, Y. Kawahara, and T. Asami "Prototype implementation of ambient RF energy harvesting wireless sensor networks" Sensors, 2010 IEEE, Kona, HI, 1-4 Nov. 2010.

[8] Peter Jamieson, "Arduino for Teaching Embedded Systems. Are Computer Scientists and Engineering Educators Missing the Boat?" *International Conference on Frontiers in Education: Computer Science and Computer Engineering (FECS'11), 2011*. Las Vegas, NV

[9] Debra J. Mascaro, Stacy J. Morris Bamberg, and R. Roemer," Spiral Laboratories in the First-Year Mechanical Engineering Curriculum," *Proceedings of the American Society for Engineering Education,*

Vancouver, BC, Canada, 2011.

[10] Ghassan T. Ibrahim, Aaron J. Homiak, Alexander Hallden-Abberton, and John R. Pulaski," Smart Box for Secure Delivery of Controlled Substance in Medical Centers," *Proceedings of the American Society for Engineering Education*, San Antonio, Texas, 2012.

[11] Emil H Salib, Joshua Alfred Erney, and Matthew Edwin Schumaker," Designed-for-Motivation based Learning for Large Multidisciplinary Team One Semester Hands-on Network based Course Case Study," *Proceedings of the American Society for Engineering Education*, Atlanta, Georgia, 2013.

[12] M. Rastmanesh "High Efficiency RF to DC converter with reduced leakage current for RFID applications" Dalhousie University, April 2013.