A WIRELESS SENSOR NETWORK POWERED BY MICROWAVE ENERGY

Undergraduate Students: **Emily Adams, Ayman Albagshi, Khaleel Alnatar, Gregory Jacob, Nathan Mogk, Alexis Sparrold**
Advisors: **Michael W. Marcellin and Hao Xin**
Department of Electrical and Computer Engineering
University of Arizona, Tucson, AZ 85721
Email: eadams@email.arizona.edu

Abstract

Systems that monitor environments often rely on cumbersome wires to supply power to the sensing equipment or batteries that require monitoring and replacement. As technologies continue to advance, the use of self-sustaining, wireless powering becomes more essential to satisfy challenging requirements that necessitate continuous measurement and general functionality. This paper focuses on the creation of a wireless sensor network with emphasis on the implementation of wirelessly charged sensing nodes by utilizing microwaves. Three subsystems make up this "proof of concept" wireless sensor system: a power transmitting base station, three sensor nodes, and a communication base station. Interfacing and power regulation are of the utmost importance in order to ensure all of the subsystems are able to communicate with one another and power all necessary functions. The power transmitting base station transmits microwaves to the nodes. A rectenna on each node converts the transmitted microwaves into DC power. Each node contains sensors to monitor the temperature and light of the environment. For the communication aspect of the system, Zigbee protocol, which belongs to IEEE 802.15.4 protocol, is used fore wireless communication between the base station and the nodes. Through the combination of power regulation, microwave energy, and radio transmission, users are able to utilize this system to collect environmental sensor data wirelessly.

1 Introduction

Wireless sensor networks are a beneficial technology that can be used for many potential applications. They can be used for monitoring of indoor and outdoor environments to facilitate the use of energy for climate control efficiently. As technologies continue to advance, the use of self-sustaining, wireless powering becomes more essential to satisfy challenging requirements that necessitate continuous measurement and functionality. This project is a "proof of concept" that focuses on the creation of a wireless sensor network with an emphasis on the implementation of wirelessly charged sensing nodes using microwave energy.

The project is based on designing, setting up, and testing a wireless sensor network for measuring temperature and light. The network nodes are composed of a rectenna that is provided by the sponsor, sensors, a power regulator, and a radio transmitter. A rectenna consists of an antenna and a rectifier that converts the AC power signal received by the antenna into DC power in order to power the system.

In this project, microwave energy is used to power the nodes in order to eliminate batteries. Batteries cause the system to be interrupted when they die or need to be replaced or recharged. For this reason, the microwave energy is used to provide a continuously operable system. A wireless set-up is useful for remote locations where no infrastructure currently exists. Wires can be subject to breakage and damage, which cause system interruption and failure. Also, wireless setup is less complicated to install and maintain in terms of hardware.

The XBee transceivers on each of the nodes utilize an ISM band of the radio spectrum. The ISM band is a set of frequencies called the industrial, scientific and medical band, which is intended for unregulated utility or re- search use. ISM bands are internationally provided for these usages. ISM bands often act as a host for unified protocols such as WiFi, Bluetooth, and ZigBee.

The limitation of a wireless sensor network is power. Because this system is transmitting energy by converting microwaves into DC power, there is a limit on the amount of power that can be collected and stored. Since a certain amount of power must be accumulated to complete a full sensor measurement, the rate of data collection is dependent upon the rate of power accumulation. If a particular user requires rapid monitoring of data, then this wireless sensor network may not be a feasible option. The rate of data collection constraint depends on the rectenna area, the conversion efficiency of the rectenna, the effective power transmission radius, and the distance between the microwave generated in relation to the rectenna. Another limitation is the loss often associated with the storage device and inefficiency of the power regulator.

2 System Requirements

The system must demonstrate the ability to support three nodes. The system must utilize a power base station provided by the sponsors. Also, the system must have a central base station where data is monitored and transmitted. USB must be used to connect a computer to the central base station. Moreover, the system must operate in low power mode when inactive. XBee radio modules must be used in order to transmit and receive data, which implement IEEE 802.15.4 (ZigBee) protocols. Each node will be equipped with a rectenna that collects power signals from a microwave generator and converts that signal to a DC signal to feed the system. The nodes must consume a low amount of power. The system shall harvest enough energy to operate efficiently. In addition, the system must not allow base station interference with node communication. The node must take consecutive measurements successfully and data must be transmitted to the base station.

2.1 Functional Decomposition of the System

The system consists of three subsystems. Subsystem 1 is Power Transmission, subsystem 2 is Power Conversion and Regulation and subsystem 3 is Communication.

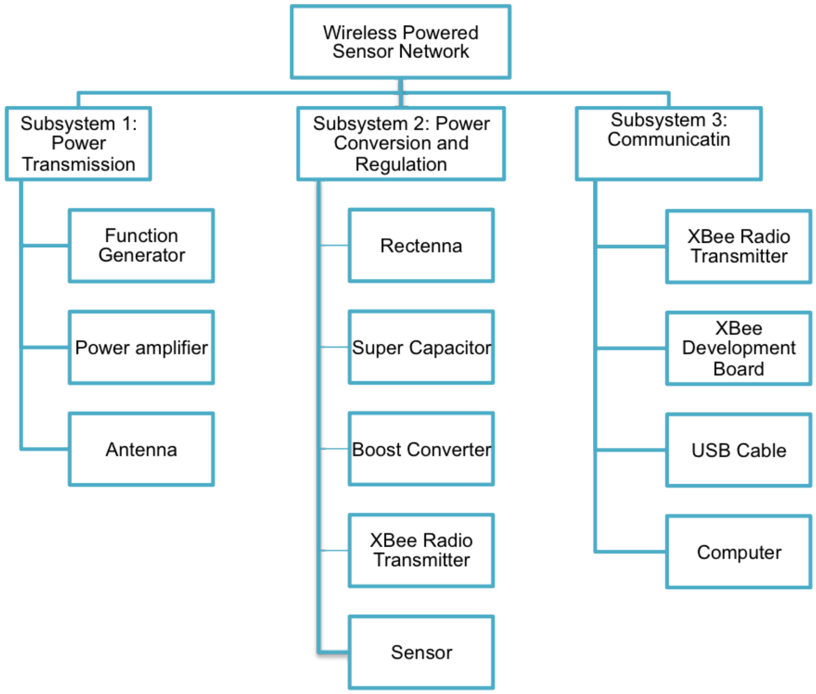

Figure 1: Functional decomposition of the system

1. Power Transmission Subsystem
   (a) Function Generator: produces microwave energy.
   (b) Power Amplifier: amplifies the signal received from the function generator.
   (c) Antenna: used to transmit the power signal from the function generator to the node.
2. Power Conversion and Regulation Subsystem
   (a) Rectenna: receives the AC power signal from the function generator and converts to DC power.
   (b) Super-Capacitor: stores energy received from the rectenna.
   (c) Boost converter: increases the level of the voltage on the super-capacitor.
   (d) XBee: is a radio transmitter that sends and receives data.
   (e) Sensor: reads the temperature and the light measurements.
3. Communication Subsystem
   (a) XBee: is a radio transmitter that sends and receives data.
   (b) XBee Development Board: XBee radio transmitter is mounted on the Xbee development board. Xbee development board connects the Xbee to the computer.
   (c) Computer: displays the collected data.
   (d) USB cable: used to connect the XBee Development Board to the computer to send the data collected.

2.2 Description of System Operation

The system consists of a power transmitting base station, nodes, and a communications base station. The power transmitting base station consists of a function generator connected to a wall outlet. The function generator produces microwave signals. Then, the signal is amplified by a power amplifier in order to be sent by the horn antenna. The rectenna receives the AC signal and converts to DC to charge the super-capacitor. The boost converter increases the voltage on the super-capacitor to supply the sensor and XBee radio transmitter on the node. Then, the XBee radio collects the data read by the sensor to send it to the communication base station. The XBee on the node causes the node to sleep long enough for enough power to be collected to maintain operations. The sleep time for this system is approximately ten minutes. The XBee radio transmitter at the communication base station receives and sends data to the computer. The XBee radio on the communication base station is mounted on an Xbee development board, which connects the XBee radio to the computer. The computer is connected to the XBee development board via a USB cable.

2.3 Interfaces

The components of the system interact with each other via physical and wireless interfaces. The user receives and displays the data through a computer. A USB 2.0 cable is used to connect the computer to the communication base that contains the radio transmitter. Alligator clip leads are used to connect the node to the rectenna. A microwave generator sends power at 1.575 GHz to the rectenna wirelessly through a power transmitter. The Zigbee protocol, specified in IEEE 802.15.4, is used as a wireless communication protocol between the communication base and the node. This protocol is implemented by the XBee. The XBee is used as radio transmitter that sends data at 2.54 GHz.

3 Subsystem and Interface Design

3.1 Subsystem 1

The first subsystem is comprised of a signal generator that passes a 1.5 dBm RF signal at 1.575 GHz through an isolator which acts as a switch. Once the signal has passed through the switch, it is then amplified by a power amplifier. The power amplifier has a power source, which is providing a DC voltage. This boosts the signal to 38.5 dBm. Then the signal is sent through a directional coupler. The directional coupler couples a defined amount of the electromagnetic power in a transmission line to another port where it can be used in another circuit. An essential feature of directional couplers is that they only couple power flowing in one direction. Power entering the output port is not coupled. This signal is also sent to the spectrum analyzer, which is connected to a computer for data recording. The signal is then sent to the horn antenna. By this time, the signal gain is 40 dBm. This means that 10 Watts of power are being broadcast from the horn antenna. At the rectenna, the received power is much lower at around 0 dBm or 1 mW.

3.2 Subsystem 2

Subsystem 2 is comprised of the rectenna, super capacitor and part of the actual node. The rectenna is 1-1.34 m away from the horn antenna. This rectenna is a half-wavelength dipole antenna that receives the power from the horn antenna. A half-wavelength dipole antenna consists of two poles, or sections, that are equal in length. The received signals are taken away from the receiver through a feeder. The feeder serves to transfer the power to or from the antenna with as little loss as possible. The total length of the dipole is a half wavelength, which makes each section or leg of the dipole a quarter wavelength long. In order for power to flow into or out of an antenna, there must be associated currents and voltages. The voltages and currents vary in a sinusoidal manner along the length of the antenna. The voltage is low at the middle and rises to a maximum at the ends, whereas the current falls to zero at the end and is at a maximum in the middle. This provides a low impedance feed point. A low impedance feed is ideal because it makes it convenient to match. The feed impedance is measured at the point in the antenna where the feeder is connected and matching it ensures that the maximum amount of power is transferred between the feeder and the antenna.

Then a series inductor acts like a bandpass filter. The bandpass filter blocks the re-radiation of harmonics, which are generated by the rectifying diode. Diodes are nonlinear devices so they always generate some frequency harmonics. By blocking those harmonics, they will be reflected at the band pass filter and go back to the diode so that they will eventually be rectified again and improve RF-DC conversion efficiency. The energy is then sent through a rectifier known as a Schottky diode. A low-pass filter is used to bypass DC and block RF current toward the load. The rectifier diode generates DC and harmonics. It is only desired to have DC and not harmonics. A 10F super capacitor is used as a storage device. The node is comprised of a boost converter, another super capacitor on the output of the boost converter, a Xbee radio, and 2 sensors. The super capacitor from the rectenna is placed on the input of the boost converter. The boost converter then boosts up the voltage to 3.3V. During initial designs the boost converter was connected straight to the radio, however during experimentation, it was determined that the radio would quickly drain the energy in the super capacitor before the radio could send a message. By placing another super capacitor on the output of the boost converter, we were able to charge up the secondary super capacitor and allow for more time, so the radio could send a message. The super capacitor on the output of the boost converter is a 0.1F super capacitor. The energy is then sent to the Xbee Radio. The Xbee is configured to sleep for 10 minutes so that power can be allowed to recharge once a measurement has been transmitted. Once 10 minutes have passed, the Xbee radio will wake up and have the temperature and light sensors send data. This is then communicated to a base station where a coordinator Xbee radio will be listening for the transmissions.

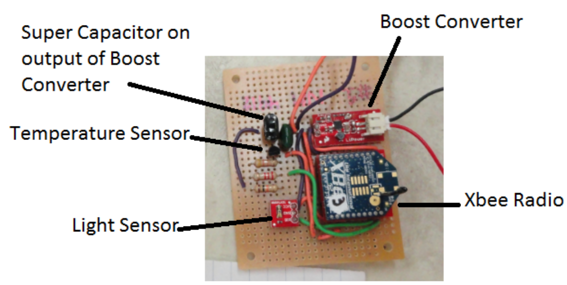

Figure 2: Picture of node showing major components and layout.

3.3 Subsystem 3

The final subsystem is comprised of a coordinator Xbee development board which as a Xbee radio configured for this role. This radio will be listening for the transmissions that the 3 nodes will be communicating. This is connected to a computer that monitors the input using LabVIEW as a GUI (graphical user interface). The data that is collected is shown in a diagram to indicate the amount of light and the temperature at each sensor.

4 Analysis

The project was able to charge the super capacitor on the rectenna to 0.8V. This became an equilibrium point between the super capacitor on the rectenna and the boost converter on the node. Once the voltage was able to stabilize the voltage, it became possible to take measurements from the sensors using the Xbee Radios. The blue line in Figure 4 shows a test that was successfully conducted in the anechoic chamber. This test operated for 1800 seconds or 30 minutes. The super capacitor would temporarily discharge as the measurement was being taken. The graph indicates these measurements, by the drops in the blue line on the graph. This was due to the fact that measurements required quite a bit of energy. However, with a duty cycle of 10 minutes we were able to recharge the rectenna's super capacitor to 0.8V and maintain its equilibrium point. A secondary node was placed in the chamber and exposed to the horn antenna's radiation. However because the secondary rectenna was not placed directly in front of the horn antenna, it was not able to maintain voltage. This is due to the fact that horn antennas are directional.The lack of alignment with the horn antenna did not allow for proper charging, this in turn causes the capacitor to discharge as measurements were taken. In addition, the node indicated by the red line was taking measurements at a rate much faster than the rectenna could sustain. The analysis of this behavior indicates that, with proper alignment with the horn antenna, this system is able to maintain itself for indefinite periods of time at a constant rate of 0.8V input, allowing for measurements every 10 minutes.

5 Acceptance Test

5.1 Acceptance Test Plan

Successful tests are completed by meeting minimum set requirements that are able to demonstrate whether the system does in fact prove that wireless charging of sensor nodes is a working concept. For this reason, the system may not necessarily demonstrate consistent success, but the success should be repeatable. The major requirements that must be met are the system shall take at least two consecutive measurements, contain three nodes on the network, and harvest enough power to operate indefinitely without charging or changing batteries. Clearly, an indefinite testing period is not feasible, so the system must demonstrate that the average charge rate equals the average discharge rate to demonstrate the operation is sustainable. All final tests were performed in an anechoic chamber to absorb any microwave radiation or signals that may stray from the system once emitted by the horn antenna. Also, any external frequencies that may interfere with functionality are blocked out by the chamber. Voltmeters were hooked up throughout the system in order to monitor the output voltages of the super capacitors onboard the rectennas, as well as the output voltage of the super capacitor on board the boost converter. This verifies whether there is enough power being supplied to and stored on the nodes in order to successfully transmit data to the communications base station. If the current that enters the node maintains a level that is sufficient to send a data measurement, then the system is working properly and should theoretically maintain this level indefinitely.

5.1.1 Test Setup Overview

In order to test the wireless charging capabilities of the rectennas, the anechoic chamber was utilized for testing. These tests required a complex test setup developed by the team and a post doctorate student. As explained above, the test setup began with a signal generator set to 1.5dBm that is connected to a power amplifier powered by a high-power DC power supply. The power amplifier is used to boost the signal to 38.5dBm, and this signal is sent through a directional coupler. After the coupler, the signal is sent to the spectrum analyzer that is connected to a computer to read data, as well as to the horn antenna in order to emit the specified frequency of 1.575 GHz at 40dBm.

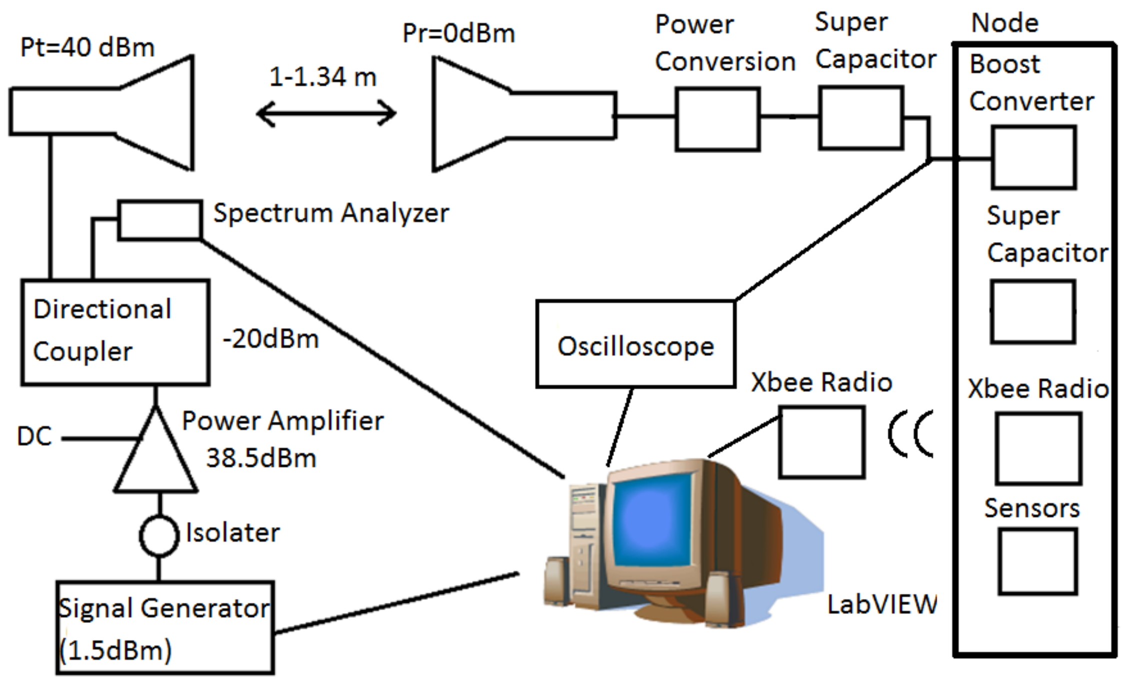

Figure 3: Test setup functional block diagram

The horn antenna is fed through a cable that runs beneath the door of the closed anechoic chamber. Within the chamber are two towers: one for the horn antenna and one for the rectennas. These two towers are limited to about 5 ft of separation distance due to the constraints of the chamber walls. Testing was typically done at around 1-2 meters. Once the signal is passed through the coaxial cable to the horn antenna, 10 Watts of power are sent from the directional antenna to the rectenna. The rectenna converts the AC power into DC power, which is stored on the super capacitor. Lead cables from the super capacitor are fed under the chamber door to the nodes located outside of the chamber. The nodes containing the sensors, boost converter, super capacitor, and XBee radio are then connected to an oscilloscope whose data is being fed into a computer/monitor to readily display the rectenna super capacitor values to the user.

In addition, the computer serves to interface with the coordinator node as the communications base station. The computer powers and configures the coordinator XBee through an XBee Development Board connected by a USB cable. This programs the coordinator to request and receive the sensor data from any nodes within the network. The data is then displayed on a graphical user interface for quantitative temperature and ambient light sensor measurements. Node measurements and the collected data strings are also displayed for easy user interfacing.

5.1.2 Chamber Test Results

Setup involving the chamber was extensive, leading to the choice to test one node's functionality before implementing all three nodes. After connecting a node configured with sleep mode, a test was run with the complete test setup. The charging profile of the super capacitor connected to the rectenna demonstrated successful charging; however, once the node began to take measurements, the power would subsequently drop drastically and no data would be received. Based on the sleep cycle and the timing of the power loss, it was concluded that the XBee's were most likely waking up and attempting to send a measurement, but the node lacked the power to transmit the message. This led to the decision to add a super capacitor to the boost converter circuit in order to create a power reservoir. The hope here was to acquire some extra time and power to successfully send a message to the base station. Upon testing this configuration, the node was able to successfully send consecutive data measurements to the base station.

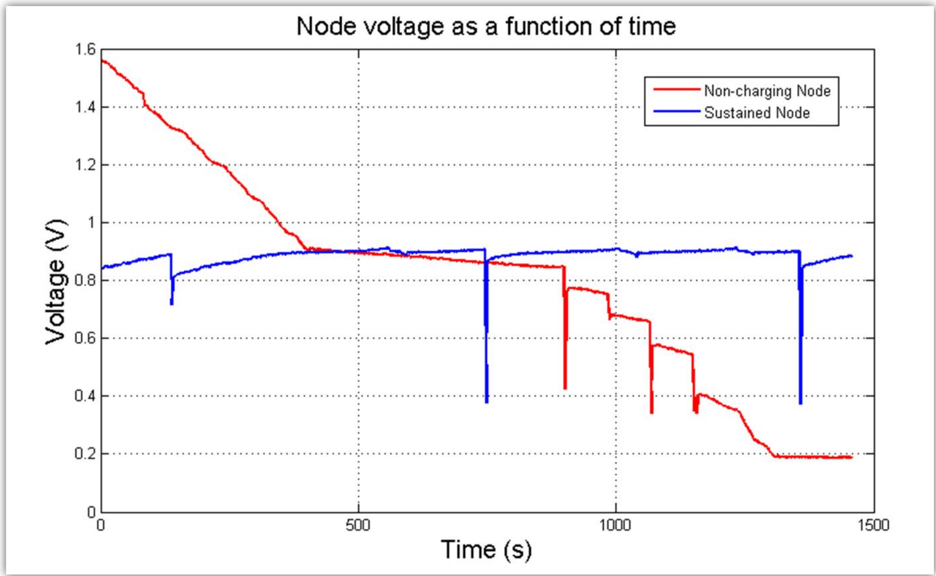

Figure 4: Node voltage as a function of time during testing.

Final testing consisted of testing all three rectennas, each connected to a separate node outside of the chamber. Variation was somewhat high in this testing due to the differences in design and orientation of the three rectennas used. Upon completion of the first test, one successful node was able to send data measurements in time increments of around ten minutes. Three successful measurements were recorded over the course of approximately thirty minutes, and the input power level from the rectenna super capacitor would always charge back and sustain itself at around 0.8 V. The second node had a connection problem within the chamber that could not be alleviated until the test was complete. The third node was able to take measurements, but the super capacitor was never able to charge back up to sustain functionality. This graph demonstrates a successful node, as well as an unsuccessful node (due to an inefficient rectenna and higher sampling rate). As shown by the graph, the input voltage to the node from the efficient rectenna super capacitor was around 0.8 V. The sudden drop in voltage represents the node draining power in order to send a measurement. Gradually, this power is regained as the rectenna slowly recharges its super capacitor. The duty cycle on these nodes was around ten minutes, providing sufficient time for the rectenna to recharge. Although this data only pertains to a single node, a sensor network containing three nodes with rectennas of identical design and efficiency would theoretically produce a sensor network that would successfully sustain three nodes through wireless charging indefinitely.

Again, a major area of variability involved the rectennas. Part of this variability was not under the jurisdiction of the team because this "proof-of-concept" system is building off of previous work and research done by the graduate students under our sponsors. These areas that are out of the scope of the project include general rectenna design and construction. Therefore, the only rectenna available for use were the three rectenna provided to the team, each containing a different design and consequently different performance capabilities. This variability became especially evident when a certain rectenna did not appear to be charging while another rectenna appeared to be operating more efficiently than other rectennas.

6 Closure

This project set out to demonstrate a prototype of a system that can transfer power wirelessly to multiple nodes in a network and perform useful functions once established. This system progressed from concept to implementation over the course of two semesters, and the final product met all of the major requirements satisfactorily. The system was able to demonstrate operation for essentially an indefinite period of time in the laboratory conditions. A stable equilibrium of rectenna capacitor voltage was reached at 0.8 V and did not seem to vary with received power.

6.1 Project Improvements

Future improvements to the system could include ruggedizing the rectennas and adding a full wave rectifier. The nodes can also be improved by finding components that require less power. The components that were chosen do not use a lot of power, but there is significant room for improvement. The less power that the node requires, the farther away from the power source the node can operate. Ideally, the system would be operational at tens to hundreds of meters from the base station. Another improvement that would improve the efficiency of the nodes is a switch that can detect when the node has sufficient power to transmit data, so that nodes would be less sensitive to rectenna performance or distance from the power supply. Such a feature would allow the nodes to dynamically update their cycle time to be most optimum.

7 References

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