Rectifier Antenna Design for Wireless Sensor Networks

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***Abstract*—Wireless Sensor Networks (WSNs) is a technology which is increasingly implemented in a multitude of data acquisition, data processing, and control applications. A rectifier antenna, or rectenna is a device used to convert radio frequency energy into electrical energy through the use of a rectifier circuit attached directly to a regular antenna. For most purposes, rectennas are used for microwave energy transmission, due to their high efficiency in converting microwaves into electrical energy. In this paper, we study the efficiency of rectifier antennas in harvesting energy and their applicability for powering Wireless Sensor Nodes.**

***Keywords*-Rectifier Antenna, Wireless Sensor Networks, Energy Harvesting**

I. Introduction

There are many publications that deal with rectifier antennas and their design, such as [1], [2], [3]. In the past, research was focused on the efficient transmission and reception of high amounts of power, but in recent years the paradigm shifted to the capture of microwave radiation of relatively low power densities [4], [5].

This is the case of wireless sensor nodes, which, due to their specifications, need to operate far away from the RF transmission source. We focused on the development of such an antenna, which operates at low power densities but has good conversion efficiency because it would allow one to power nodes located several feet away from the emission source.

A simple rectifier antenna consists of a dipole and a diode connected across its elements, usually a Schottky diode due to their low forward voltage drop. The alternative current that the antenna picks up from the environment is rectified by the diode in order to produce a DC voltage output. Of course, multiple rectenna cells can be combined into an array, in order to increase the amount of energy gathered from the environment.

When employed in Wireless Sensor Networks, rectennas are normally tuned to the ISM frequency bands which impose restrictions on the maximum transmission power. Thus, the challenge is to formulate a very efficient design within reasonable dimensions.

II. Rectifier Antenna Theory

A typical rectenna setup is shown in Figure 1. The microwave energy is converted into AC voltage by the antenna and then passed through an impedance matching circuit to the rectifier, which, in turn, converts it into DC voltage for the load. The impedance matching circuit ensures maximum power transfer by matching the input impedance of the rectifier to that of the antenna. In some designs, however, the matching circuit is rendered useless by creating an antenna that matches perfectly the rectifier input impedance.

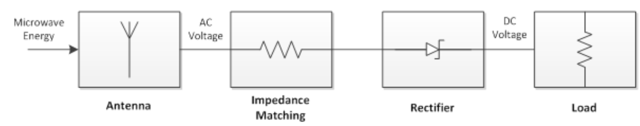

Figure 1. Typical rectenna circuit.

In our research regarding wireless energy transmission, we studied its applicability on a family of antennas called microstrip patch antennas. The reasons for this choice are the small dimensions of the antenna and its low manufacturing cost, which would make it an ideal choice for wireless sensor networks.

A patch antenna is a flat, low-profile type of radio antenna which is easily mountable on any even surface. It is typically built out of two parallel sheets of conductive metal, one of which serves as an active element and the other, usually larger, one serves as a ground plane. A dielectric usually lies between the two sheets. The ensemble forms a resonant segment of microstrip transmission line which needs to have the length of approximately half of the wavelength of the radio waves it is tuned to. Over conventional microwave antennas, patch antennas have the advantage of being able to be constructed on the same materials and using the same techniques as those used in the printed circuit board industry. In 2 a simple patch antenna is presented. It consists in two plates separated by a ground plane which are placed on a common printed circuit board (PCB). The dimensions of the antenna are determined by the resonant frequency. The resonant length is approximated to $\lambda/2$. Some parameters like the dielectric constant of the PCB material, metal thickness, patch width are also taken into account for more precise results.

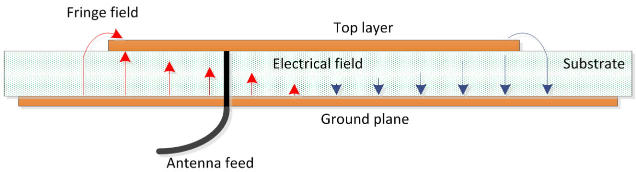

Figure 2. Patch antenna diagram.

The radiation pattern of a patch antenna differs from a design to another. By changing its form, a directional or omnidirectional antenna can be obtained. For this case, as presented in [6], maximum radiation will be obtained on the normal axis of the patch's plane and radiation to the back of the substrate is reduced due to the shielding effects of the ground plane. The radiation pattern for the patch is presented in Figure 3. A narrow beam width can be observed both in x and y axis which results in a cone of radiation.

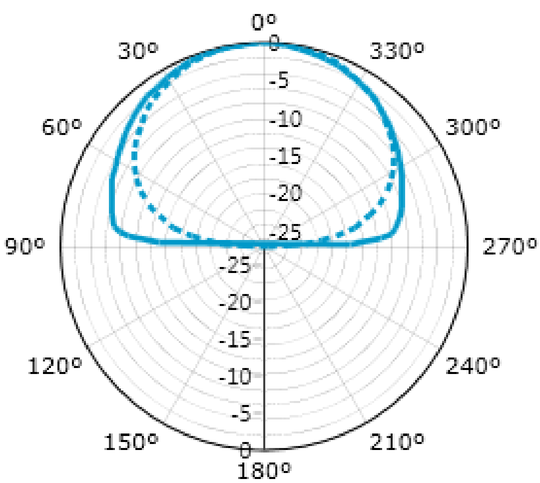

Figure 3. Typical patch antenna gain.

The antenna designed in this section is tuned for the 2.4GHz ISM band, as most of the WiFi, Bluetooth and Zigbee transceivers that can be found in a typical use-case scenario utilize this frequency for communication. The simplest model of a patch antenna consists of a conducting top layer, which forms the effective surface of the antenna, an insulating dielectric substrate and a bottom conductive ground plane. Due to this fact, most patch antennas can be easily fabricated out of a two layer PCB, which significantly decreases their price. Most patch antennas differ in design by the way they are fed, as shown in Figure 4

For our purposes, we settled on designing a patch antenna that is using edge feed, as an inset feed would introduce some parasitic capacitance between the line of the feed and the patch itself, which could cause performance degradation.

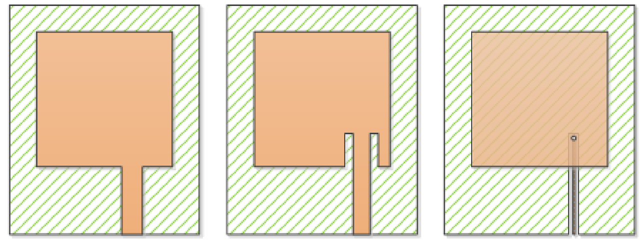

Figure 4. Different types of feeds for rectangular microstrip antennas. From left to right: edge feed, inset feed and probe feed.

III. Implementation of the Design

Design and simulation of the patch antenna was done with the help of Ansys HFSS suite, which is a 3D full-wave electromagnetic field simulation tool employed in high-frequency and high-speed component design. The antenna was made out of a FR4 double layer PCB with a thickness of 1.6mm. Its relative permittivity is $\varepsilon = 4.28$ and a loss tangent $tan(\delta) = 0.016$. We used the standard copper layer conductivity for a FR4 board, $\sigma = 5.8 \cdot 10^7 \Omega^{-1} m^{-1}$.

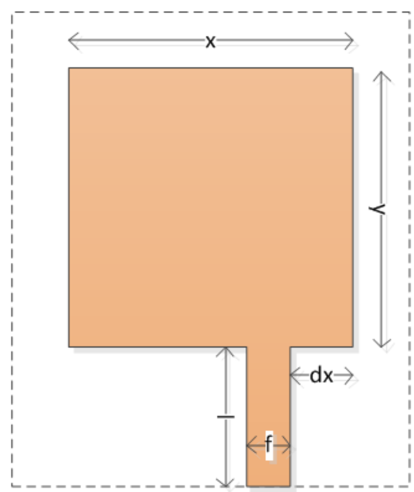

Figure 5. Dimension specifications for an edge feed patch antenna.

Finding the antenna patch dimensions for the frequency of 2.45GHz was done through iterative testing and simulation in the full-wave simulator software, choosing a design that yielded the best results. The dimensions we found for the patch antenna in Figure 5 are the following: x=27.1, y=31.2, dx=0mm, dy=0.6mm and l=0.38mm.

IV. Simulation of the Rectenna

Simulation data shows that the antenna resonates at the frequency of 2.45GHz as shown in Figure 6 and that it can deliver a gain of around 6dB for that frequency, which is encouraging, taking into consideration its dimensions.

The rectifier antenna system was formed when the antenna was coupled with a diode rectifier circuit, as shown in Figure 7.

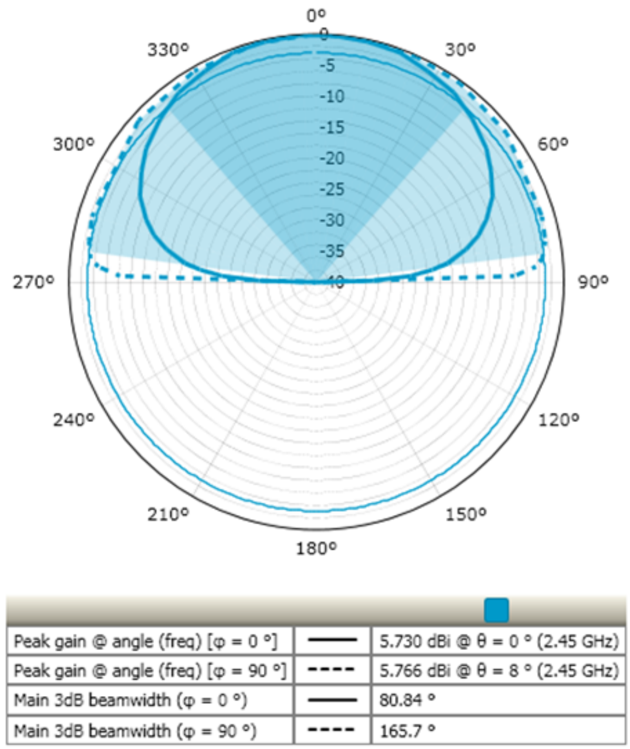

Figure 6. Total antenna gain patterns in polar and Cartesian coordinates.

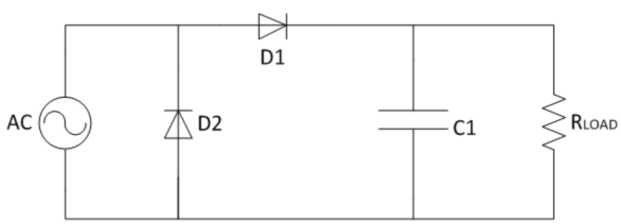

Figure 7. Voltage doubler rectifier circuit.

The antenna voltage output is a 2.4GHz sinusoidal AC voltage of varying amplitude, depending on the distance from the transmitter and its power. In order to convert it to a DC voltage, the rectifier circuit in Figure 7 is employed. However, due to the very low voltages induced in the antenna, a very efficient diode rectifier circuit is used which also acts as a voltage doubler. The capacitor C1 value was chosen to act as a shortcircuit at 2.4GHz and the two Schottky diodes, D1 and D2, are connected in series, virtually doubling the rectified voltage.

The most important aspect of designing such a circuit is matching its input impedance to that of the antenna. The diodes we used for our design were HSMS2852, two zero bias small signal diodes in a single package. Their low forward voltage drop and fast switching time proved them ideal for our purposes. We calculated their input impedance and halved it, as they can be viewed as connected in parallel at microwave frequencies. This gave us the input impedance for the rectifier circuit which we used to determine the patch antenna dimensions that would yield matching impedance. Results were incorporated in the design of the patch antenna described in Figure 8.

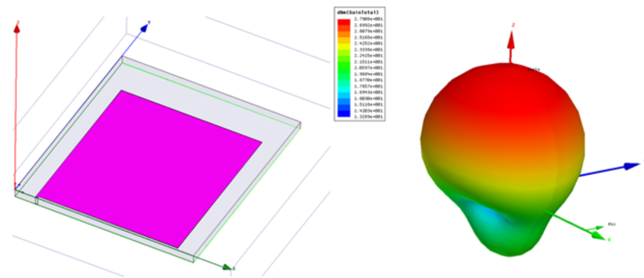

Figure 8. Patch antenna model and simulated 3D radiation pattern.

V. Experimental Results

In order to test the effectiveness of powering a device using scavenged microwave energy, an experiment has been set up. We needed to test the harvester in a situation close to a real life scenario, so we employed a standard 2.4GHz wireless router as an energy source. The output of the router was connected to a cylindrical wave guide and the router was set to transmit at maximum power, which we measured to be around the regulated limit of -10dBm or $100\mu W$.

Efficiency of the RF energy harvester circuit presented in Figure 1 can be derived as the ratio between the power available at its output and power collected by the antenna from the environment. This relation can be expressed as:

$$\eta = \frac{P_{DC}}{P_{harv.}} = \frac{V_{DC}}{R_{load}^2 \cdot P_{harv.}} \qquad (1)$$

The Friis [7] equation allows us to compute the received power of an antenna as a function of the distance from the transmitter.

$$P_{harv.} = P_T \cdot G_T \cdot G_R \cdot \left(\frac{\lambda}{4\pi R}\right)^2 \qquad (2)$$

, where P_T is the transmitter power output, G_T and G_R are antenna gains, λ is the wavelength of the microwave radiation and R is the distance between transmitter and receiver.

The harvester was oriented parallel to the wave guide aperture, in order to ensure the highest power transfer possible. The harvester was connected in parallel with a 10mF capacitor that was intended to simulate an energy storage medium. Several measurements of the capacitor charging curve were taken while incrementally increasing the distance from the wave guide from 20 to 60 centimeters.

The capacitor charge curves are plotted in Figure 9 and they clearly show that energy is being received by the patch antenna and converted into usable DC voltage. After

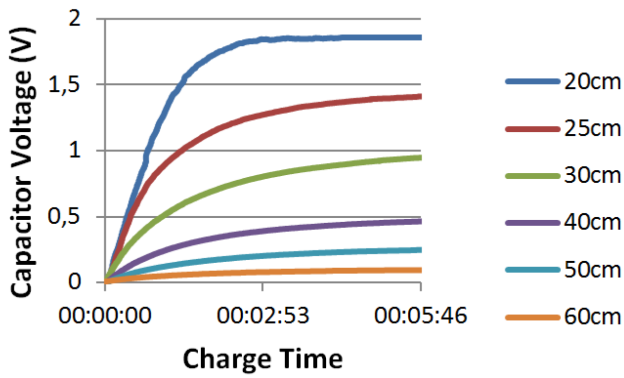

Figure 9. Capacitor charge curves depending on the distance from the microwave emitter

each charge, capacitor voltage reaches a steady value which decreases with distance.

This is more clearly shown in the second plot from Figure 10 which shows how the average DC power generated at the output of the RF harvester varies over distance.

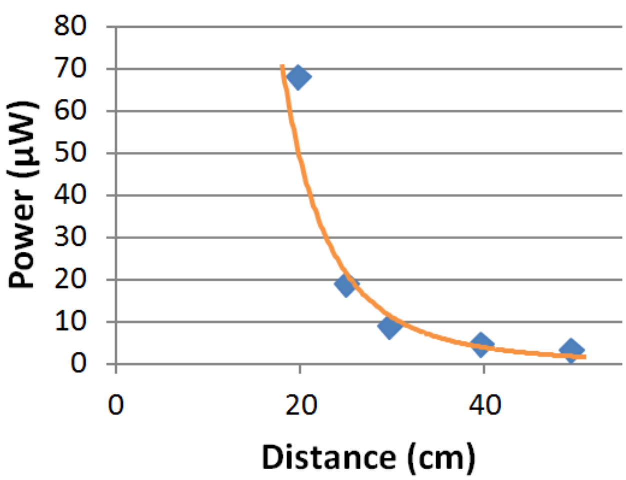

Figure 10. Average harvested power depending on the distance from the microwave emitter

Maximum power transfer was achieved at 20cm and was $67\mu W$ (due to experimental setup constraints, this was the nearest we could reliably measure the power transfer), or a 67% efficiency in energy transfer from the transmitter to the harvester. However, this figure dropped dramatically when we increased the distance between the two entities to around $2\mu W$ at 0.5m. This is in accordance with the Friis equation in (2), where is it shown that received power varies by the inverse square of the distance from the transmitter.

In order to overcome the drop in harvested RF energy with distance, a simple solution of using multiple rectifier antennas was successfully employed. The antennas were all etched on the same PCB in an array and linked together in series to form a wireless battery, as shown in Figure 11.

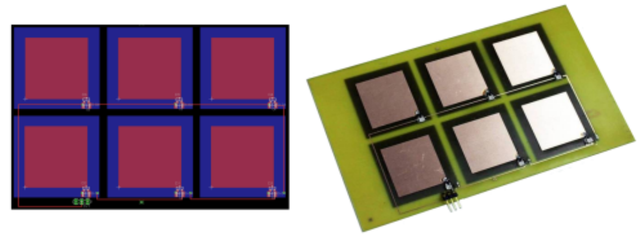

Figure 11. Rectenna array of six elements employed as a wireless battery. Printed circuit board design and actual harvester.

VI. Testing on Wireless Sensor Nodes

The platforms we will be testing this method on are the SparrowV3, a sensor board developed in our University for wireless sensor network research and development featuring the ATMega128RFA1 processor from Atmel, a controller that has an on-chip transceiver.

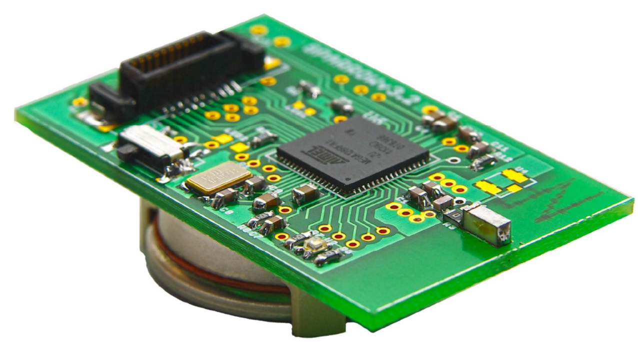

Figure 12. The SparrowV3 sensor node.

The miniature sensor board contains several sensors and connectors for programming and is supposed to consume very little power in sleep mode. According to [7], the microcontroller's power consumption levels under normal operating conditions (25C, 16MHz crystal oscillator, no watchdog, 3V supply voltage) are: $P_a = 43.5mW$ during power on and $P_i = 15\mu W$ during sleep.

Given these energy consumption constraints and the rectenna performance curves measured in the previous section, it is obvious that powering up a wireless sensor node at full capacity using this method is highly impractical, due to the large size of the wireless battery array needed to supply such high energy demands. However, wireless sensor nodes are rarely employed in applications where they need to be fully powered for the whole length of their life. Instead, the vast majority use duty-cycling to maximize the time spent in sleep and, as a result, their battery life. It is, thus, conceivable to imagine a scheme where the node will be powered by a rectenna array while functioning at full capacity only for a very small amount of time compared to its period.

We can estimate the minimum time a node needs to spend in idle state in order to fit an energy consumption profile, by deriving it from the following formula:

$$P_{harv.} \geq \frac{P_a \cdot T_a + P_i \cdot T_i}{T_a + T_i} \quad (3)$$

, where Ta and T_i are the active and idle periods for the node.

Therefore, the minimum time a node needs to sleep given a fixed power budget of $P_{harv.}$ can be written as:

$$T_i \geq T_a \cdot \frac{P_a - P_{harv.}}{P_{harv.} - P_i} \quad (4)$$

Applied to our case, we can calculate the duty cycle of a SparrowV3 node powered in such a manner. Given the node is powered by a rectenna array of eight elements from a distance of 0.5m, as in the previous section, the total harvested power of the array $P_{harv.}$ is $16\mu W$. The typical time the SparrowV3 node needs to power up, take a measurement and send it forward to the network is $T_a = 100ms$.

$$T_i = 0.1 \cdot \frac{43.5 - 0.016}{0.016 - 0.015} = 4348s \simeq 1.2h \quad (5)$$

This long period and can be interpreted as the minimum amount of time the storage capacitor attached to the rectenna array needs to trickle-charge in order to power the node for one single measurement burst. While it might seem impractical and not suited to applications where nodes need to sample sensor data with a high frequency, most environmental sensing applications are not subject to such measurement constraints and can easily work with much higher duty cycles.

VII. Conclusion

We have designed and tested a working rectifier antenna prototype tuned to the 2.4GHz ISM band and measured its performance in harvesting excess wireless energy from an off-the-shelf WiFi router. As predicted, harvested power levels decrease by the inverse square of the distance from the microwave emitter. This phenomenon can be counteracted by using a narrow beam microwave emitter in order to focus the radiation at greater distances or by using multiple rectifier antennas coupled in an array.

Results prove that, under careful power management, it is feasible to deploy such a solution in remotely powering a wireless sensor node.

VIII. Acknowledgements

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