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Improvement of Internet of Things (IoT) Sensor Powering Using Multi Node Radio Frequency Energy Harvesting (REH)

B.I. Bakare[1], I.A. Salami[2] and S. Orike[3]
[1,2](Department of Electrical Engineering, Rivers State University, Port Harcourt, Nigeria.)
[3](Department of Computer Engineering, Rivers State University, Port Harcourt Nigeria.)

Abstract: *RECTENNA as the name implies is a rectifying antenna, which is a special type of receiving antenna that is used for harvesting electromagnetic energy into direct current (DC). The major problems of other Rectenna is the inability to harvest much electromagnetic energy in order to produce an amazing DC voltage output. However, this Research work is focused on designing and testing of an antenna rectifier circuit (RECTENNA) optimized for incoming signals and to improve the electromagnetic energy to direct current (DC) conversion rate. This research work seeks to improve energy harvesting from 2.4 GHz to 10 GHz with a corresponding DC output voltage of 0.85v to 2.4 v respectively. The RECTENNA is applied in harvesting of RF signals that has been transmitted by communication link and also broadcasting industries within the range of 10 GHZ. This work also contains the methods of harmonic balance modeling and simulations, impedance matching with corresponding smith charts and two powerful Schottky diodes which were used for the dc voltage rectifiers. In order to achieve the aim we designed a 2 by 2 Micro Strip Patched Antenna (MSPA), moreover, the patches of the antennas are converted to a layout component using advanced model composer. The antenna is placed into a schematic and the system composed of this antenna and the rectifier is simulated using Advanced Design System (ADS) respectively. The goal of this work is to achieve the low power rectification and improve the dc output voltage of the RECTENNA. This research work has produced a RECTENNA operating at 10 GHZ with an output voltage of 2.4 volts respectively.*
***Key Word**: Rectenna; Antenna; Radio Frequency (RF); IOT; RF Harvester;*

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I. Introduction

RF Energy Harvesting [REH] has become a prominent research area because of its various applications and significance [1]. The major issue of RF Harvesting is low output power produced by the RECTENAS, however the voltage generated is almost insignificant to take over from batteries in the terms of powering other conventional electronics gadgets. It's so astonishing that harvesting a Wi-Fi signal of 2.4 GHz will amount to an outputs of about 200-300mV which is not enough to bias a transistor. As it is stated above, IOT sensors have been powered by batteries. Also, most of today's world technology gadgets are dependent on the battery power. This may create a problem of having the battery constantly charged, which is hard to maintain outdoors (example hazardous plants). RF vitality is communicated from various purposeful or accidental electromagnetic assets [2], For example, GSM- 900, GSM-1800, Wi-Fi (2.4 GHz), 3G et cetera. This research work seeks to harvest a 10GHz frequency and also to improve the output DC voltages. This might be used to power low-power sensors with the availability of free Wi-Fi vitality, REH innovation may usher in a new age of self-powered devices. Recently, several efforts have been made to outline Rectennas from diverse perspectives

Energy harvesting is a mechanism for transforming readily available energy from natural or artificial resources into usable electrical energy. From the law on conversion of energy which states that "Energy can neither be created nor destroyed, can only be converted from one form to another". One of my childhood fantasies is to transmit energy as wireless link transfer data. This made possible the invention of Rectenna, (Rectifying Antenna) which converts RF energy to dc power, which power equipment in IOT/IET (internet of things / internet of everything).This can be used in wireless power transmission systems that transmit power by radio waves. It is made of dipole antenna, with an RF diode mostly Schottky diodes are used. The rapid evolution in the promising paradigm of IoT/IeT has resulted in a massive distributed network of intelligent objects possessing a highly varying compute, storage, and networking capabilities [3].

This research work seeks to improve energy harvesting from 2.4 GHz to 10 GHz, this would enable the Rectenna to be an improved Rectenna compared to what is existing before now. However it would not just create an improved output voltage but an improve efficiency for the system drive IOT sensors effectively even without batteries or mains. The RF harvesting method is a growing method used in gaining free energy for powering of devices that doesn't really needs much power but in this paper we will be laying more emphasis on studying about the RF energy harvesting, studying and analyzing the types of power harvesters, batteries and other power storage devices and conducting an explicit simulations on the RF Energy Harvesting Rectenna system. With the growing popularity and applications of large-scale, sensor-based wireless net- works (e.g, structural health monitoring and human health monitoring,), the need to adopt inexpensive, green communications strategies is of paramount importance. One approach is to deploy a network comprising self-powered nodes, i.e., nodes that can harvest ambient energy from a variety of natural and man-made sources for sustained net- work operation [4]. This can potentially lead to significant reduction in the costs associated with replacing batteries periodically. Moreover, in some deployments, owing to the sensor location, battery replacement may be both practically and economically infeasible, or may involve significant risks to human life.

II. CONCEPT OF RADIO FREQUENCY ENERGY HARVESTING (RECTENNA)

The RF energy harvesting is a "Green" self-sustainable operation which can potentially provide unlimited energy supply that can be used to remotely power up low power devices [5]. In particular, it helps to eliminate the need for a battery, which not only increases the cost, weight, and size of the device but the battery replacement is also costly and time-consuming especially when a lot of devices are spread over wide or inaccessible areas [6]. The basic block diagram of a Rectenna is shown in Figure 1. It comprises of a single or a combination of antennas, a band pass or tunable filter (BPF), a broadband or multiband impedance matching network, a rectifier, and a low-pass filter that delivers the output to the load. The antenna is used for receiving the RF waves. The impedance- matching network is used to match the impedance of the antenna to the rectifying circuit for the maximum power transfer of RF energy to the rectifier. In addition, a matching network is used between the rectifier and the load to avoid impedance mismatches which can limit the maximum power available at the load. The rectifier converts the alternating voltage generated by the incident RF waves at the receiving antenna terminals to a DC voltage. A low-pass filter is used for obtaining ripple-free DC voltage across the connected load. In the following sections, these diff erent components of the Rectenna system will be discussed.

2.1 Receiving Antenna

The antenna is an integral part of the Rectenna that should poses several requirements for harnessing the ubiquitous RF energy and converting it into a useful output DC voltage. Circularly polarized antennas are preferred in Rectenna designs as they can receive both linearly and circularly polarized RF signals without any polarization loss. In contrast, linearly polarized antennas receive only half of the power of the circularly polarized wave and also suff er from polarization loss factor in capturing linearly polarized waves. This eventually results in the degradation of the over- all efficiency of the Rectenna. Furthermore, the antenna should be broadband so that it can receive all the ambient RF energy present in multiple frequency sources present in the surroundings. This is due to the fact that the power levels of the ambient signals are already in microwatts and more energy harvesting is required in order to get a sufficient output voltage for powering up ultralow power wireless sensor nodes. The antenna should also be miniaturized and compact so that it can be used in portable and wireless charging applications

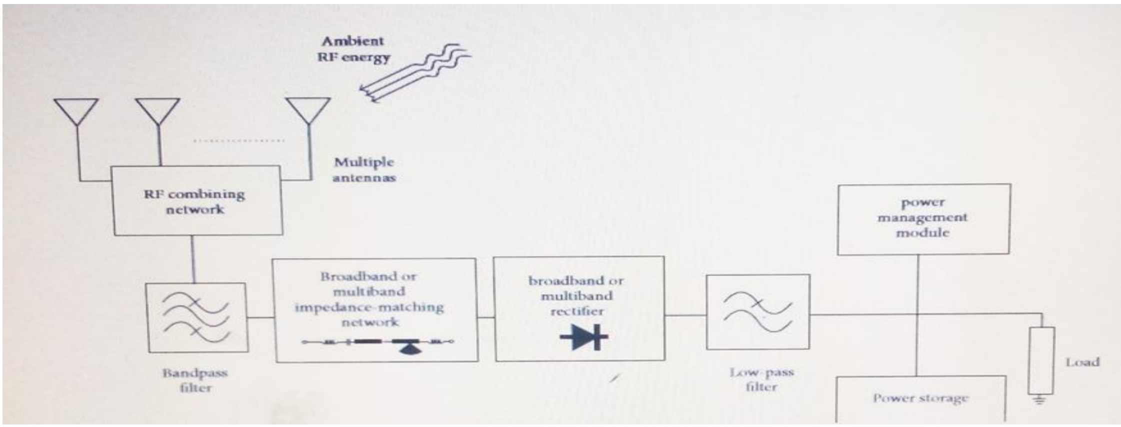

Figure 1: Rectenna [7].

In order to achieve more received power and an improved efficiency of the rectifier, both transmitting and receiving antennas should have high gain. One of the methods to increase the gain of the antenna is by making an antenna array as shown in figure 1. The array increases the RF power available at the rectifier input, but it also results in the increase of antenna size rendering it unsuitable for portable applications. Similarly, if the antenna is omnidirectional, then it can receive radiations from all the directions; however, its gain will be lower. These are some of the common trade-offs faced by researchers to achieve antennas that exhibit high efficiencies and output voltage, the ultimate goal of RF energy harvesting. Several antenna types such as micro strip antenna, dipole, monopole, and Yagi Uda antenna are used as the receiving antenna for RF energy harvesting. Most of the antenna designs found in literature are micro strip based owing to their low profile, compactness, light weight, high efficiency, low cost, easy fabrication, and conformity. The most commonly used micro strip antennas are square, rectangular, and circular patch antennas mainly due to their low cross-polarization levels [5].

2.2 *Matching Network*

Impedance-matching network is an integral requirement in a Rectenna design and was found between the antenna and the rectifier. The RF-DC conversion efficiency of Rectenna greatly depends on its impedance-matching network. The design of matching net- work is challenging and requires several considerations. This is due to the fact that the input impedance values of rectifier circuit as well as antenna change with frequency. Further complexity is added due to the power-dependent behavior. Of rectifier's input impedance, therefore, a broad band or multi band impedance-matching network needs to be designed for impedance matching over a wide range of frequencies and input power level. The matching networks for the Rectenna can be implemented using lumped elements or distributed micro strip lines. Each method of implementation has its own trade- offs. The quality factor Q of the lumped element-based matching circuit is lower as compared to the distributed line network, thus offering wider bandwidths.

However, at frequencies higher than 1GHz, the lumped components are not suitable due to the parasitic effects associated with them. Thus, micro strip line-based matching circuits are used at higher frequencies. The matching network is designed in such a way that the input impedance of the antenna is the complex conjugate of the input impedance of the rectifier circuit at a specified input power level. A number of matching networks have appeared in literature for Rectenna circuits.

2.3 Rectifier

Rectifier, also called a charge pump, has three basic types:

i. Basic rectifier,
ii. Voltage doubler,
iii. Voltage multiplier.

For Rectenna application, a rectifier should have high RF to DC conversion efficiency. Typically implemented through one or more diodes, the choice of diode is of prime importance as it can be a major source of loss and its performance determines overall efficiency of the system. The power conversion efficiency of the rectifier mainly depends on the following:

i. Series resistance of the diode (Rs), which determines the efficiency of the rectifier;
ii. Zero-bias junction capacitance (Cj0) which affects the oscillation of harmonic currents through the diode;
iii. Diode breakdown voltage, (Vbr), which limits the power-handling capability of the diode;
iv. Switching speed of the diode which should be fast so that it can follow a high frequency signal;
v. Low threshold voltage so that it can operate at low RF input power [8].

The maximum operating frequency of the diode is limited by the junction capacitance (Cj). The substrate and transmission line losses also contribute to the overall reduction of the efficiency of the energy- harvesting devices which depends on the type of substrate chosen and the length of the transmission line [9].

2.4 Low-Pass Filter

A standard low-pass filter is typically utilized and it consists of a capacitor connected in parallel with the load after the rectifier circuit. It is used to filter out the higher order harmonics from the DC component that is provided to the load as shown Figure 1

III. MATERIALS AND METHOD

The design and simulation of the RF harvesting 2 × 2 antenna and the RECTENNA Circuit is done using Advanced Design System (ADS).software. Simulation is an imitation of the operation of a real-world process or system. Before live implementation, testing of the developed technique is required. Most of the time, testing and evaluating the protocols or theories proposed is not practically feasible through real experiments as it would be more complex, time consuming and even costly. So, to overcome this problem, "SIMULATORS and TESTBEDS are effective tools to test and analyze the performance of protocols and algorithms proposed [10]. Furthermore, the emulation of the operation of a real live system or process is called simulation [11].

3.1 Antenna Design

Coupled electromagnetic double patched antennas are used for building the RECTENNA antenna as shown in the Figure 2. The dual patched antennas and the feeding lines are etched on the substrate with it dielectric constant. The slots are etched in the ground which is localized between the substrates. The antenna system shown in Figure 2 and Figure 3 for the two topologies are designed and simulated using an Advanced Design System (ADS) of Agilent technologies using Harmonics Balance (HB) simulators. And for conversion of the RF-DC a zero bias HSMS2880 Schottky diode was used and the circuit was optimized in order to obtain an impressive impedance matching and a valuable conversion efficiency for the dual topologies at 10 GHZ.

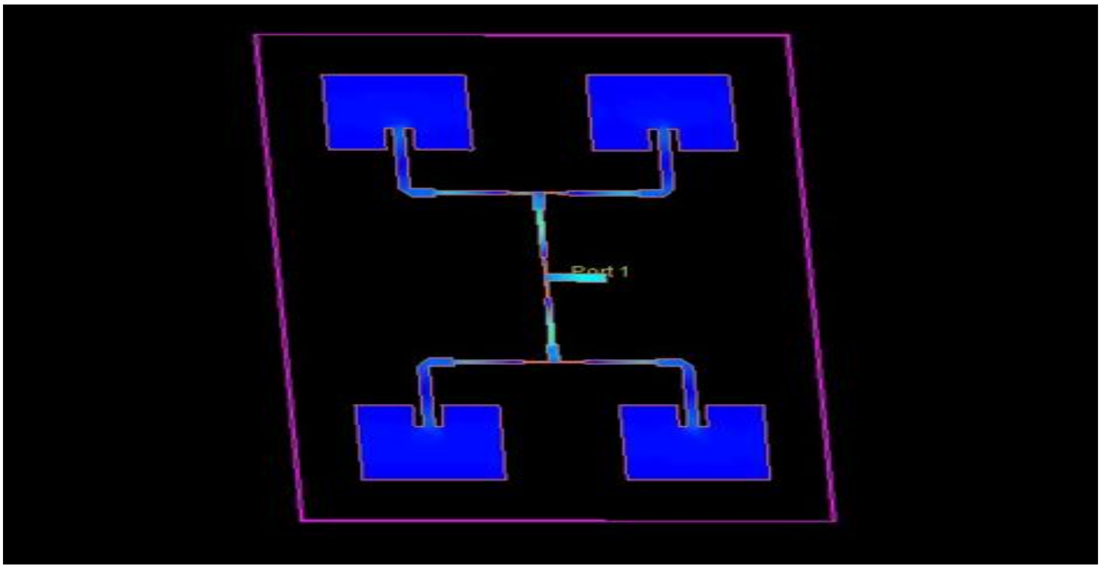

Figure 2: 3D 2x2 Rectangular MSPA

3.1.1 A *2 by 2 Patch Rectangular Microstrip Antenna Design*

Most of MSPAs have a high quality factor (Q), which may enable them to reduce the losses associated with these antennas. Therefore, antennas with high quality factor may have a narrow bandwidth and operate at lower frequencies. Straitened bandwidth and low-frequency. The patch length of the antenna can be calculated using equation 1[12].

$$P_L = \frac{\lambda_0}{2}\sqrt{\epsilon_r} \qquad (1)$$

Where the ε_r is the dielectric constant, lambda is the wavelength at resonant frequency.

For efficient radiation patterns, the patch antenna width can be calculated by reference [12] as:

$$W = \frac{c}{2f_0\frac{\epsilon_r-1}{2}} \qquad (2)$$

The resonant frequency f_0 for a given rectangular patch antenna can be expressed as follows.

$$f_0 = \frac{\epsilon_r-1}{2}\sqrt{\left(\frac{m\pi}{L_{eff}}\right)^2+\left(\frac{n\pi}{W_{eff}}\right)^2} \qquad (3)$$

Where, m and n are orthogonal modes of excitation, the effective length of the patch antenna L_{eff} to be designed can be calculated via equation 3 [12].

$$L_{eff} = L + 2\Delta L = \frac{\lambda_0}{2\sqrt{\epsilon_e}} \quad (4)$$

At a specific resonant frequency , the effective length of patch antenna can be calculated using equation 5.

$$L_{eff} = \frac{1}{2f_0\sqrt{\epsilon_e}} \quad (5)$$

The rectangular shape of the patch antenna is the most widely used in MSPA structures. The transmission feeding-line shown in Figure 3 is the most appropriate, and easiest method for modeling and applied analysis for MSPAs.

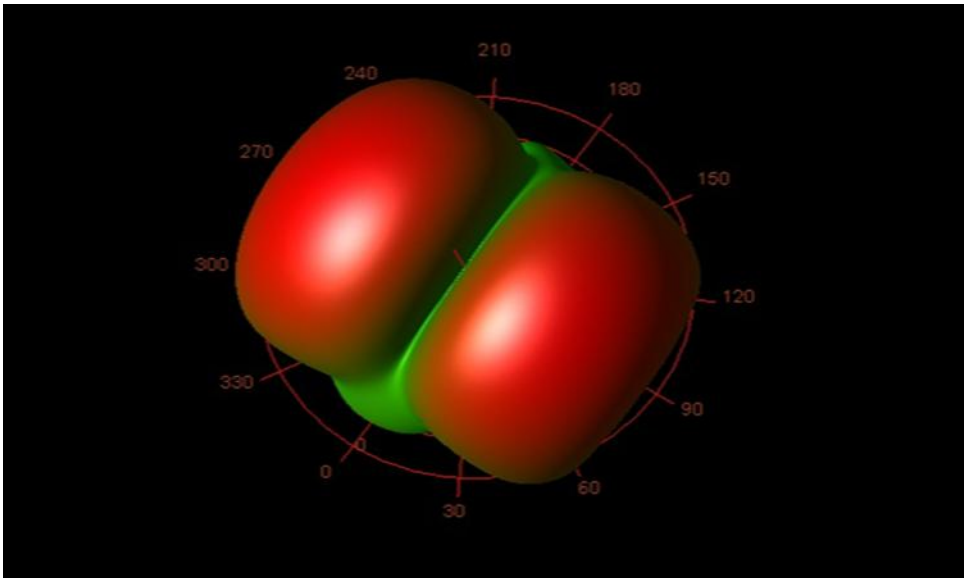

Figure 3: Internal 2 by 2 MSPA Topology Designed with ADS

This model provides good physical insight as well as depicts the MSPA by a two slots. This is separated by a low impedance "Y " to the transmission feeding-line by a length of. Figure 3 shows the equivalent circuit of the rectangular patch antenna where, Z_1 is the impedance of the antenna at quarter-wavelength [12].

$$Y_1 = G_1 + jC_1 \quad (6)$$

To design our proposed MSPA at resonant frequency of 10 GHZ, initially, a type (RT/Duroid 5880) substrate was used with a dielectric constant, and transformation at a quarter wavelength. After applying the above mathematical equations; length, width and height of the patch antenna and the effective dielectric constant were calculated [12].

To calculate the characteristic impedance of the line, we start first with the mathematical analysis of the equivalent circuit of the patch antenna, as follows:

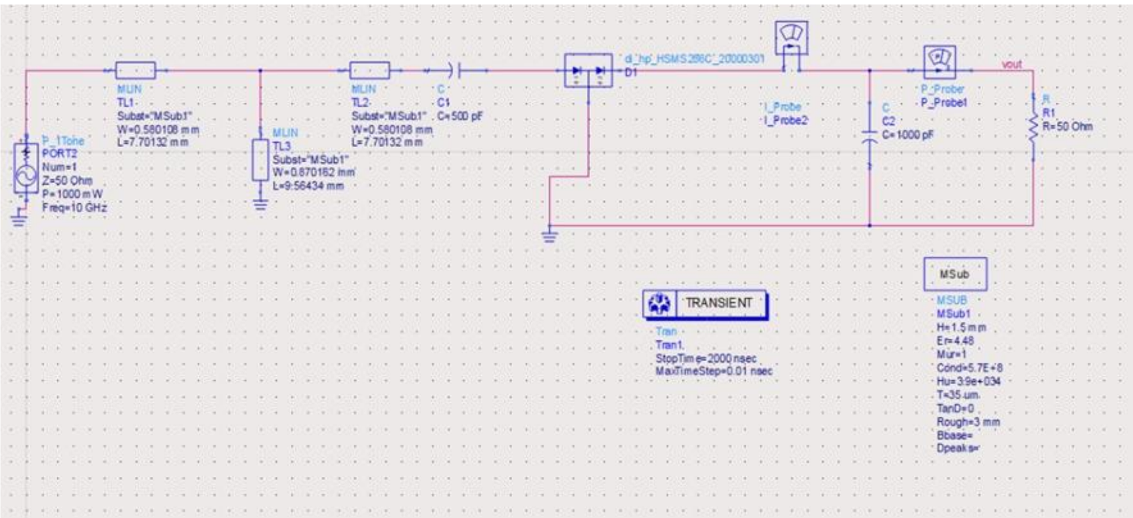

Figure 4: Rectenna Impedance Matching Circuit Topology

IV. Results and Discussion

4.1 RF Rectenna at 2.4 GHz

Figure 5 illustrates a 2.4 GHz RF harvester. This design was carried out using the ADS software but a lower output voltage was achieved at the rate of 850 mV at 2.4 GHZ. The curves as illustrated has two peaks -0.5 and -1 respectively. Figure 6 is an illustration of the smith chart impedance corresponding matching network for the 2.4GHz RF harvester.

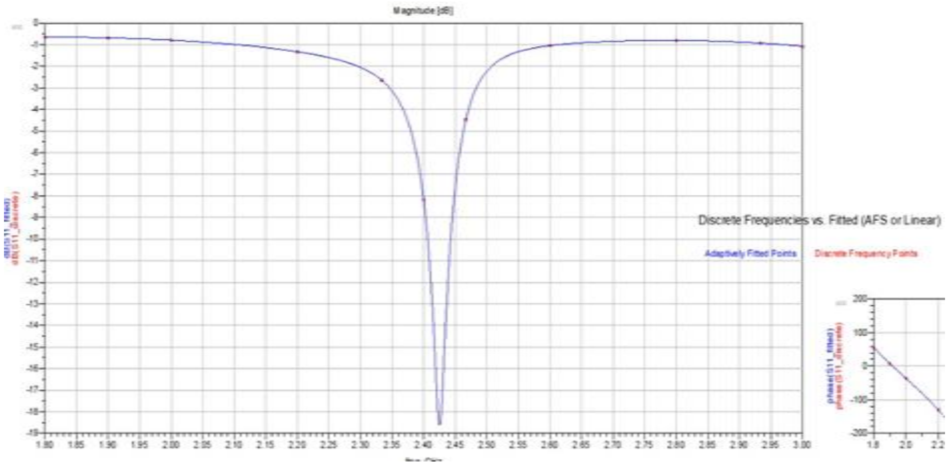

Figure 5. A 2.4 GHz RF Rectenna

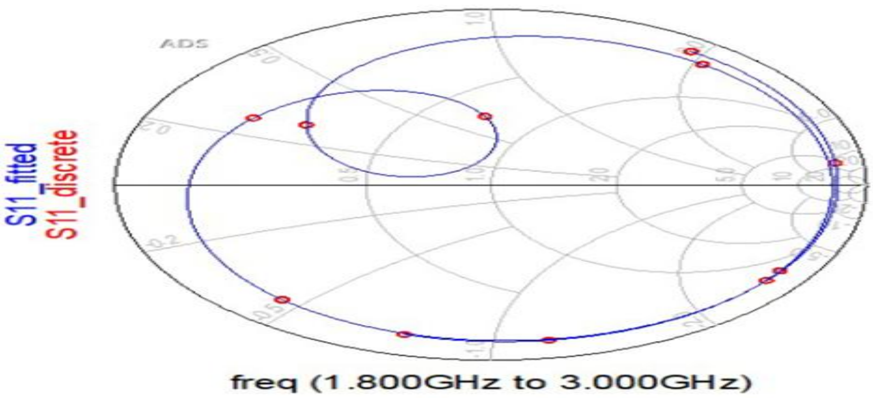

Figure 6: A 2.4 GHz Smith Charts Impedance Response

4.2 RF Rectenna at 5.8 GHz

The results of the 5.8 GHZ RF harvester is a good result when compared with the output voltage of the 2.4 GHZ RF harvester as shown in Figure 7. The output voltage of the 5.8 GHZ is 1.55 volt which is way higher than that of the RF 2.4 GHZ. With ADS we weren't just able to design the antennas but also to get the corresponding smith chart impedance response.

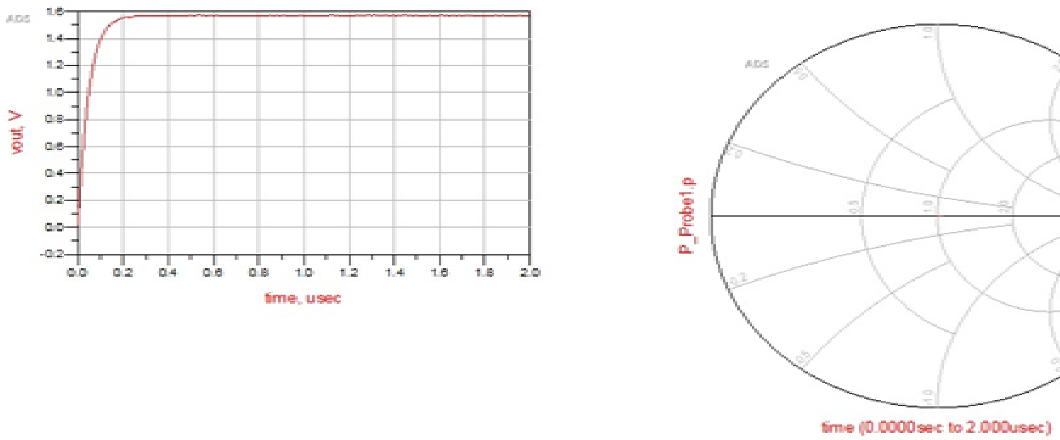

Figure 7: A 5.8 GHz RF Rectenna and it Corresponding Smith Chart Impedance Design

4.3 RF Rectenna at 10 GHZ

After the last tuning process, an optimized value was achieved for the circuit components. Figure 8 illustrates the DC power output voltage as a function of input power. However, with the ADS we were able to realize output DC voltage of 2.4 volts at 10 GHZ, which is an improvement from previous works. And also it corresponding smith chart for matching the impedance network of the RF harvester.

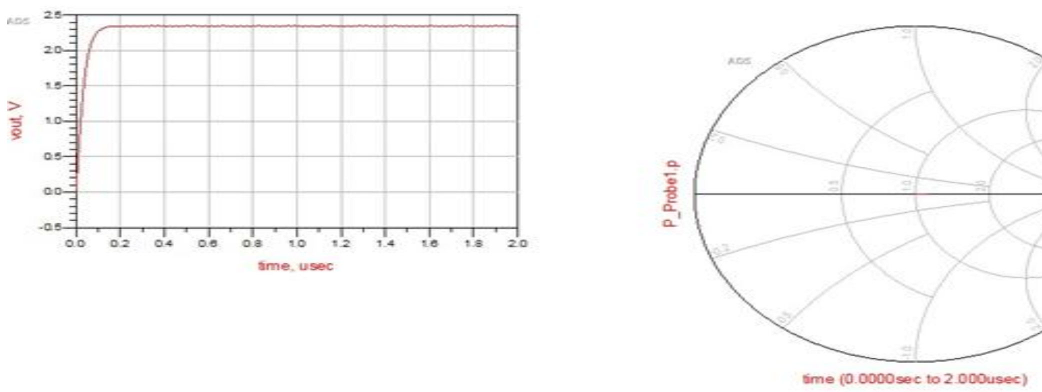

Figure 8: A 10 GHz RF Rectenna and it Corresponding Smith Chart Design.

4.4 Comparative Analysis of RF Harvesters

The histogram chart in Figure 9 illustrated the comparative results of the three different RF harvester. This illustration has shown that the higher the energy harvested the higher the DC output voltage would be gained and the lower the harvested energy then the lower the output DC gained voltage. As you can see the lowest output voltage at 0.85v came from the lowest harvested frequency and the highest 2.4v from the highest harvested frequency 10 GHz.

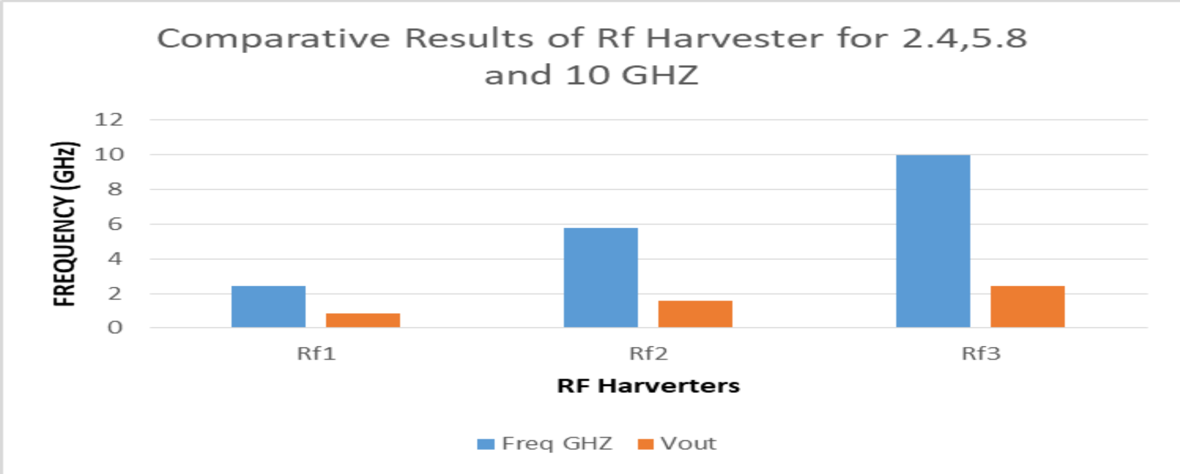

Figure 9: Comparative Analysis of RF Harvester for 2.4GHz, 5.8GHz and 10GHz

V. Conclusion

The RF harvester antenna is one of the most important part of the RECTENNA, in this research work we were able to design the antenna suitable for harvesting 10GHz and with equivalent impedance matching as shown in the results above. In order to harvest a frequency that could amount to a reasonable DC output voltage that could comfortably power up a sensor then, we harvested a 10 GHz frequency with our double patched RECTENNA. However, we designed a RECTENNA with a double patches for rectangular MSPA. We used a co- simulation method for the global system design which includes ADS schematics. With ADS we were able to design a RECTANNA with an improved dc voltage and also harvested larger frequencies. Talking about the area of RF harvesting at some point you will find out that the dc output voltage is really small based on other works, take for example a 2.4 GHZ RECTENNA is having an output voltage of 0.85v and so on, also the low voltages being generated by the RECTENNA has made it not thrive much.

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