Design and Development of RF Energy Harvesting System

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Abstract: This study investigated the available means of RF energy harvesting and introduces elements for an improved collection circuit for implementation into an arbitrary electronic device with low power requirements, such as a handheld calculator or wireless node sensors. The inclusion of microstrip patch antenna with an impedance matching network adds an opportunity for higher energy collection rates and thus faster charges accumulation. The main contribution of this research project remains on the design of a 'rectenna' circuit, comprised of a microstrip patch antenna, and rectification section that is made up of seven elements. This is to increase power conversion efficiency towards a workable solution that is efficient enough for market adoption in low power mobile devices. The harvesting in this study is focused on RF energy bands that are available in Nigeria. These include Wi-Fi hotspots (and other 2.4GHz sources), as well as cellular (850MHz, 900MHz bands), Personal Communications Services (1900MHz band) and WiMax (2.3GHz) network transmitters.

Keywords: Radio Frequency; Energy Harvesting; Cellular Networks; and Microstrip Patch Antenna

I. INTRODUCTION

Radio frequency (RF) energy is presently emitted via various radio transmitters in Nigeria, such as mobile base stations, TV/radio broadcast stations, Wi-Fi, Bluetooth and many more. The total number of active mobile phone subscriptions in Nigeria has increased to over 152 million in the month of November 2015, according to latest statistics from the telecommunications industry regulator, Nigerian Communications Commission (NCC, 2015). Harvesting novel RF energy, via Wi-Fi, cellular networks and broadcast masts, offers another means of powering low energy gadgets and could be used to supply substantial energy enough to elongate the life span of such gadgets [1]

RF energy harvesting cannot be achieved without enough levels of ambient RF energy density readily available for harvesting. In contrast to many other energy sources, RF signals are purposely generated and regulated. Due to the development of new radio technologies, the radio spectrum is becoming heavily populated: television, radio, and cellular, GPS, Wi-Fi, satellite and radar, among many others [2],[3] .The available energy is often regulated and transmitted according to standards of how it shall be used. Depending on the location the RF power, energy densities can vary from 0.01 $\mu W/cm^2$ to 100 $\mu W/cm^2$, and in some cases, where a dedicated RF transmitter is available; the RF power density can reach 300 $\mu W/cm^2$[4]. Mobile network growth continues to expand exponentially, driven by mobile broadband access, smart phones, tablets and applications such as mobile video and social networking. Combined with the continued growth of Wi-Fi 33 enabled equipment, RF energy density will continue to increase over the years, expanding the possibilities of deploying devices powered by ambient RF energy harvesting system.

Even though there is high availability of RF energy readily for harvesting, there are certain factors that restrain us from doing so. One of these factors is the difficulty in designing a system that can harvest RF energy in a quantity that is high enough to make it useful and applicable [5]; [6]. Other challenges of harvesting RF energy in office, retail and city environments originates mainly from the variation in RF energy density in different locations, power consumption of the harvesting device, sensitivity of the harvesting device as well as problems due to impedance mismatching. RF energy harvesting requires sufficient levels of ambient RF energy density to be effective. Sometimes making maximum utilization of RF energy harvesting is restrained by challenges of narrow band and broadband systems [7]; [8]. The design of antennas and their associated matching networks generally results in a compromised design resulting in lower efficiencies and hence, less energy recovered. Impedance matching is required to provide maximum power transfer between RF energy source and its load [9]; [10]. To this end, the present study seeks to optimize the direction and gains of the receiving antenna, improve the RF to DC conversion efficiency and redesign existing schemes and algorithms for conventional networks so as to develop and optimize the RF harvesting system.

1.1 Objectives of the Study

The study archived the following objectives:

1. Develop a flexible micro strip patch antenna to harvest RF energy from GSM900 and GSM1800;
2. Design and develop an impedance matching network using ADS platform;
3. Design and develop a rectifier circuit to convert harvested RF energy to DC voltage.

II. LITERATURE REVIEW

[4] designed a system which consists of three modules: a single wideband 377Ω E-shaped patch antenna, a pi matching network and a 7-stage voltage doubler circuit. The DC voltage obtained from the harvester system in the field test at an approximate distance of 50m from GSM cell tower was 2.9V. This voltage was enough to power the STLM20 temperature sensor.

[12] developed a device which uses a capacitive loaded T-shaped monopole with acoplanar waveguide feeding line as receiving antenna and a five-stage voltage multiplier as rectifier. Experimental results, referring to a power density incident on the antenna of 80µW/cm2, demonstrate an RF-to-DC conversion efficiency higher than 48% over the entire European UHF RFID band i.e., 865.6–869.6MHz.

Using the MPPT principle of Perturbation and Observation (P&O), an MPPT-based RF energy harvesting system (M REHS) was constructed for energy harvesting [5].The design is highly optimized and can be effectively adapted at larger scales with suitable d rivers and increased storage capacity to energize significant loads for various applications.

Taylor (2014) developed what may be referred to as an example for an indoor application wavelength up into the low GHz would be a better choice, due to their ability to propagate well in these environments, rather than lower VHF/UHF transmissions. These might be more useful to outdoor or remote location harvesting applications.

[14] This article presents an RF energy harvesting system that can harvest energy from the ambient surroundings at the downlink radio frequency range of GSM-900 band. The design and simulation of the voltage doubler circuit were performed using Multisim software. The three modules were integrated and fabricated on a double sided FR 4 printed circuit board. The DC voltage obtained from the harvester system in the field test at an approximate distance of 50m from GSM cell tower was 2.9V. This voltage was enough to power the STLM20 temperature sensor.

[15] Designed two systems enable to harvest RF power at 900MHz GSM band (single frequency) and at 900MHz GSM–2.4GHz Wi-Fi bands (multi frequency) have been designed and realized. A summary of the Literature review indicates that RF energy harvesting is a promising technology. However, RF energy harvesting has been under development for many years but it has so far, been limited in its application and commercial deployment by lots of factors. Therefore further research and development is needed in multiple areas to fill this identified gap, including impedance matching, antenna design, as well as the ongoing research to design an RF energy harvesting system that can operate at a high enough efficiency to harvest ambient RF energy from the very low power densities that are present in most cities.

III. METHODOLOGY

The RF energy harvesting system consists essentially of the following key materials and components; 1) Receiving Antenna, 2) Impedance Matching Network (inductors and capacitors), 3) Rectifiers (schottky barrier), 4) Power conditioning devices, 5) RF power density meter, 6) CST studio SUITE 3-D electromagnetic simulator, and 7) PC. The Research work for the realization of RF energy harvesting system is divided into four (4) stages. A block diagram of the system is shown below:

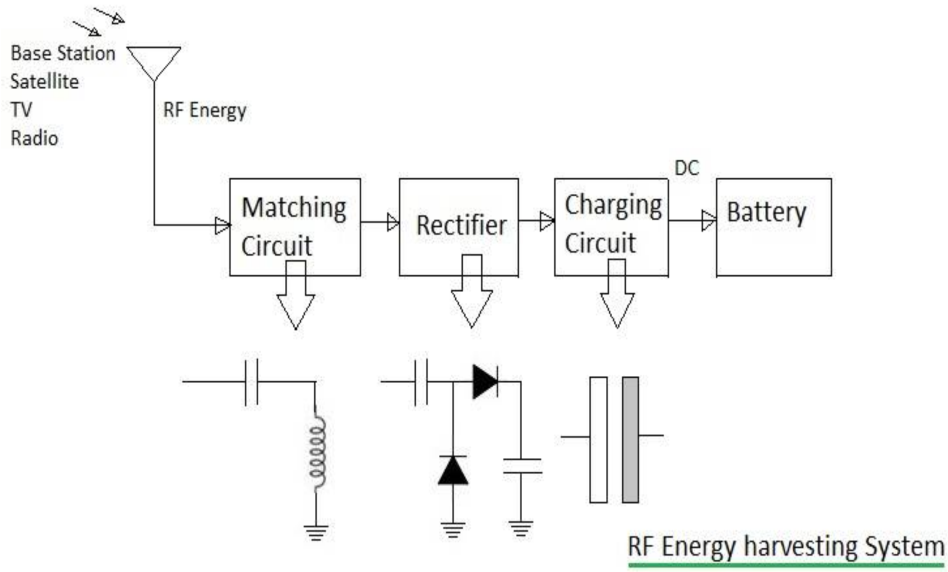

Figure 1: Block Diagram of the RF Energy Harvesting System

This research work involves designing and simulating the system using PC software in order to provide a working model for RF energy harvesting system. This provided a good insight into the effect of several design parameters to be used for the selection and development of the system. The overall system development involved laboratory measurements on various building blocks. These were implemented to form a complete system whose overall performance was assessed using both test equipment and "off air" signals to allow modifications to be made where necessary. The evaluation work took into account all relevant technical, economic and social factors. The technical evaluation included factors such as operating performance of the system as a whole, operating performance of each main component with a view to identifying possible improvements. Other factors include visual appeal, ease of operation, durability, social and environmental context in which the system will operate.

IV. RESULT AND DISCUSSION

A. Objective One: Development of a flexible micro strip patch antenna to harvest RF energy from GSM900 and GSM1800 -

A MATLAB/GUI based education tool was used to calculate the antenna parameters for the rectangular patch by means of transmission and cavity modeling. After the entering of the design specification, the shape of the antenna was chosen and all the calculations were performed and displayed. Introduction of this Graphical User Interfaces in-conjunction with CAD tools such as CST studio suite provided the means of determine the antenna characteristics performance. This software provides a user-friendly interface to help the researcher to understand the process involved in micro strip patch antenna design and make necessary adjustment before fabrication (See Figure 2). This interface can be used as an educational tool in Electromagnetic courses.

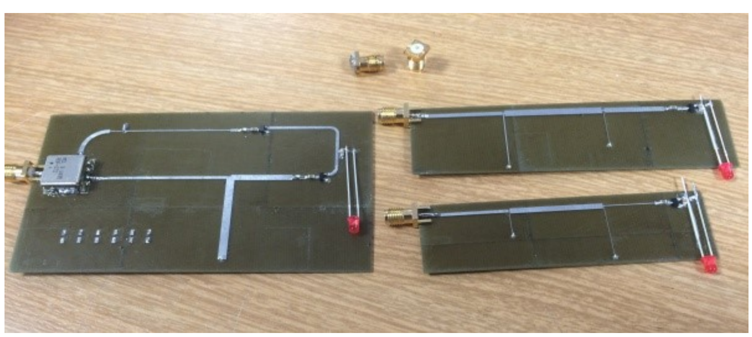

Figure 2: Fabricated Microstrip Patch Antenna

B. Objective Two: Design and development of an impedance matching network using ADS platform-

The matching network in the geometry was designed to provide a good impedance match for complex load (RF-DC convertor) impedance 63-j117- to source (antenna) impedances 377- to transform maximum power from the source to the load. The output of the pi matching network is directly connected to the input of RF-DC converter circuit. The design of pi matching network starts off with the lumped elements model where by the matching network shunt open circuit capacitors and a series inductor. The lumped elements in the matching network are then transformed into distributed elements to obtain the initial values of length and width for each distributed component. By using ADS the optimized dimensions of the distributed elements in the matching network were obtained.

C Objective Three: Designing and development of a rectifier circuit to convert harvested RF energy to DC voltage-

Modeling and simulation was carried out in LTspice software environment. The simulation and practical implementation was done with fixed RF at 945MHz 100 MHz, which is close to the down link center radio frequency (947.5 MHz) of GSM-900 band. The voltage obtained at the final node ($VDC7$) of the doubler circuit was recorded for various input power levels from -40dBm to +5dBm with power level interval (spacing) of 5dBm. The input impedance 63-j117- of the voltage doubler was obtained using the network analyzer. This 63-j117- was tested from 900MHz to 1000 MHz as the antenna was designed for the down link radio frequency range of GSM-900 band.

Figure 3 shows the photograph of the assembled circuit board of 7-stage RF-DC conversion module. The design of the printed circuit board (PCB) was carried out from the DipTrace software. The PCB was manufactured on FR 4 substrate and has thickness of 1.6mm and dielectric constant of 3.9. The dimension of PCB is 98mm £ 34 mm. The SMA connectors are used at the input and output of PCB to carry out the measurements. The circuit consists of active and passive components. Special handling precautions have been taken to avoid Electrostatic Discharge (ESD) while assembling the surface-mount zero bias Schottky diodes. Also special attention has been given to mount other components and the SMA connectors on to the PCB. In this work, the DC output voltages obtained through simulation and measurement at 0dBm are 2.12V and 5.0V respectively.

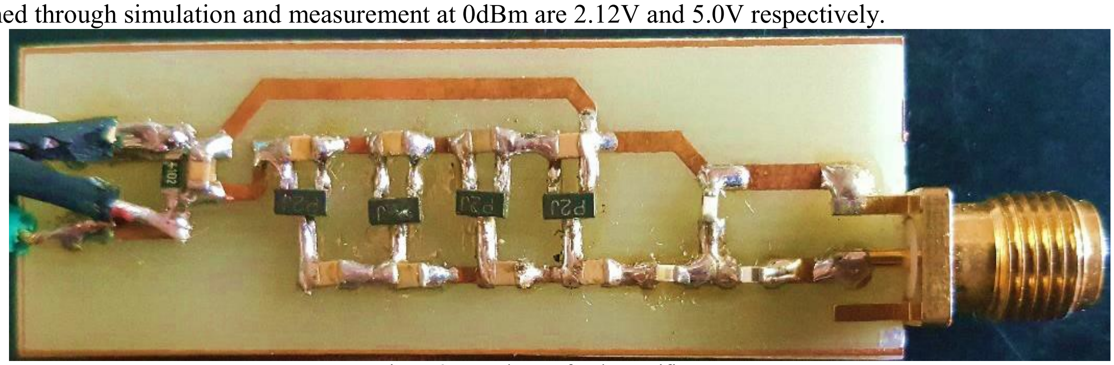

Figure 3: PCB layout for the rectifier stage

The output voltage V_0 represents the maximum voltage obtainable for the n-stage multiplier. The simulated and measured voltages recorded at each of the subsequent stages for the 7-stage multiplier also shown in Figure 3.

V. CONCLUSION

A novel 900MHz RF energy harvesting system for powering low power devices has been designed developed and tested. The novelty lies in the partial ground plane in the antenna structure which resulted in maximizing the energy captured and generating a higher DC output voltage that can power low power devices. A micro strip patch antenna with partial ground plane with compacted size was designed, simulated and implemented. Subsequently the pi matching network located in between the patch antenna and the RF-DC conversion module was designed simulated and implemented to provide a good match from the load to the source. The energy conversion module that comprises of 7-stages voltage doubler circuit with zero bias Schottky diodes was successfully incorporated, tested and found to be efficient in converting the RF signals captured by the antenna to the required DC output voltage for powering low power devices. A key improvement to this design is increasing the number of antennas used to harvest more power from the same frequency band.

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APPENDICES

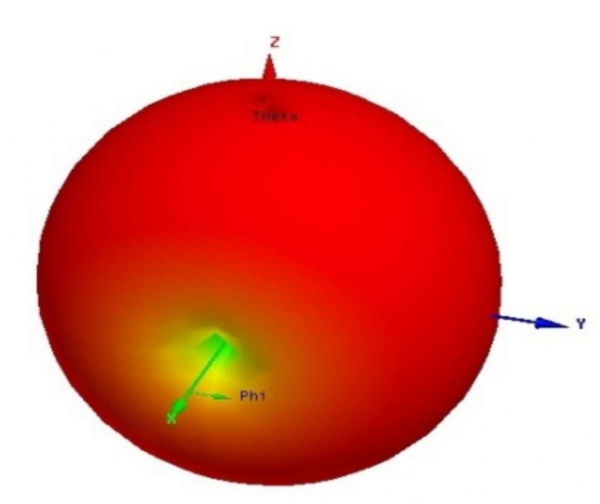

Figure 4: 3D-Polar-Plot when the Dipole Antenna Radiates At 900MHZ

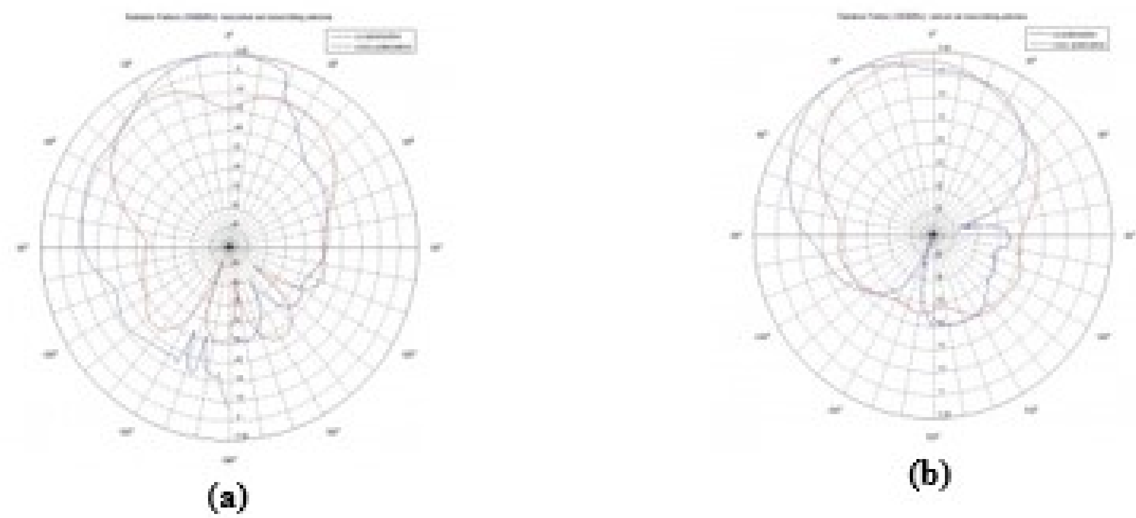

Figure 5: Radiation-Pattern at (a) 900MHZ and (b) 1800MHZ

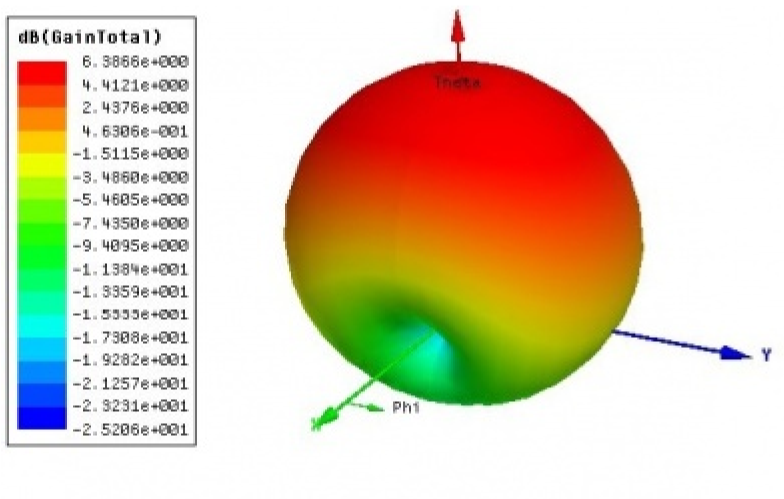

Figure 6: 3D-Polar-Plot when the Patch Antenna Radiates at 900MHZ

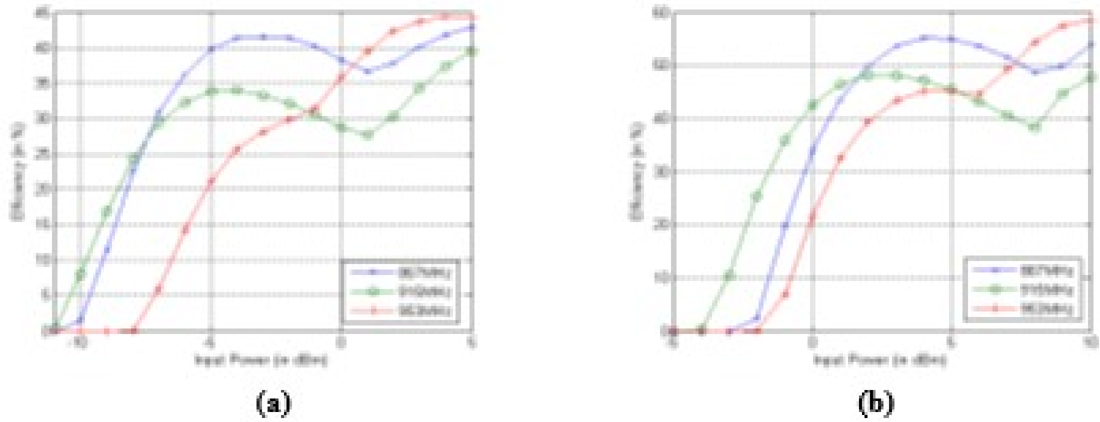

Figure 7: Circuit Efficiency versus Input Power, (a) Vload= 2.95V (b) Vload= 3.70V

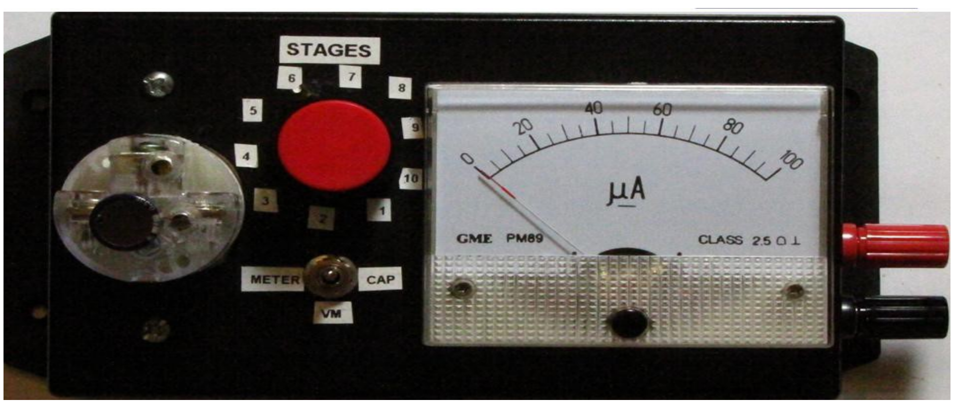

Figure 8: Completed Work