**IMPEDANCE MATCHING OPTIMIZATION: A CASE OF RF ENERGY HARVESTING**

YUSUF ABUBAKAR MAIWADA

Electrical Engineering Department, Hassan Usman Katsina Polytechnic, Katsina Nigeria
E-mail: yusadeeq@yahoo.com

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**Abstract**— RF energy harvesting has drawn much interest recently for providing a possibility of powering low energy devices but it has so far, been limited in its application by lots of factors. One of the major factors has been the ability to design a system that can operate at a high enough efficiency to harvest ambient RF energy. Impedance matching is required to provide maximum power transfer between RF energy source and its load. In this work analytical modeling and simulation of the antenna operating at 2.45GHz and the rectifier unit is carried out to improve impedance matching and provide maximum power transfer. The performance of the rectenna system has been optimized using simulation softwares. The RF-DC conversion efficiency of about 37% was achieved.

**Keywords**— RF Energy, Low Energy Devices, Impedance Matching, Modeling, Power Transfer.

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**I. INTRODUCTION**

Multiple sources of different Radio frequency (RF) energy (such as WI-FI, cellular networks and broadcast masts, Bluetooth etc) are radiating power in all directions in a rich scattering environment. RF energy density will continue to increase year on year, expanding the possibilities of deploying devices powered by ambient RF energy harvesting.

RF energy harvesting has drawn much interest recently for providing a possibility of powering low energy devices such as remote sensing devices etc. It can reduce the installation and maintenance costs of having to change batteries integrated within numerous low power devices. By providing an “always on” source of energy for these devices, ambient RF energy harvesting can reduce the dependency on battery swapping or plug in charging. Radio frequency (RF) energy harvesting requires sufficient levels of ambient RF energy density to be effective. 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, cellular, GPS, Wi-Fi, satellite and radar, among many others. Each of these frequency bands has an associated standard, which stipulates how it is used and the amount of RF authorized power to be transmitted. Depending on the location the RF power, energy densities can vary from 0.01 µW/cm² to 100 µW/cm², and in some cases, where a dedicated RF transmitter is available, the RF power density can reach 300 µW/cm² [1].

The major component used to convert this RF energy into utilisable DC power is a rectifying antenna, also termed as rectenna. Among various entities of rectenna, antenna is one of the major elements which is responsible for collecting the incoming RF signals of various frequencies. The source of incoming RF energy can be WLAN (2.4 GHz, 5.8 GHz), WiMax, RFID (microwave band: 2.45, 5.8, 24.125 GHz) and so forth with various frequency ranges.

In the last few years, several antenna designs of rectenna that meet various objectives have been proposed for use in RF energy harvesting. Among various antennas, microstrip patch antennas are widely used because of their low profile, light weight, and planar structure. Conventional patch antennas are rectangular or circular in shape, but variations in their basic design are made for different purposes [2]. Ambient energy harvesting has so far, been limited by lots of factors. One of the main limiting factors has been the ability to design a rectenna system that can operate at a high enough efficiency to harvest the ambient RF energy from the very low power densities that are present in most cities. This work explores a method to design and simulate microstrip patch antenna and a rectifier unit to improve efficiency and provide maximum power transfer to supply low energy devices.

**II. ANTENNA DESIGN**

2.1. Antenna Parameters

A rectangular microstrip patch antenna was designed and optimized using the antenna design software CST studio suite. The frequency of the proposed antenna is in the range 2.4 to 2.5GHz with the center frequency of about 2.45GHz.

The antenna design required to look into the permittivity or dielectric constant of the substrate, width, length of the patch antenna and the ground plane. The effect of variation in substrate thickness and its permittivity on a microstrip patch antenna was studied [3]. The permittivity of the substrate plays a major role in the overall performance of the antenna. It affects the width, the characteristic impedance, the length and therefore the resonant frequency that resulting to reduce the transmission efficiency [4]. The key property of FR-4 relates to the flame retardant qualities of the material. The important
specifications chosen in simulation for this design are the thickness of substrate 1.6 mm, the thickness of copper 0.035 mm, the relative permittivity 3.8 and the loss tangent 0.08. The antenna size is characterized by its length, width and height (L, W, h) and is fed by pi matching network, feed line and is followed by a partial ground plane as shown in figure 1.

2.2. CST Simulation
On the CST MICROWAVE STUDIO SUITE platform, a CAD model of the patch antenna was built based on the appropriate dimensions from the values obtained above (using MATLAB software). Appropriate settings for frequency range, ports, boundary and symmetry conditions etc. were made. The transient solver was used to calculate the antenna properties.

2.3. Impedance Matching
In the RF energy harvesting system, a power harvesting circuit is employed for converting part of collected RF power to DC power supply voltage. A matching network is usually applied between the antenna and the power harvesting circuit to ensure maximum power transfer.

To improve the power transfer efficiency by matching the rectifier to the antenna, many factors must be taken into consideration, i.e. incident power density $P_{in}$, load condition $I_{load}$, nonlinear effect of the voltage rectifiers, antenna design technology, etc. Due to the non-linear effect, the input impedance of the voltage rectifier is not constant but depends on both the incident RF power level and the output load $[5]$. 

$$Z_{in} = f(P_{in}, I_{load})$$  

To design a matching network for maximum power transfer, a deeper investigation of the rectifier input impedance must be done. Barnett et al. $[5]$ developed a mathematical expression for the input impedance of the rectifier built of schottky diode as a function of the load current consumption.

III. RECTENNA DESIGN

3.1. Power Conversion Efficiency
One of the performance parameters of the rectifier design is the power conversion efficiency, which is defined as the output DC power over the RF power at the input of the rectifier. A large part of the power is consumed by the rectifier. Generally, the power conversion efficiency depends on many design parameters: load condition, input power level, number of stages, etc. $[6]$. The RF-DC conversion efficiency is directly proportional to the DC power ($P_{DC}$), divide by the RF input power:

$$\eta_c = \frac{P_{DC}}{P_{in} - P_{re}}$$  

where, $P_{in}$ is the incident RF power at the antenna, and $P_{re}$ is the reflected RF power due to the impedance mismatch. The power transfer efficiency, which is also an important performance index of the rectenna design, is defined as the power transferred to the rectifier over the incident power received by the antenna:

$$\eta_t = \frac{P_{in} - P_{re}}{P_{in}}$$  

The overall efficiency is defined as the output DC power PDC over the RF power at the input of the rectifier $[17]$:

$$\eta_o = \frac{P_{DC}}{P_{in}}$$  

3.2. Rectifier Configurations
Different implementations of diodes have been investigated for RF harvesting. Schottky diodes were originally used due to their inherently low turn on voltage, low conduction resistance and low junction capacitance $[7]$. Since diodes in the voltage multiplier must have a switching time smaller than the period of the input signal, Schottky diodes are preferred because they are typically faster than normal diodes. Furthermore, higher saturation current can be obtained using Schottky diode which in turn is shown to result in higher conversion efficiency $[8]$. The number of rectifier stages has a major influence on the output voltage of the energy harvesting circuit. Each stage here is a modified voltage multiplier, arranged in series. The output voltage is directly proportional to the number of stages used in the energy harvesting circuit. However, practical constraints force a limit on the number of permissible stages, and in turn, the output voltage. Here, the voltage gain decreases as number of stages increases due to parasitic effect of the constituent capacitors of each stage, and finally it becomes negligible.
Figure 3 shows an N-stage voltage doubler circuit connected in cascade. Each stage uses the DC voltage output of the preceding stage as a base voltage, in such a way, the DC voltage of each stage is a multiple of the number of stages. The DC output of an N-stage voltage:

\[ V_{dc} \approx 2N \times (V_{rf} - V_n) \]

(5)

In order to optimize the rectenna system for maximum power transfer, the patch antenna must be matched to the rectifier input impedance [9]. For this design, HSMS-2852 Schottky diode having a turn on voltage of 150mV, measured at 0.1mA suitable for low power density (LPD) was used for rectification. The antenna is designed to capture the energy from the ambient WI-FI signal with input power of -10dBm, operating at 2.45GHz. A resistive load of 1KΩ was selected for the simulation.

IV. RESULTS AND DISCUSSION

4.1. S-Parameter Simulation

The return loss indicates how much of the incident power is reflected by the antenna due to mismatch. An ideal antenna when perfectly matched will radiate the entire energy without any reflection. If the return loss is infinite, the antenna is said to be perfectly matched to the TL. S11 is the negative of return loss expressed in decibels. Fig. 4 shows the simulated return loss of the patch antenna. It can be seen the resonant frequency of 2.45 can achieve a return loss of lower than -35dB. The return loss of an antenna signifies how well the antenna is matched to the 50-Ω transmission line. Fig. 5 shows a plot of the input impedance against the operating frequency.

4.2. Voltage Standing Wave Ratio

The VSWR is an important antenna performance parameter which is used to measure the efficiency of the transmission line. As a rule of thumb, a VSWR between 1 and 2 is considered sufficient. Fig. 6 shows a plot for the VSWR of the proposed antenna. It indicates a value of about 1.195 at the specified resonant frequency.

4.3. Bandwidth

Bandwidth indicates the frequency response of an antenna. It signifies how well the antenna is matched to the 50-Ω transmission line over the entire band of interest. The simulated result is shown in Fig. 7 The bandwidth at the resonating frequency 2.45GHz is 25.5MHz with the corresponding value of return loss as -10.007 dB.

The Radiation pattern indicates the directional property of radiation, that is, which directions have more radiation and which have less. This information helps to orient the antenna properly in an application Fig. 8 shows the radiation pattern of the patch antenna.
4.4. Simulation Results for the RF-DC harvester
Simulation results for the designed RF-DC harvester indicates that for the RF input power of -10dBm at 2.45GHz, a maximum output DC voltage of about 2.48V at 37µW is achieved. Fig. 9 shows a plot of the DC output voltage against the incident RF input voltage while fig. 10 shows a plot of conversion efficiency against the RF input power.

CONCLUSIONS
The properties and performance of the RF-DC harvester have been successfully predicted and optimized with the help of antenna software CST studio suite. This antenna shows a low VSWR at 2.45GHz. The highest RF-DC conversion efficiency of about 37% for an input RF power of -10dBm was achieved. The results show that an optimization routine can effectively be applied to the design of an efficient impedance matching system. To maximize the overall power efficiency, the concept of a tunable matching network is recommended for further work.

REFERENCES

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