Design and Implementation of Cost-Efficient Radio Frequency Energy Harvesting Technique

Suprosanna Shit, Sayak Mukherjee, Soumyadip Ghosh, Kaustav Dey and Biswendu Chatterjee

Abstract — **Nowadays, researchers from all over the world are concerned about energy and environment. Non-conventional sources, which are eco-friendly, are getting more importance. Energy harvesting is a technique to provide a real time solution for alternative sources of energy that are eco-friendly and low cost. In near future, many wireless devices need to operate for longer durations away from conventional power sources. Several technologies had been developed that try to fulfill the constraint of devices that operate through wireless power transfer technology. Radio Frequency (RF) energy harvesting is one of the energy harvesting technique that could able to convert radio frequency electro-magnetic waves from ambient air to electrical energy. Harvested energy can be used to build a wireless charger. This paper presents a low cost radio frequency energy harvesting technique and its implementation based on different type of experiments to supply power for low-power devices.**

Index Terms — **Radio Frequency energy harvesting; wireless power transmission; loop antenna.**

I. INTRODUCTION

AT present, wireless power transmission is one of the challenging research fields and RF energy harvesting has become a growing research topic in this field due to the availability of different ambient sources [1]. Harvested energy can be used as a wireless charging scheme for rechargeable batteries. The energy can be stored and used to supply the low powered wireless devices [2]. There are different types of RF energy sources that can be used for harvesting purposes such as mobile phones, TV antennas, Radio broadcast, wireless internet modems, etc. and these ambient energy are free to harvest. However, several challenges are associated with RF energy harvesting. The main issue is that the amount of power available is too small and it varies with the time of the day. So the device that will run on RF energy should have lower average power consumption than the average harvested power and it shouldn't have constant power requirement. The objective is to convert RF energy into usable form of electrical energy. In electrical system, direct current (DC) is the simplest form to produce. So the RF energy is captured and converted into DC for practical use. Section II discusses about related work, section III describes proposed scheme, section IV shows the result and section V concludes the paper.

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II. RELATED WORK

The use and development of antennas for RF Energy Harvesting has been done by various researchers. Progress in this field has been made by designing rectangular patch antennas [3], spiral antennas [4], array of hexagonal spiral antennas [5], and rectennas (rectifying antennas) array [6]. Gunathilaka et al [7] used three different types of antenna, namely monopole antenna with ground plane, dipole and micro-strip antenna. They suggested that micro-strip antenna showed best performance whereas for monopole antenna, the concern is with loss due to impedance mismatch in the feeding point and frequency dependence of the co-axial cable. For dipole antenna the direction of the device is the main concern.

III. DETAILED SCHEME AND DESIGN

The basic scheme for RF energy harvesting device has three main components: antenna (transducer), rectifier & multiplier (energy conditioning) stage and energy storage unit. The transducer converts RF energy into electrical form which is then easier to condition and store.

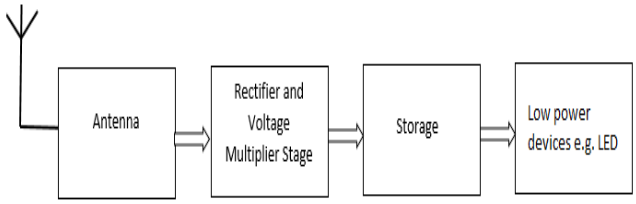

Fig1: Basic block diagram

The transducer should be efficient in order to convert more RF energy into the system. So the challenge lies in designing an energy efficient rectifying circuit and a voltage multiplying circuit to amplify the incoming signal with minimum amount of loss in the conversion stage. In reality, available RF energy is not constant over the time. Therefore it is necessary to have an energy storage unit altogether with RF energy harvester to fulfil the demand of the devices.

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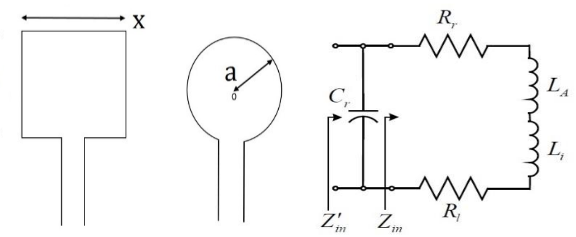
A. Antenna

The antenna is the most important thing for harvesting RF energy. The function of the antenna is to capture the RF wave and give input to the rectifier subsystem. There are different types of antenna depending on the operating frequency and application. So the first step is to select the frequency band of RF energy that is to be scavenged. In this case, the GSM mobile frequency range (806-960 MHz) is selected. Patch antenna is a very good antenna for high frequency application but it is quite costly and has narrow bandwidth [8]. So a loop antenna made of copper wire of square and circular shape which is easy to make at a nominal cost, is proposed here.

The design of antenna is precisely application specific and the parameter has to be designed accordingly. Assuming constant current application, for square loop antenna, the side of the square is $x = \lambda/4$ and for circular antenna, radius is $a < \lambda/6\pi$, where λ is the wavelength of the electromagnetic wave.



(a) (b) (c)

Fig2: Different types of loop antenna a) square b) circular c) equivalent circuit of a loop antenna

The equivalent circuit of loop antenna is shown in Fig 2(c)
Where, C_r = resonance capacitor,
L_A = external inductance of the loop antenna,
L_i = internal high frequency inductance of the loop conductor (wire)
R_r = radiation resistance
R_l = loss resistance of the loop antenna
The radiation resistance [9] can be calculated by following equation

$$R_r = \frac{\eta 8\pi^3}{3}\left(\frac{NA}{\lambda}\right)^2 \tag{1}$$

Where, N = number of turns of antenna conductor
A = loop area of conductor in space
$\eta = 120\,\pi$ for free space, Now,

$R_{in} + R_l = R_r$ & $X_{in} = j\omega(L_A + L_i)$

$Y_{in} = G_{in} + B_{in}$ Where,

$$G_{in} = \frac{R_{in}}{R_{in}^2 + X_{in}^2} \tag{2}$$

$$B_{in} = \frac{-X_{in}}{R_{in}^2 + X_{in}^2} \tag{3}$$

The susceptance of the capacitor is $B_r = \omega C_r$

If resonance condition occurs, then capacitor is parallel with the antenna circuit and $B_r = -B_{in}$ Now,

$$C_r = \frac{X_{in}}{2\pi f(R_{in}^2 + X_{in}^2)} \tag{4}$$

The input impedance of the antenna now has become

$$Z_{in}' = R_{in}' = \frac{1}{G_{in}} = (R_{in} + \frac{X_{in}^2}{R_{in}})\Omega \tag{5}$$

For maximum power transfer from the antenna to the next stage, impedance matching should be proper. i.e.

$$Z_{antenna} = (Z_{circuit})^* \tag{6}$$

Where $Z_{circuit}$ is the impedance of the external circuit and * indicates the complex conjugate. For better performance, impedance matching circuit can be used as intermediate stage between antenna and rectifier.

B. Rectifier and voltage multiplier

Rectifier is used to convert the high frequency RF energy captured in the antenna into DC. There are different topologies of rectifier available i.e. half wave, full wave, bridge rectifier etc. But voltage level obtained from simple rectifying circuit is quite low. Therefore the voltage multiplier circuit is instrumental in achieving an amplified voltage level required for practical use. There are different types of voltage multiplier circuits available [10]. Here we use Cockcroft-Walton voltage multiplier circuit.

For high frequency application, Schottky diodes are used for their low voltage drop, but they are costly. So we use 1N34A diode instead of Schottky diodes for rectification. The forward voltage drop is 0.3V and capacitor of 4.7 µF is used in rectifier assembly.

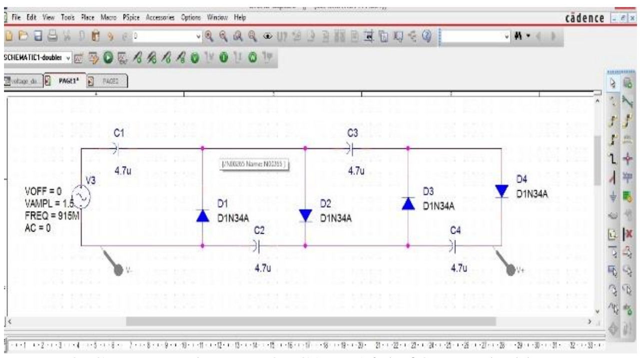


Fig3: Circuit simulation at ORCAD v16.5 of 2 stage doubler circuit

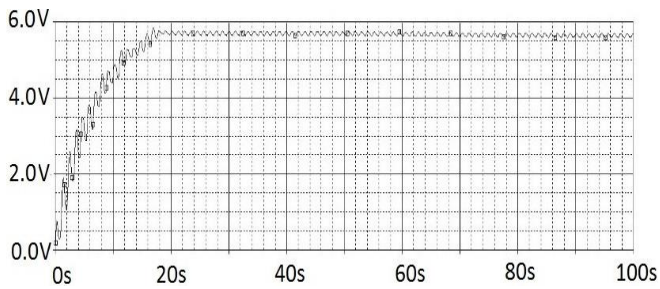


Fig4: Operating frequency simulation result using ORCAD v16.5 for voltage multiplier circuit of double stage

The simulation is done in ORCAD v16.5 software using the PSPICE interface. The SPICE model of 1N34A has been implemented to simulate the model. The simulated output from the aforesaid software is shown in Fig. 4.

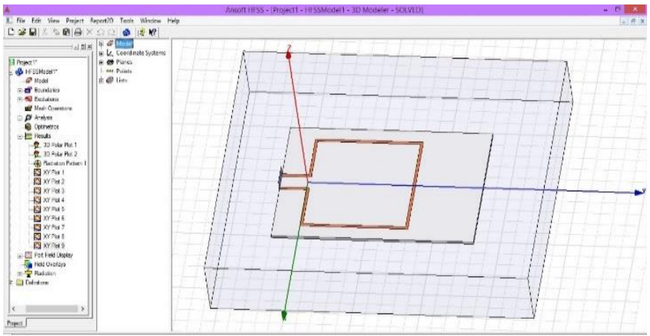
As the number of stages are increased, the output voltage increases, but there is a constraint for using more number of stages. For the same power level, current level decreases as the voltage increases. At higher voltage levels, the current level drops considerably and hence cannot meet the minimum input current required for the devices. Also at the higher stages, loss in the multiplying circuit will also increase and hence the efficiency decreases. The number of stages are therefore restricted up to two in the present work.

C. Storages and use

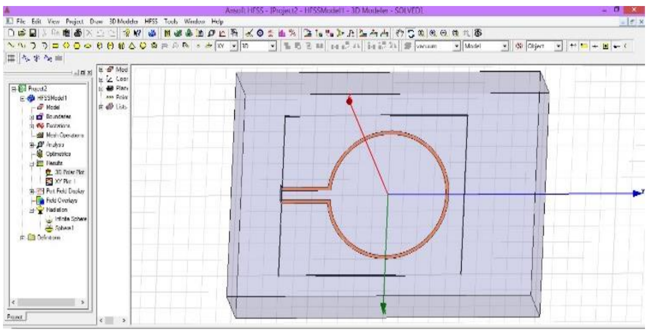
The harvested energy can be stored in battery with proper charging circuit. Energy can also be stored in super-capacitor having properties like low self-discharge, durability, superior energy density, and low impedance. This energy can be used in devices that operate at low power, such as wireless sensor networks, ambient intelligence devices and medical systems.

II. Results and Discussions

A. Simulation



(a)



(b)

Fig5: Simulation at HFSS v9.2 a) square loop antenna b) circular loop antenna

TABLE I. DESIGNED ANTENNA PARAMETER

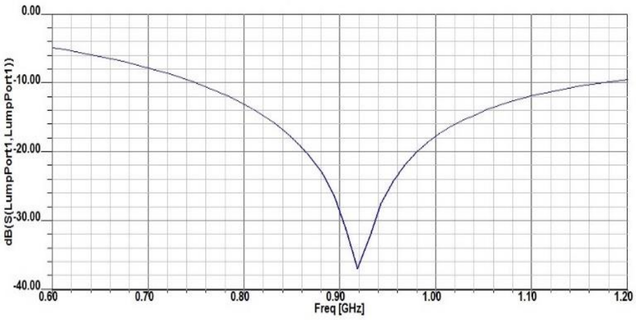
Type of antenna	**Antenna Specification**			
	Dimension (cm)	***Impedance [a] (Ω)***	***Center frequency (MHz)***	***Bandwidth [b] (MHz)***
Square loop	7.6 x 7.6	60	918	720-1200
Circular loop	Radius = 3.8	75	910	810-1100

a. *Impedance is calculated according to the equation 1*

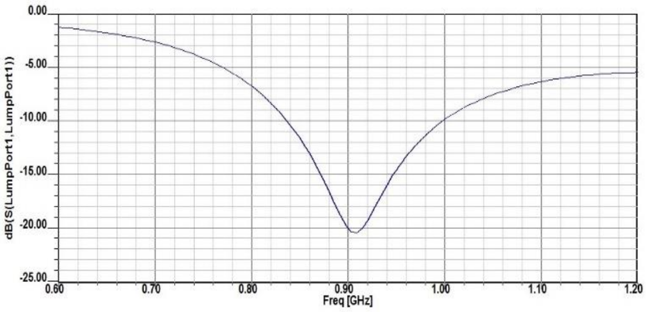
b. *Bandwidth is calculated on the basis of 2.0 voltage standing wave ratio (VSWR) ratio*

The antenna has been designed to harvest RF energy from the GSM mobile frequency range (806-960 MHz). The dimensions are calculated and simulation is performed in Ansoft HFSS v9.2.

Bare copper wire of diameter 1 mm is used to prepare the antenna and it is connected to the circuitry via a pair of metallic clip as shown in figure 8.

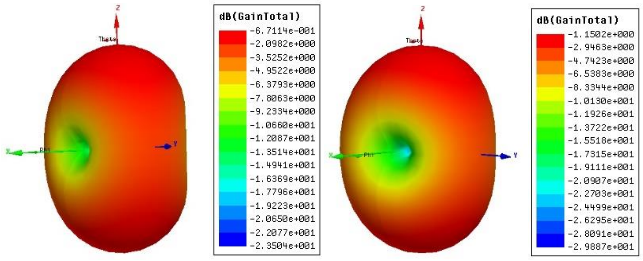


(a)



(b)

Fig6: Return loss a) square loop antenna b) circular loop antenna



(a) (b)

Fig7: Radiation pattern at the center frequency of a) square loop antenna b) circular loop antenna

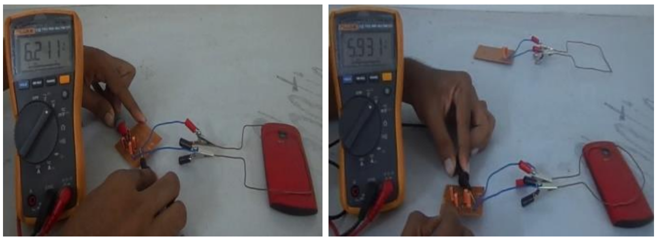
B. Experimental results

The designed antennas have been tested with two multiplier circuits - single stage and double stage. When the mobile phone is within 5 cm of the antenna, it is able to illuminate a LED. The result is compared in the following table.

The output power available can be measured directly. A 33kΩ resistor is connected at the output end and voltage across the resistor is measured. The output power $P = \frac{V^2}{R}$.

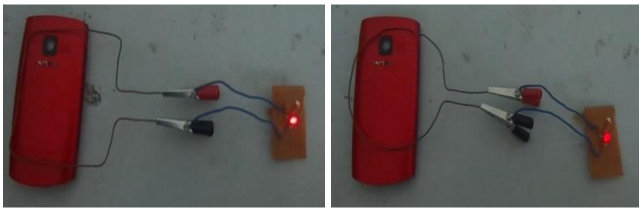
TABLE II. ANTENNA OUTPUT

Type of antenna	Single stage doubler		Dual stage doubler	
	Voltage (V)	*Average Power (μW)*	*Voltage (V)*	*Average Power (μW)*
Square loop	3.4	112	6.2	110
Circular loop	3.1	94	5.9	93



(a) (b)

Fig8: Open circuit voltage obtained from dual stage doubler circuit a) square loop b) circular loop



(a) (b)

Fig9: LED glowing by a mobile phone a) square loop b) circular loop

The mobile phone used in the above figure to glow the LED light is NOKIA X2-01 with a GSM 915 MHz frequency.

C. Analysis

We found that the results obtained analytically and the simulated results comply with each other. From the result (table II), it is clearly visible that the induced voltage in square loop antenna is greater than the circular loop antenna. It is to be noted that the induced voltage available after two stage doubler is greater than the previous work [3] [4]. When a load, i.e., LED is connected, operating point lies where the V-I characteristics of LED and V-I characteristics of designed RF module intersects. From the bandwidth (table I), it is clear that the designed antenna is not narrow band like patch antenna. The average power rating of the module is sufficient to power up low power devices whose rated power is below this average power.

III. CONCLUSION

Technology will continue its evolution of devices using nanotechnology and molecular electronics. As these devices become smaller in size and energy-efficient, their power consumption reduces. This paper is dedicated to propose a scheme that can be used for these low-power devices. Wearable gadgets such as intelligent watches, eye glasses etc. can be charged by this scheme. Another possible application can be charging pacemaker batteries which are expected to benefit many people. RF energy from mobile phones, with which almost everyone moves around, serves as the primary source for charging these wearable devices. In conclusion, the novelty of the paper lies in the facts of higher induced voltage, use of IN34A diodes in the design and implementing wideband antenna.

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