

Energy Harvesting Techniques for Low Power RF Sensors

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Abstract— This paper presents the research conducted and the progress achieved in the design and implementation of the low cost Energy Harvesting System for low power remote RF Sensor applications. In this implementation, conventional battery is replaced with a super-capacitor which is charged by DC voltage harvested out of RF EM waves. The Friis equation was used to evaluate free space losses in RF Energy at each stage of the system. The amount of time for the charging of the 3F/2.7V super-cap in the best case scenario was 3.5 hours.

Keywords— Energy Harvesting, RF (Radio Frequency), Low Power, Super-capacitor, Low Cost, Friis Equation, Onboard antenna design

I. INTRODUCTION

Due to the reduced size and less power consumption of the modern electronic circuits we are able to use an alternative energy source, which in return, expands the product life. Energy can be harvested from the environment from discrete sources like sunlight, vibration, heat or even RF waves. The study of various harvesting techniques such as Piezoelectric, Thermoelectric and Radio Frequency resulted into the implementation of Radio Frequency Electromagnetic waves for harvesting due to its feasibility and reduced cost amongst the three. The applications which require low power (in milli watts) and are located in remote locations where replacing batteries is unattainable, use RF power for their working [1]. These applications use a conversion circuit that extracts sufficient amounts of RF Power for DC voltage generation. These circuits basically are the voltage multiplier circuit with a minute modification for the RF to DC conversion. As there is no controller unit in the proposed system, the power consumption of the circuit is less resulting into better conversion efficiency.

II. EM WAVES AND WIRELESS POWER TRANSFER

Microwaves and radio waves are a part of the electromagnetic spectrum which consists of electrical and magnetic components. In this model, the two centre frequencies used are 434 MHz and 2.4 GHz, which belong to the two ISM bands used for unlicensed purposes. The output power of RF devices is regulated by International bodies such as the FCC for USA and ETSI for Europe for health and safety related issues due to EM radiations [2]. The powering

capabilities of RF and microwave wireless power transfer (WPT) system can be divided into three types i.e. near field power transfer, microwave power transfer and ambient microwave power harvesting. For near field power transfer the output power is tens of watts but for a limited distance i.e. couple of meters. The micro power transfer output is tens of milli watt for a distance of a few meters and for the ambient microwave power harvesting, the output power is up to hundreds of microwatts.

III. ENERGY HARVESTING FRAMEWORK

This energy harvesting device consists of an RF Power Transmitter, RF Power receiver, RF to DC Subsystem and a storage device.

A. RF Power Transmitter

It was observed that ambient Radio Frequency energy was far less than acceptance threshold for Radio Frequency to DC Convertor circuit to power the Radio Frequency sensor; hence, the need for a customized Radio Frequency transmitter located at an appropriate distance from the remote Radio Frequency sensors emerged.

B. RF Power Receiver

Different on board receiver antenna designs were evaluated to meet compact packaging requirements of Low Power Radio Frequency Sensors. The Friis equation was used to evaluate free space losses in Radio Frequency Energy at each stage of the system.

C. RF to DC Subsystem

RF to DC conversion is achieved by using the Dickson Circuit with the required changes in components and circuit for RF to DC conversion. This voltage is used to charge the super-capacitor.

D. Storage Device

In this design, the need of the battery is completely eliminated by the use of a super-capacitor. As the energy density of a super-capacitor is far lesser than that of a battery, super-capacitors are not considered in applications requiring continuous discharge. This is stated considering that the capacitor is not charged continuously by an external source at all times. A typical 3 Volt, CR2032 coin cell battery with

capacity 200 mAh is equivalent to the bank of 240 super-capacitors with capacity 1 Farad, 3V each! In the proposed application, the super-capacitor is constantly being recharged by the RF to DC subsystem (charging circuitry). Thus, we can substitute the battery with a single super-capacitor.

IV. EXPERIMENTS PERFORMED

A. Analysis of Radiated RF Power of known Sources

To analyse whether the radiated RF power (in dBm) transmitted by various known sources in the ambient was sufficient for harvesting; relative measurements were performed using a spectrum analyser and a flex antenna. The following table shows the maximum values obtained during this experiment.

TABLE 1. POWER RECEIVED FROM DISTINCT SOURCES

AMBIENT RF SOURCES	LOCATION	CENTER FREQUENCY	POWER RECEIVED
AMBIENT RF	OPEN SPACE	1.77 GHz	-33.53
Wi-Fi ROUTER	OFFICE AREA	2.41 GHz	-5.89
MICROWAVE	KITCHEN AREA	2.43 GHz	-12.59
RKE	OPEN AIR	434 MHz	-32.31
CELLPHONE	OEPN AIR	915 MHz	-24.96

B. Validation of Designed RF Power Receiver and RF to DC Subsystem

To check the operation of RF to DC Subsystem along with RF Power Receiver was kept in the vicinity of above mentioned known RF Power Sources. Following table shows the open circuit output voltage while using RFD102A [3] for conversion.

TABLE 2. POWER RECEIVED FROM DISTINCT SOURCES

AMBIENT RF SOURCES	LOC;ATION	CENTER FREQUENCY	OUTPUT VOLTAGE (V)
AMBIENT RF	OPEN SPACE	1.77 GHz	0
Wi-Fi ROUTER	OFFICE AREA	2.41 GHz	0.01
MICROWAVE	KITCHEN AREA	2.43 GHz	2.58
CELLPHONE	OEPN AIR	915 MHz	0.15

V. DESIGN AND IMPLEMENTATION

A. The Transmitter

The transmitter generates pure sinusoidal RF carrier waves to minimize harmonics with RF Power and frequency adhering to the regulatory requirements of the ISM radio band.

1) 434 MHz Transmitter:

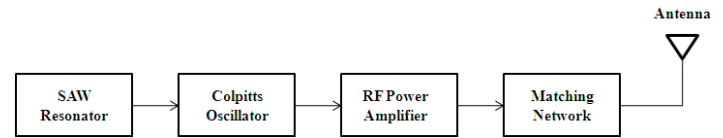


Figure 1. The 434 MHz Transmitter Block Diagram.

The frequency is generated by a common-base transistorised BFU590G [4] Colpitts oscillator circuit using one port SAW Resonator RO3101E [5] with center frequency of 433.92MHz. The schematic for the 434 MHz transmitter is shown below. The RF Power Amplifier, BGA7130 [6] increases the transmitted RF Power by 10 dBm as shown in Table 3. The impedance matching between antenna and Power Amplifier is performed using discrete passive components in Pi-Network.

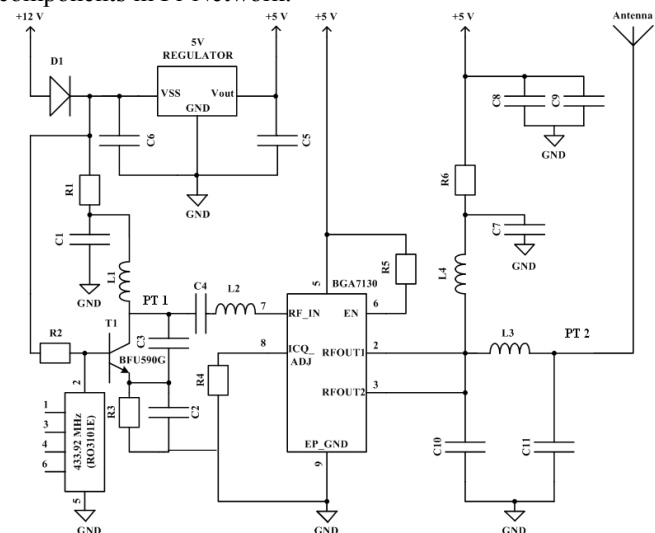


Figure 2. Schematic Diagram of the 434 MHz Transmitter

TABLE 3. POWER OBSERVED

RF POWER MEASUREMENT STAGE	POWER OBSERVED IN CONDUCTIVE MODE
AT POWER AMPLIFIER (PT 2)	15
AT SAW RESONATOR BASED COLPITTS OSCILLATOR (PT 1)	3

2) 2.4 GHz Transmitter: A voltage controlled oscillator MAX2750AUA+ [7] was used considering the center frequency of 2.4GHz necessary for the circuit to be operating

the ISM band and also to comply with the cost limitations. The selected RF Power Amplifier SST12CP11 [8] provides gain of 33 dB at 2.4GHz. The impedance matching between antenna and Power Amplifier is performed using discrete passive components in Pi-Network.

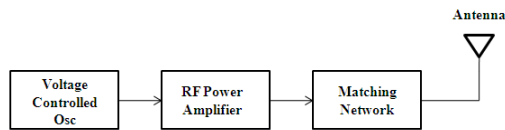


Figure 3. The 2.4 GHz Transmitter Block Diagram.

B. The Receiver

The receiver consists of the matching circuitry for frequencies, the conversion circuitry and the super-capacitor.

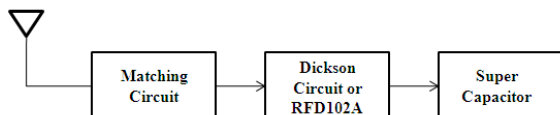


Figure 4. The Receiver constituents

1) Matching Circuit: Various factors determine the impedance of the receiver circuit such as PCB trace inductance, coupling with neighbouring copper traces and planes. Matching circuit is necessary to ensure maximum power transfer from antenna to the Dickson circuit. The pi network consisting of impedances Z_1 , Z_2 and Z_3 contribute to match the circuit to 50 ohms. These impedances can be a combination of multiple inductors and capacitors.

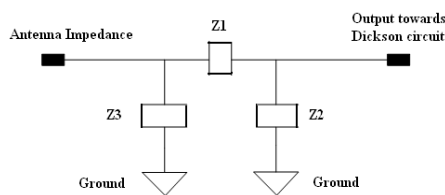


Figure 5. Pi Network for matching

2) Conversion Circuitry: In the proposed model two types of conversion circuits using discrete diodes and Integrated Circuit (RFD102A) were designed. The RF to DC conversion using discrete diodes can be implemented using either the Dickson Circuit or the Villard Circuit. The Dickson circuit was chosen as the performance of this circuit during simulation showed promising results which are shown below. We can see that the Villard circuit produces more ripple than that of the Dickson circuit. The simulation was done for 434 MHz frequency. Figure 7 shows the implemented Dickson circuit using HSMS-258X [9]. The output voltage and efficiency of the design is shown in the graphs below. In the proposed model, there was an obligation to use zero biased Schottky RF detector diodes due to low forward bias voltage (as low as 0.1V) characteristics exhibited by them. In this implementation $N=8$ and $C=10\text{nF}$.

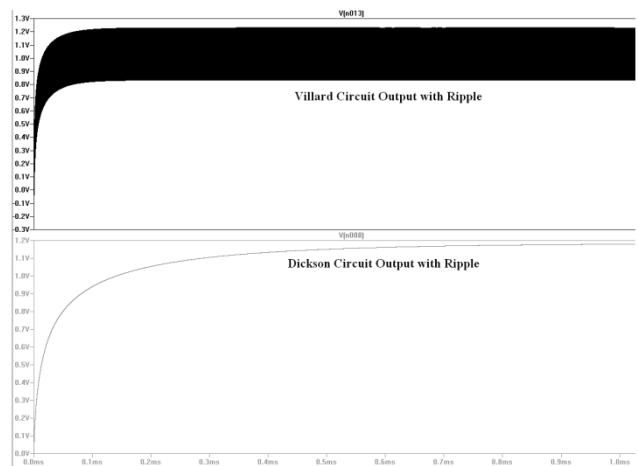


Figure 6. Comparison of the outputs of the Villard Circuit and Dickson Circuit.

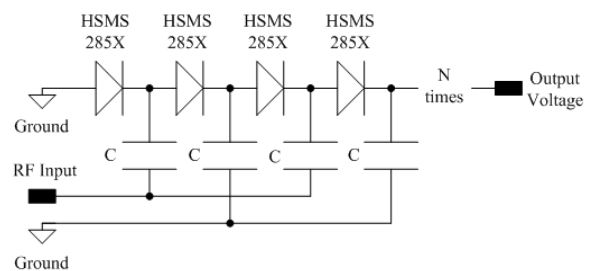


Figure 7. Dickson Circuit implemented

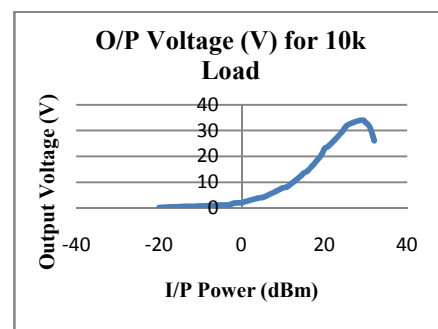


Figure 8(a). This graph presents the output voltage delivered by the conversion circuit at various power received by the antenna.

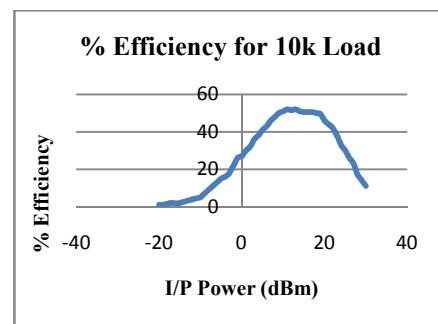


Figure 8(b). This graph informs us about the efficiency of the receiver at the different possible input powers. Note that the efficiency of the receiver is maximum when the input power is between 5 to 22 dBm.

3) Super-capacitor: The Panasonic 3F/2.7V super-capacitor was selected considering the operational and standby current

demand of the RF sensor. Protection was added for overvoltage or short circuit events. The super-capacitor is charged by the current I_{charge} .

$$I_{\text{charge}}(\text{mA}) = \frac{P_{\text{out}}(\text{mW})}{V_{\text{out}}(\text{V})}$$

Where,

$$P_{\text{out}}(\text{mW}) = P_{\text{inmW}} \times n$$

$$P_{\text{inmW}} = P_r$$

Where V_{out} and P_{out} is the output voltage and power respectively of the RF to DC Subsystem 'n' is the percentage of the conversion efficiency of the RF to DC Subsystem and P_r is the RF power received at the input of it. The charging time of the capacitor is defined by the following set of equations.

$$I_{\text{charge_discharge}} = I_{\text{charge}} - I_{\text{avg_discharge}}$$

Where,

$$I_{\text{avg_discharge}}(\text{mA}) = \left(\frac{I_{\text{op}} \times T_{\text{op}}}{1000 \times T_{\text{event}}} \right) + \frac{I_l}{1000} + \frac{I_q}{1000}$$

Wherein, $I_{\text{op}}(\text{mA})$ and $T_{\text{op}}(\text{msec})$ is the operating current and time by the RF sensor, $T_{\text{event}}(\text{sec})$ is periodicity for the sensor operation. $I_l(\text{uA})$ is the leakage current of the super-capacitor and $I_q(\text{uA})$ is the quiescent current of the other loads.

The time (t_{hours}) required to completely charge the capacitor was theoretically obtained from the following equation.

$$t_{\text{hours}} = t_{V_{\text{opmin}}_V_{\text{opmax}}} + t_{V_{\text{opmin}}}$$

Where $t_{V_{\text{opmin}}}$ is the time to charge capacitor from zero to minimum operating voltage of RF sensor. $t_{V_{\text{opmin}}_V_{\text{opmax}}}$ is the amount of time required to charge the capacitor to it V_{opmax} from V_{opmin} . The time taken for the capacitor to reach its V_{opmin} is given by the following equation:

$$t_{V_{\text{opmin}}} = \left(\frac{C \times V_{\text{opmin}}}{I_{\text{charge}} - \frac{I_l}{1000} - \frac{I_q}{1000}} \right) \times \frac{1000}{3600}$$

Where $V_{\text{opmin}}(\text{V})$ is minimum operating voltage of RF sensor, C is the value of the Capacitance(F). Amount of time required to charge the capacitor to it V_{opmax} from V_{opmin} is given by following equation:

$$t_{V_{\text{opmin}}_V_{\text{opmax}}} = C \times \left(\frac{V_{\text{op}} - V_{\text{opmin}}}{I_{\text{charge_discharge}}} \right) \times \frac{1000}{3600}$$

VI. MATHEMATICAL MODEL FOR LOSS ANALYSIS

The path loss of signals will differ from environment when compared to free space [10]. The losses were calculated using the following Friis equation. For the received power in watts the equation is,

$$P_r = P_t \times G_t \times G_r \times \left(\frac{\lambda}{4\pi R} \right)^2$$

For received power in dBm,

$$P_r = P_t + G_t + G_r + 20 \log \left(\frac{\lambda}{4\pi R} \right)$$

Where gain has units of dB and power has units of dBm. To calculate the received power in dBm considering the mismatching losses, polarization losses, path losses and the losses due to intervening medium the following equation is used.

$$P_r = 10 \log(P_t \times G_t \times G_r \times \left(\frac{\lambda}{4\pi R} \right)^2 \times (1 - |\Gamma_t|^2) \times (1 - |\Gamma_r|^2) \times |a_t \times a_r|^2 \times e^{(-\alpha r)})$$

Where, P is the power transferred, G is the gain, Γ is reflection coefficient, α is the absorption coefficient of the intervening medium and a is the polarization vector. Subscripts t & r represent the transmitter and receiver respectively.

VII. RESULTS AND ANALYSIS

A. Results

As the project is still in its pilot stage, the preliminary results of the initial stage are portrayed below. The results stated are of the 434 MHz transmitter circuit giving output up to +13 dBm. The interfacing of the 2.4 GHz VCO and the amplifier is still in process as the measured conducted power is -25.78 dBm at the output of the VCO without amplifier.

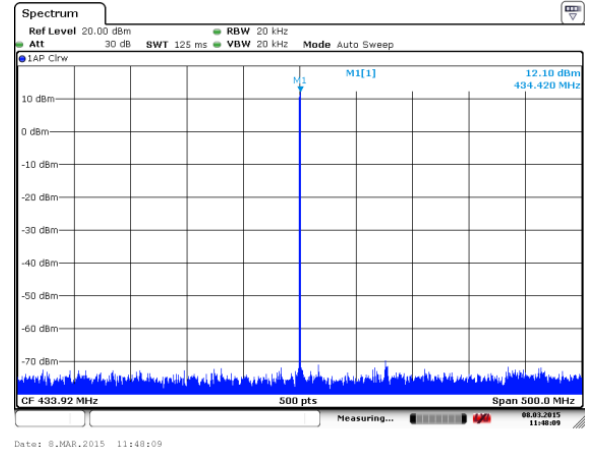


Figure 9. The power observed in conductive mode on the Spectrum Analyzer is 12-13 dBm.

With 434 MHz Transmitter Circuit, following results are obtained from the receiver subsystem with both the conversion circuits

1) RFD102A: The time taken to completely charge the 3F/2.7V super-capacitor in conductive mode is 3.5 hours; wherein a load resistance of 100K was selected as it is equivalent to the quiescent current of the RF Sensor.

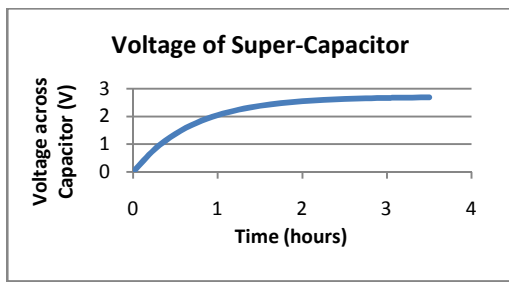


Figure 10. Graph of the charging of Super-Capacitor using RFD102A

2) **HSMS 285X:** The time this setup took to charge the super cap to 2.2V was 22 hours with a 100k load.

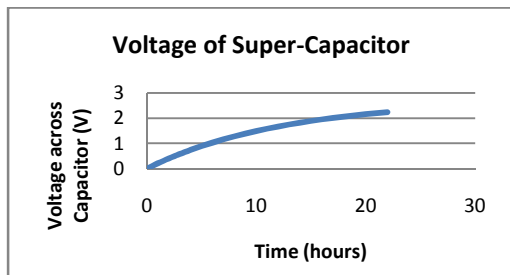


Figure 11. Graph of the charging of Super-Capacitor using HSMS 285X

B. Analysis

The graphs show that the RF to DC circuit using the RFD102A charges the Capacitor faster as compared to the HSMS 285X circuit. This is because RFD102A is an integrated circuit and the stage to stage loss is minimal. The proposed RF Energy Harvesting System is best suited in Low Power Remote RF sensor applications where the rate of charging of the capacitor is greater than the rate of discharge. As far as limitations of the proposed system are known, presence of RF absorbing or reflecting materials such as metal, vehicles between transmitter and receiver subsystem will decrease the received RF power. As the maximum operating temperature of the super-capacitor is 85° C, this cannot be used in high temperature environments. Adequate considerations are required for selection of the super-capacitor as its leakage current (usually couple of micro-amperes) will increase with increase in ambient temperature; hence it has to be charged continuously. Design of RF Transmitter shall conform to various regulatory and statutory requirements with respect to frequency stability, tolerance and maximum RF Radiated Power.

VIII. CONCLUSIONS

The RF energy harvesting technique discussed in this paper has prospective potential to be implemented on a wider scale in industrial, automotive, defence as well as space applications. The overall conversion efficiency can be improved further by rigorous experiments with onboard antenna types and RF

matching. Furthermore the energy from the RF Power Transmitter can be used to harvest multiple remote sensors in the vicinity. The proposed energy harvesting system is being experimented with an automotive application to establish its reliability and benefits.

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