Low RF Power Harvesting Circuit for Wireless Sensor Nodes In Industrial Plants

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***Abstract*—Techniques and methods of energy harvesting are developed to recuperate energy coming from the ambiance to be transmitted to electronic systems. Energy should be useful in specific applications, to generate a certain voltage level and make capable of delivering a recommended Power to the load. So, the main challenge for energy harvesting is to obtain a significant amount of power efficiently from the environment. This paper describes an overview of power transfer systems and methods of charging low power sensors in industrial plants using harvested RF signals. It introduces a scheme investigation of the RF harvester consisting of receiver antenna and a rectifier circuit to convert the RF signal to DC voltage. Low power consumption circuits are used to achieve the target of highest conceivable efficiency in order to produce the maximum power transfer.**

***Index Terms*—RF Energy Harvesting; wireless sensor network; RF power transmission; industrial plants.**

I. Introduction

Many wireless sensor node architectures are adopted for use in a wireless access point, listen and control system. A major challenge affecting wireless sensor network (WSN) application in industrial plants is to develop a way to regenerate power to the sensor nodes in a reliable and efficient manner. An alternative to this is to use energy harvesting [1].

Energy harvesting system determines the distribution between ambient sources and the used energy. The functions of energy harvesting are to generate intelligently the available energy to the operating node and reduce the energy losses of the conversion. The combination of a sensor with a wireless link and an energy harvester creates an autonomous energy system. This system is characterized by an easy maintenance, and easy to install because no cables are required [2].

Other challenges for WSNs is the ability to support harsh environmental conditions and the aim of transmitting energy on relatively long distances in real time during a periodic time interval. To supply systems within this condition is a big problem mainly for WSNs in industrial plants because there is not enough energy from ambient due to reduced efficiency of solar cells for indoor applications and no stability of mechanical energy.

To remedy these problems, a study of state of the art is necessary to define the aim and to investigate wireless methods used for transmitting power to some storage site. In particular, many researches study the development of a wireless sensor node that can be charged with harvesting radio frequency (RF) or microwave energy [3]. In this paper, we explore a potential method to this challenges for recharging wireless sensor nodes by RF Power transmission and harvesting energy from RF ambient sources. The transmitted RF energy is captured by a receiver antenna, transformed into microwatts (μW) to low milliwatts (MW) DC power, useful for charging batteries or powering battery-free devices, by a rectifier circuit.

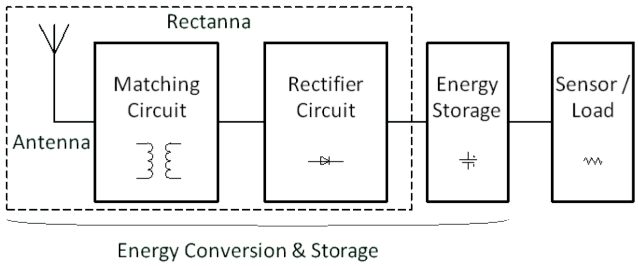

Fig. 1. System diagram for RF energy harvesting sensor application.

II. RF Energy Conversion and Storage

RF power transmission and RF power harvesting applications require more specific and complex circuit for receiving conversion and storage the available RF ambient energy [4].

Many applications can benefit from this technology to provide some milliwatts. Energy harvesting enables to deliver the required power to the interrogated WSN placed far to the RF source or the base station. As shown in Fig. 1, this can be attributed to the interface optimization between the rectenna (rectifying antenna), and typical sensor storage for low-power. The main goal is to load high overall efficiency. It will be operated successfully under good impedance matching and perfect operating conditions in order to minimize discontinuities and signal reflections [5].

RF propagation wave models are available to evaluate the received RF power. The received power ”Pr” is determined by multiple factors: power of RF source, distance from RF source, size/performance of receiving antenna and Transmission frequency [6]. The power impinging on the receiver antenna placed at a distance R from the transmitter antenna can be expressed as in (1):

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi}\right)^2 \left(\frac{1}{R}\right)^n e^{-\alpha R} \quad (1)$$

where P_t is the power transmitted or the input power to the transmitter antenna, G_t and G_r are, respectively, the gains of receiving and transmitting antennas, λ = c / f denote the wavelength of radiation when c is the light velocity and f is the RF signal frequency. α (=0.001) is the effective decay coefficient in air. n denote the path loss exponent, n=2 in free space and in urban environments takes a value between 3 and 5. Also, recognizing that the RF power density signal S [7], is given by (2).

$$S = \frac{P_t G_t}{4\pi.R^2} = \frac{EIRP}{4\pi.R^2} \quad (2)$$

Since special regulations exist for RF power transmission, it makes sense to operate this process in the free license frequency bands or ISM (Industrial, Scientific and Medical Band). They should be classified as either SRD (nonspecific short-range devices), wideband data transmission systems or Radio Frequency Identification (RFID) applications [9]. The Table 1 shows the standard RF ranges used for RFID, the frequency used for and the maximum power transmission/field strength.

Many rule parts specify RF power transmission limits in terms of ERP (effective radiated power) or EIRP (equivalent isotropically radiated power). ERP and EIRP are defined in linear terms as the product of the antenna gain and the input power to the antenna. The antenna gain for ERP is relative to a half-wave dipole antenna whereas, the EIRP is expressed relative to an isotropic antenna gain. ERP is related mathematically to EIRP as follows (3):

$$ERP = EIRP - 2,15\ dB \quad (3)$$

A lot of calculations and analyzes is required to study the efficiency and performance of RF power transmission. After this approximate study it is necessary to note that with increasing frequency, the received power decreases and thus the decrease in the yield. To solve this problem, it remains to study the rectification systems characterized by low power loss, high efficiency and ability to recover the maximum RF energy transmitted.

III. Rectifier Circuit Basic for RF Applications

An impedance matching circuit between the received aerial and rectifier circuit is necessary to increase the voltage gain and further reduce reflection and transmission loss. Simply defined, the rectification is to convert an alternating current (AC) to (DC) direct current.

The principal aim to satisfy after rectification, for low power and sensing applications, is to recover the maximum of power and reduce the power loss caused by the rectifier circuit. Many investigations showed that when the applied power was low, the rectifier circuit efficiency was also low. Therefore, and in order to rectify low RF signals at a high efficiency, it is very essential to improve the rectifier [10].

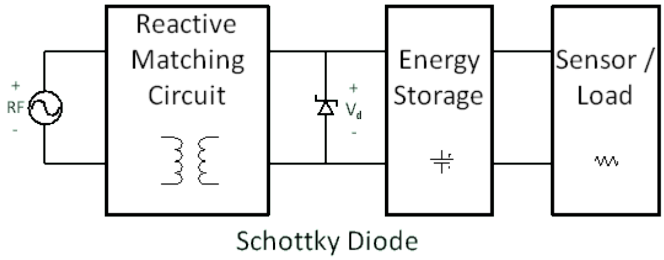

Fig. 2. Schottky diode for rectifier circuit.

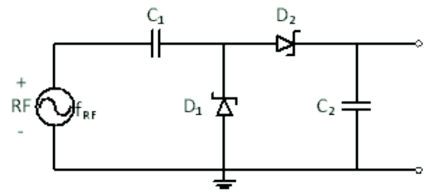

Fig. 3. Single stage voltage doubler rectifier.

A. Schottky diode for rectifier circuit

Different investigations were conducted to study many AC/DC conversion solutions for low power. Among them the illustrated in Fig. 2, based on zero-bias Schottky diode appropriate to its high efficiency using the circuit at low incident RF power densities and a high frequency range. Schottky diode with low turn on voltage and high switching operating frequency, are generally used for achieving a high Power Conversion Efficiency (PCE) from half-wave [11].

B. Conventional voltage doubler rectifier

Another solution for the rectifier circuit is the conventional voltage multiplier rectifier given by Fig. 3. The structure is considered for RF-DC power conversion system design because it rectifies peak to peak voltage from the full-wave of the RF signal. Two configurations are arranged in cascade using Schottky diodes to provide a passive voltage offset before rectification. The conventional voltage doubler Rectifier form a peak rectified by D_1 and C_2, while a voltage clamp is formed by C_1 and D_2.

The circuit can be also called a voltage doubler, thereby, the output voltage is approximately twice the input voltage. The RF input signal is rectified during the positive alternative. The stored voltage on the input capacitor C_1 during the negative alternative is transmitted to the output capacitor C_2 during the next positive alternative of the RF input signal. Thus, the voltage on C_2 is roughly the peak voltage of the RF source minus the turn on voltage of the diode, the total multiplied by 2 [12].

The individual stage of voltage multiplier circuit can be extended to n stages in cascade to boost and convert the AC input voltage to a higher DC output voltage level. The feature of the Villard multiplier is that when the stages are connected

Frequency Range	Description	Fieldstrength/Transmision Power
a1 2.446-2.454 GHz	SHF RFID and Automatic Vehicle Identification	$\leq$ 0.5 W EIRP outdoor Europe
a2 2.446-2.454 GHz	$\leq$ 15 duty cycle FHSS techniques should be used	>500 mW-4 W EIRP indoor Europe
b1 865.0-865.6 MHz	UHF RFID, Listen Before Talk, backscatter coupling Channel Spacing: 200 kHz	100 mW ERP Europe
b2 865.6-867.6 MHz	UHF RFID, Listen Before Talk, backscatter coupling Channel Spacing: 200 kHz	2 W ERP (3.8 W EIRP) Europe
b3 867.6-868 MHz	UHF Short Range Device, backscatter coupling Channel Spacing: 200 kHz	500 mW ERP Europe
902-928 MHz	UHF SRD, backscatter coupling	4 W EIRP - spread spectrum, USA/CA
2.400-2.483 GHz	Super High Frequency (SHF) backscatter coupling	4 W - spread spectrum, USA/CA
5.725-5.875 GHz	SHF ISM, backscatter coupling	4 W USA/CA, 500 mW Europe

TABLE I
FREQUENCY RANGES FOR RFID SYSTEMS [8]

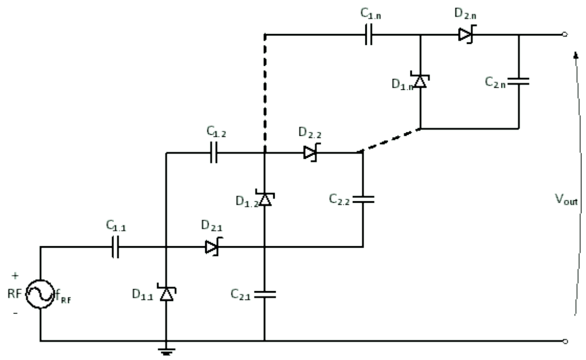

Fig. 4. N-stages voltage doubler rectifier.

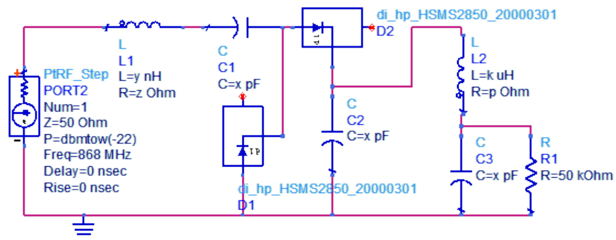

Fig. 5. Proposed Single stage voltage doubler rectifier.

in series and behaves akin to the principle of batteries in cascade to multiplying the output voltage. Fig. 4 illustrates n stages of a voltage multiplier in cascade. Each Villard stage acts as a passive voltage shifter producing a DC offset voltage for the next stage.

The stage number used in rectifier has a major influence on the harvesting circuit. Since, one rectifier stage may yield an unused output voltage and too many Villard stages damps out the Multiplier effect by reducing the impedance reactive component. Thus, practical constraints oblige a limitation on the permitting stages due to the capacitor parasitic effect of each stage [13]. So, the higher voltage can be attained by increasing the circuit stage number, and therefore increase the power loss.

IV. DESIGNING RF ENERGY HARVESTING RECTIFIER CIRCUIT

As mentioned before, the principal target of this scavenging system is to harvest energy coming from a low RF density area available at 868MHz. The received RF power in such area generally ranging from 0 to -30 dBm according to transmitted power, also, the distance between transmitting and receiving antenna. A matching circuit, a voltage multiplier and the load are components of the proposed energy harvester circuit.

The incident RF signal waves captured by the receiver antenna are converted into a DC signal by a simple topology based on a voltage multiplier used for rectifier circuit. The major feature of this architecture is it just multipliers the input voltage to its output terminal using the continuous voltage component of the previous stage adding to the rectified RF signal of the next stage. The multiplier circuit was constructed using two zero based HSMS2850 Schottkey diodes characterized by low threshold voltage and high switching operating frequency

The output voltage is dependent on the storage capacitance. High capacitance stores high energy level, and takes longer charging time. The capacitors were chosen with a lower value to reduce the charging time and rise up the switching speed of the whole circuit.

An inductor L capable of storing energy in a magnetic was added. Energy is stored during the negative cycle wave and returned to the positive one. The couple (L, C) operates like an additional power source during the positive alternation. The power stored in the magnetic field of the inductance is given by the following relation in terms of the current i:

$$P = Li\frac{di}{dt} \tag{4}$$

Fig. 5 proposes one stage circuit design tuned to the unlicensed ISM band at 868 MHz. A low pass filter is arranged in cascade with the rectifier circuit to reduce ripple and to get a well DC signal. Output inductor and capacitor were chosen to filter the high frequencies. A 50kΩ load was added at the output to measure the output power and to visualize the behavior of whole circuit (Fig. 6). For the operating frequency the signal is well filtered with an attenuation of -40 dBm. The following relation expresses the output gain of the rectifier design.

Fig. 7. (a) illustrates the simulation results of the impedance measurement using Smith charts. It contains many coordinate grids used to identify and calculate electrical characteristics of matching circuit networks. Fig. 7. (b) shows the return loss

$$G = \frac{K_1 S}{1 + K_2 S + K_3 S^2 + K_4 S^3 + K_5 S^4 + K_6 S^5} \tag{5}$$

where
S = jW
$K_1 = RC_1$
$K_2 = (C_1+C_2)R+RC_3$
$K_3 = L_2(C_1+C_2)+L_1C_1$
$K_4 = RL_1C_1C_2+(C_1+C_2)RC_3L_2+L_1RC_1C_3$
$K_5 = L_2L_1C_1C_2$
$K_6 = RL_2L_1C_1C_2C_3$

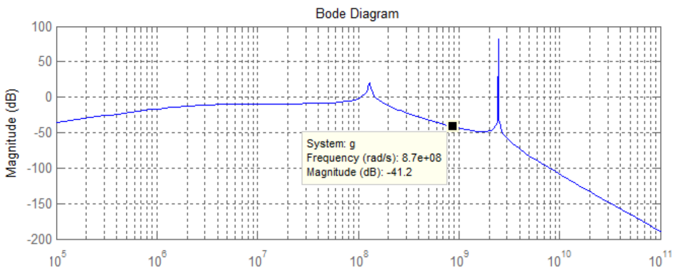

Fig. 6. Frequency response behavior of proposed rectifier design.

S_{11} of the proposed rectifier circuit.

Fig. 8 proposes two stages multiplier circuit design to load high overall efficiency. An impedance matching network, designed with inductive and capacitive reactive elements, is placed before the input rectifier circuit to ensure the maximum input power coming from the RF and reduce the power reflection.

Different simulations were conducted to measure the new impedance circuit matched to 50 ohms and plot the circuit'S_{11} parameters taking in consideration the influence of the operating frequency and the RF Power Source. Fig. 9 (a) shows the real and imaginary parts of the equivalent impedance. The simulated impedance circuit results complies with the ideal desired. From Fig. 9 (b), it is clear that the simulated return loss S11 is less than -40 dB throughout the impedance matched bandwidth. The simulated circuit design resonates at 868 MHz with -42.61dB of S_{11}.

The voltage multiplier circuit was simulated using Advanced Design System (ADS) from Agilent. The ADS sim-

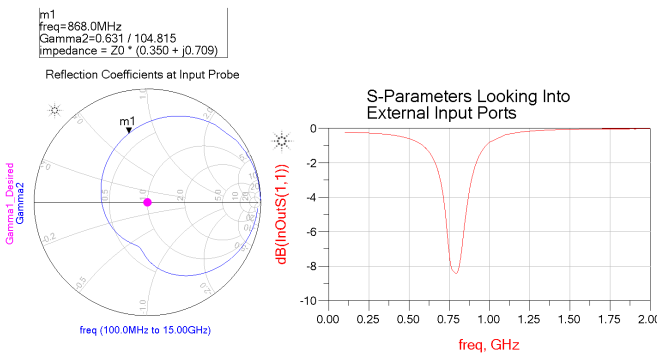

Fig. 7. (a) Simulation results of the impedance measurement, (b) Return loss S_{11}, of the proposed rectifier circuit.

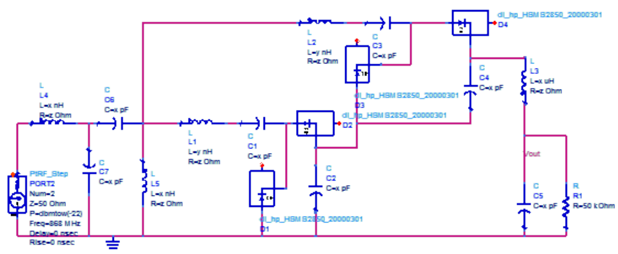

Fig. 8. A dual stages for a proposed rectifier design.

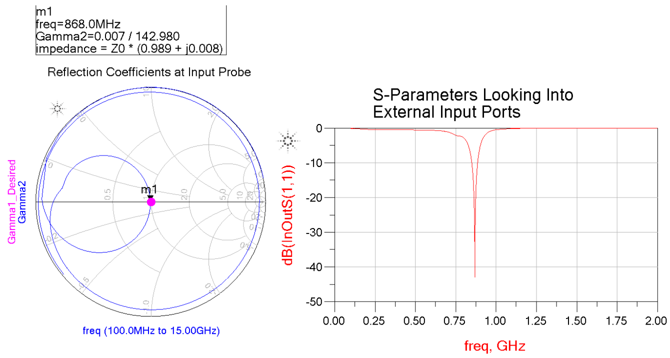

Fig. 9. (a) Simulation results of the impedance measurement, (b) Return loss S_{11}, of the proposed rectifier circuit after matching circuit.

ulation employed the device model of HSMS-2850 Schottky diode parameters to achieve the results presented in Fig. 10. The output DC power was measured around 50kΩ resistive load. From the simulation results, it is concluded that the rectifier design performs best when it matches the RF power source at the working frequency, in order to reduce transmission return loss and increase the power delivered from the source to the load.

Different simulations were conducted to evaluate the circuit parameters and the influence of the input RF Power Source. The Proposed RF harvester circuit performance was tested with a varied input power.

Since the rectifier circuit consists of diodes, which have nonlinear component behavior. In addition, the circuit design itself exhibits nonlinearity effect due to the parasitic influence of used elements. This implies that the response of the harvester circuit varies with the received power amount delivered by the antenna. Fig. 11 depicts the influence of RF input power variation, ranging from -40 to 15 dBm, on the output power of the harvesting circuit.

The novel approach for RF/DC conversion circuit is designed and simulated with a low RF power source. It has a maximum measured efficiency of 61.50% for -3.29 dBm input power.

V. Conclusion

By means of RF energy harvesting and transfer, it is possible to recover micro-power, useful for powering low-power wireless sensor nodes in industrial plants. In this work,

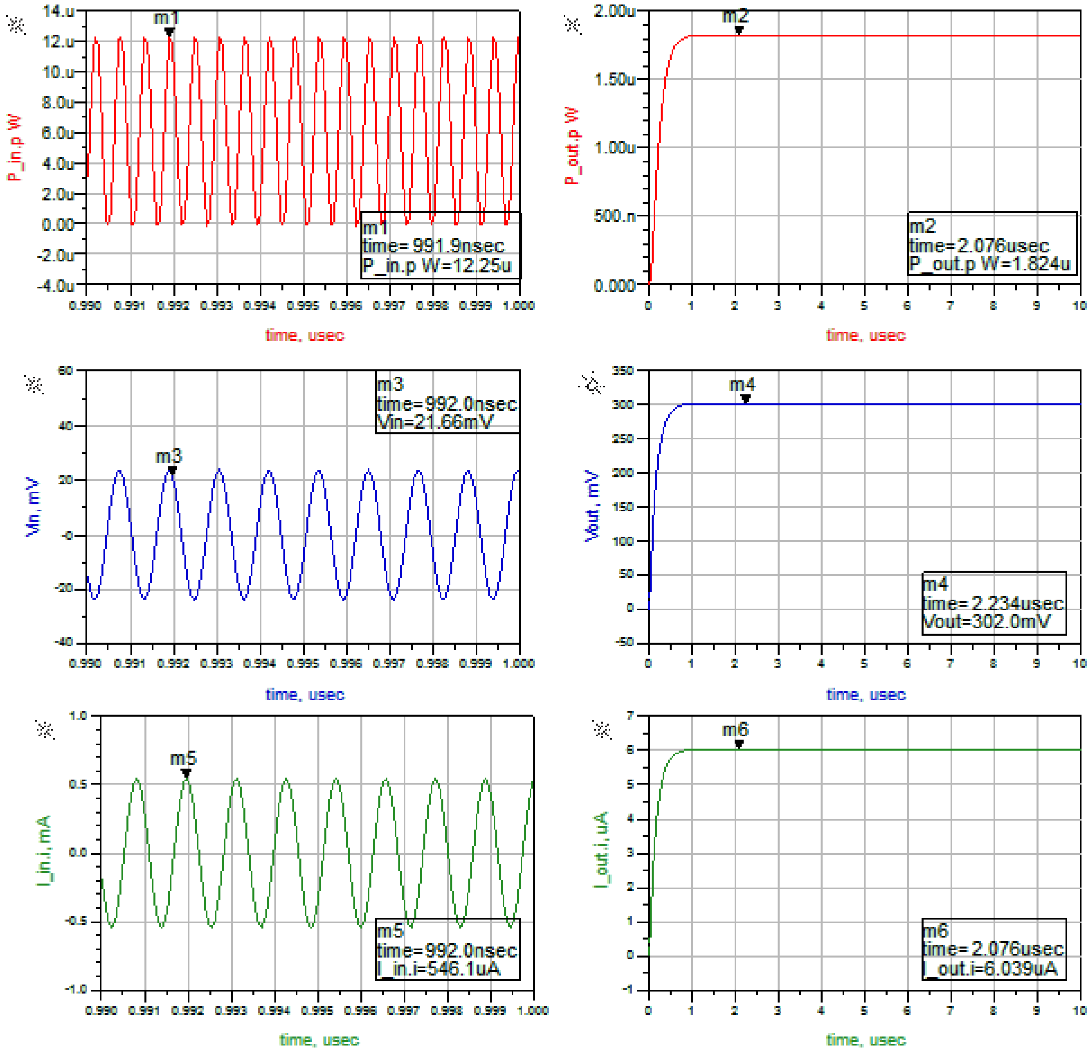

Fig. 10. Simulation results of proposed dual stages rectifier design.

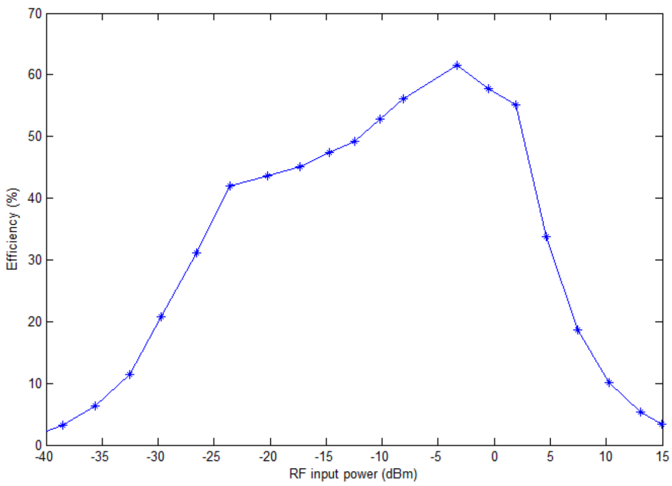

Fig. 11. Simulation results with variable RF input power.

a passively ultra-low RF rectifier circuit design operating at 868 MHz is presented. An optimal RF harvester is designed which is capable of harvesting low ambient RF power levels using a novel multiplier circuit technique and high quality components to reduce parasitic effects and threshold voltage. The proposed rectifier has a variable input power from -40 to 15 dBm according to the received RF power and across a 50 kΩ resistive DC load. A high amount of energy doesn't correlate with efficiency. The efficiency is higher at an input power of -20 dBm.

REFERENCES

[1] A.C. Patel, M.P. Vaghela, H. Bajwa, P.K. Patra, *Power Harvesting for Low Power Wireless Sensor Network*, Antennas & Propagation Conference, pp633 – 636, Loughborough 2009.

[2] S. Kawasaki, *The Green Energy Harvesting Winds by the RF/Microwave Power Transmission*, Wireless Power Transfer (WPT), pp.111–114, 2013.

[3] W. Zhao, K. Choi , S. Bauman , T. Salter , D.A. Lowy, M. Peckerar, M.K. Khandani, *An energy harvesting system surveyed for a variety of unattended electronic applications*, Solid-State Electronics 79, pp 233–237, 2013.

[4] J. Masuch, M. Delgado-Restituto, D. Milosevic, P. Baltus, *Co-Integration of an RF Energy Harvester into a 2.4 GHz Transceiver,* IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 48, NO. 7, JULY 2013.

[5] A. Dolgov, R. Zane, Z. Popovic, *Power Management System for Online Low Power RF Energy Harvesting Optimization,* IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS—I: REGULAR PAPERS, VOL. 57, and NO. 7, JULY 2010.

[6] U. Olgun, C. Chen, and J. Volakis, *Investigation of Rectenna Array Configurations for Enhanced RF Power Harvesting,* IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, VOL. 10, 2011.

[7] H. Visser, R. M. Vullers, *RF Energy Harvesting and Transport for Wireless Sensor Network Applications: Principles and Requirements,* Proceedings of the IEEE (Volume:101 , Issue: 6), pp 1410–1423, 2013.

[8] *Recommendation adopted by the Frequency Management, Regulatory Affairs and Spectrum Engineering Working Groups,* ERC/REC 70-03, August 2011.

[9] Federal Communications Commission, Code of Federal Regulations, Title 47, Part 15, 2002.

[10] H. Nishimoto, Y. Kawahara, T. Asami, *Prototype Implementation of Ambient RF Energy Harvesting Wireless Sensor Networks,* IEEE SENSORS Conference, pp 1282- 1287, 2010.

[11] K. Devi1, N. Din, C. Chakrabarty, *Optimization of the Voltage Doubler Stages in an RF-DC Convertor Module for Energy Harvesting,* Circuits and Systems, pp 216-222, 2012.

[12] P. Nintanavongsa, U. Muncuk, D. R. Lewis, and K. R. Chowdhury, *Design optimization and implementation for rf energy harvesting circuits,* IEEE Journal on Emerging and Selected Topics in Circuits and Systems, vol. 2, no. 1, pp. 24–33, 2012.

[13] L. Triet, M. Karti, F. Terri, *Efficient Far-Field Radio Frequency Energy Harvesting for Passively Powered Sensor Networks,* IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 43, NO. 5, pp 1287-1302, 2008.