Ultra-Low Power RF Energy Harvesting of 1.9GHz & 2.45GHz Narrow-Band Rectenna for Battery-Less Remote Control

Jahariah Sampe, Noor Hidayah Mohd Yunus, Jumril Yunas, and Alipah Pawi

***Abstract*—Various rectenna designs have been investigated to deal with a big growth interest in wireless energy harvesting. This paper presents a rectenna design of dual frequencies operating antenna at microwave bands which are 1.9 GHz and 2.45 GHz. Tunable impedance matching is considered necessary to supply maximum power transfer from low energy source. Since power efficiency is such a main concern, the perfect matches are desired. The front-end of dual-band receiving antennas convert microwave input signal into alternating current (AC) form. The matching network and the load impedances of the rectenna design are in matched condition to decrease reflected power and to increase input power to rectifier. Then, the power is rectified by the CMOS rectifier to generate direct current (DC) voltage that required for the electronic load. Finally, the system performance is verified with PSpice simulation results. In dual frequency operation, with -20 dBm power source over 1M Ω resistance load, the harvester system is able to generate DC output voltage of 2.09 V and the efficiency reaches 43.68% which is indicate high efficiency for a lower power input level application. The stated results represent that a dual-band rectenna of the energy harvester system could produce 1.62% to 10.18% more efficiency over a single-band rectenna at 1.9 GHz and 2.45 GHz respectively.**

***Index Terms*—Dual-band antenna, rectifying, radio frequency, energy harvester, MOSFET, microwave band.**

I. Introduction

Recently, energy independent or self-powered electronics devices by ambient energy sources for instance solar, electromagnetic wave, vibration and heat significantly attract great interest research topic. Most of the device used in daily life is portable battery-less remote controller which is used to control many appliances such as air-conditioner control, television, access-gate and sensor devices. Normally, chemical battery with finite life is used for powering the remote control (RC) devices. The current leakages happen even the battery is unused. More chemical leakages can cause environmental issues. Using power source from batteries can be both technically and economically challenging. In this motivation, energy harvesting technique is utilized to fill in the gap with the aim to avoid chemical battery usage. When ambient energy sources are totally used to power the RC, the chemical battery can be completely eliminated as a primary power source. Thus, the battery maintenance and monetary cost is reduced [1].

An increasing attractive topic of energy harvesting, has lead directed towards highly power conversion efficiency. Energy harvesting elements are efficiently and effectively used to capture ambient energies in which then is accumulated and stored for direct or indirect supply. Moreover, energy harvesting is an alternative energy source to complement a main power source, to improve the overall system reliability and to prevent interruption of power [2]. However, the electrical power by the harvester come from ultra-low power (ULP) source is usually generated in less than few milli-watts. It is significant to increase the power conversion efficiency of a system.

For the challenge, this paper presents an energy harvester design from ULP source for self-powered system. For such design, this harvester is utilizing RF energy signals as power provider to extend battery life for battery-less RC devices. This is due to potentially the abundant of ambient RF energy source at any time and present anywhere from a nearby source compared to other ambient sources. The benefit of this option lies in the fact that the RF signals able to transmit energy and process the voltage and current of the constrained nodes simultaneously. Hence, these benefits make the harvester becomes more efficient. RF energy harvesting system is important to generate sufficient electrical power to any devices.

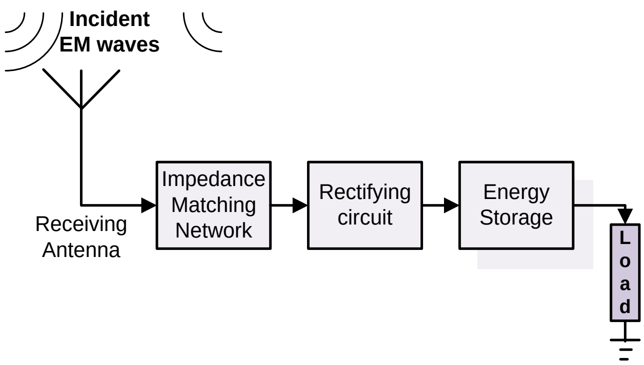

Fig. 1. Typical RF energy harvester system.

The rectenna circuit is the main module in RF energy harvester system as depicted in Fig. 1. The rectenna component consists of receiver antenna, impedance matching and rectifier. Initially, the antenna for rectenna is responsible for capturing the incident RF/microwave energy and converts it into equivalent electrical power. A system with

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narrow-band antenna needs a matching impedance circuit [3]. The matching circuit is utilized to transfer a maximum power from RF energy source to the rectifier and its load. Energy storage unit is an optional either to store the variability energy sources in a storage capacitor or instantaneous use. This unit ensures smooth energy delivery to the load when the external source is insufficient.

For this reason, the novel narrow-band rectenna architecture of RF energy harvester system is introduced in Section II. Section III presents the simulation results and the performance of the proposed RF energy harvester. Finally, discussion and concluding remarks are drawn in Section IV and V, respectively.

II. Dual Narrow-Band Rectenna Circuit Design

In designing a rectenna, frequency operation parameter is significant to consider. It brings effect on the antenna gain and the total number of power received. High antenna gain produces a highly efficient rectenna. The power received, P_r from the rectenna in the free-space path loss of the transmitted power, P_t with distance, R can be calculated by the Friis transmission formula [4] in (1).

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2 \qquad (1)$$

where G_t, G_r and λ are the gains from the transmitting and receiving antenna and the wavelength of the operating frequency. P_r strength is decreases by the proportional square of R. Thus, the rectenna requires a parameter related with the sensitivity in the circuit design. The sensitivity factor is important when dealing with ULP level source.

A challenge behind RF energy harvester technique is to optimize the rectenna design system. The optimization concept is that it is by taking into account the sensitivity and the efficiency of a system [5]. The level of power is the main concerns which determine the energy harvested performances. An efficient rectenna is required to harvest higher quantity power from the low level of incident RF ambient energy. The architecture of the proposed dual-band rectenna for RF energy harvester is shown in Fig. 2. The design system contains:

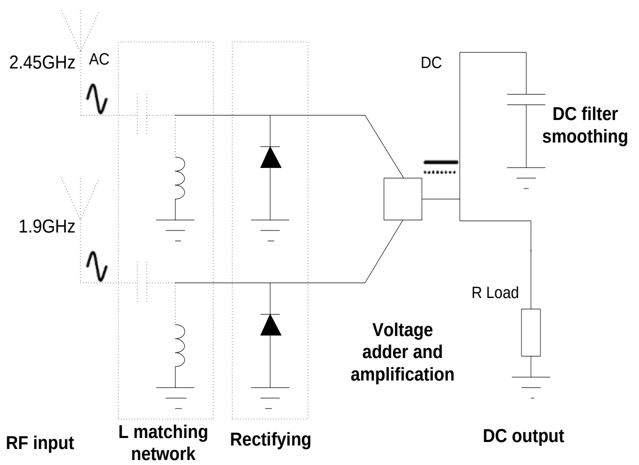

Fig. 2. Proposed RF energy harvester system.

A. Dual-Band Antenna

Antenna works as a transducer which converts one energy type into another energy type. The energy conversion is through the electromagnetic induction by the efficient antenna. The antenna used converts the incident RF energy into AC current over dual-band operating at 1.9GHz and 2.45GHz. The efficiency of antenna is depending on its impedance and the load impedance. In case these impedances unmatched, all the available energy sources are unable to be received at the desired frequency band [6]. The term 'matched' is referred to the impedance source, Z_s and the impedance load, Z_L which is fulfilled the criteria as $Z_s = Z_L^*$, where * is the complex conjugate.

B. Impedance Matching Network

The key element to maximize received power from the antenna and to minimize power loss from loads is achieved by a proper matching circuit. It is concerned in circuit design at high frequency operation. Matching circuit is consist of inductive, L and capacitive, C components. There are three configurations which are L, T and π matching network. In design circuit operating at single frequency or narrow-band, L matching network is a candidate. L network is utilized to cancel the reactive part of the load, Z_L and transform to real part. The real part is required as to obtain maximum power delivery to Z_L. Hence it is very significant to capture more energy sources for generating a required maximum power transfer. On this purpose, Q-factor is important to consider. High-Q of matching network increases output voltage and makes the harvester system more sensitive with frequency input level and the value of resistances [7].

C. Rectifier

AC current supplied from impedance matching network is converted to DC form by rectifying circuit. Schottky diode is commonly used in rectifying circuit in high frequency operation. In Cadence schematic design, Schottky diode can be replaced by diode-connected MOSFET. The effectiveness use of the MOSFET based rectifier in rectifying circuit is count on the right (W/ L) ratio [8]. W/ L ratio aspect could bring effect on a parameter such as conversion efficiency and the voltage output.

The DC voltage conversion from AC supply is containing voltage ripple and certain noise. Thus, the smoothing capacitor at the output of the rectifier is required to smooth the DC voltage. The smoothing capacitor, C_o value for a specified voltage ripple, V_r at the output can be calculated as in (2):

$$V_r = \frac{I_O}{2 f C_O} \qquad (2)$$

where I_O and f are the current at DC load and the frequency input.

III. Simulation Results

This dual narrow-band rectenna of RF energy harvester system is designed and simulated by using PSpice software. The harvester system is optimized to operate in -20 dBm input power over 1M Ω resistance load, R_{Load}. A standard resistance source, R_s of 50 Ω in transmission line impedance is used for both single band frequencies input. Circuit components selection with their performance values is tuned to match circuit design parameter in the simulation. This data is represented in Table I.

TABLE I: COMPONENTS USED IN PSPICE SIMULATION

Component	Value
L matching network capacitor	0.008, 0.0118 *pF*
L matching network inductor	0.45, 0.59 *µH*
Stage capacitor	0.01 *pF*
Diode	CMOS

The DC output voltage of proposed system for dual-band frequency operation and output voltage on L matching circuit for a single band frequency at both 1.9 GHz and 2.45 GHz as illustrated in Fig. 3. As indicated, the DC output voltage from the sum of dual single bands system is 2.09 V. Distributed DC output voltage for the R_{Load} is particularly based on combining both single-band frequencies operation. To characterize DC output voltage of a dual single-band frequencies simultaneously, parasitic smoothing capacitors placed is taking into account.

Since the proposed harvester system is optimized for 1M Ω R_{Load}, the reflected power is remained lower for the R_{Load} of 1M Ω compared to various number of R_{Load} applied as indicated in Fig. 4. Based on simulation results achieved, the power transferred is optimal in case the incident power and the R_{Load} are matched. Thus, the lower the reflected power, the higher the output power produced by the harvester system.

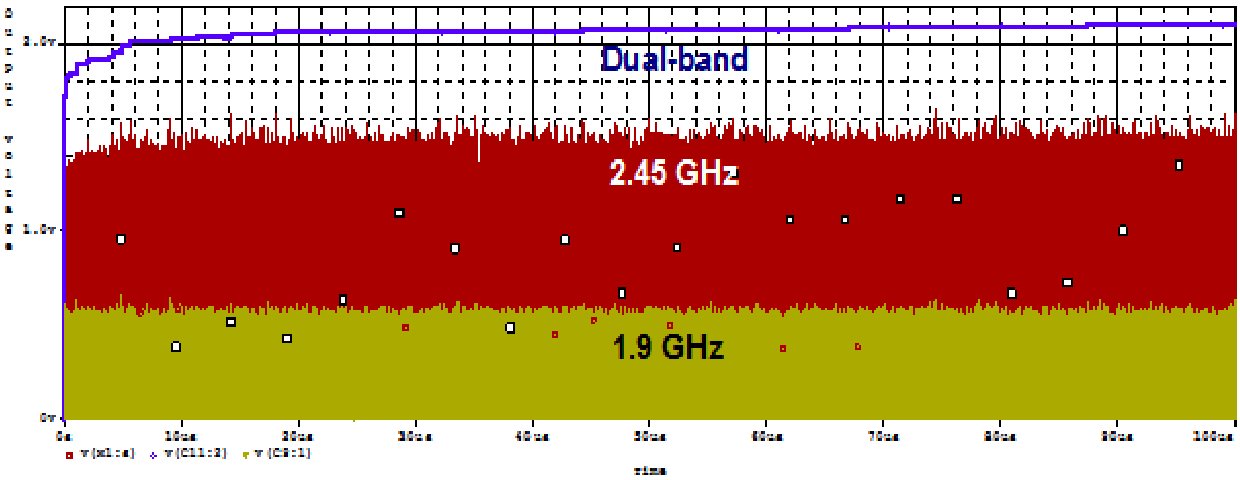

Fig. 3. Output voltage of proposed system versus time at an input power of -20 dBm.

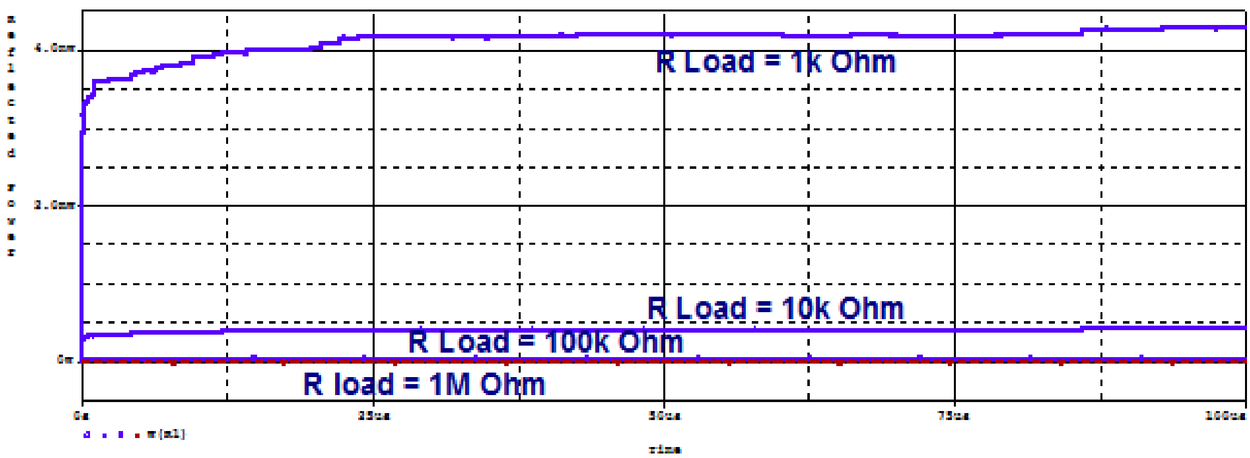

Fig. 4. Reflected power for various RLoad.

The conversion efficiency of a rectifier with commonly used diode [12]-[17] is depending on incident power intensity and the load connected. Sensitivity of the diode is affected by the threshold voltage, V_{th}. Reducing the V_{th} allow the output voltage increase. Low V_{th} diodes are preferred mainly for ULP source. Various choices of technologies such as HSMS, CMOS and SMS schottky diode are utilized in rectifier circuits. This proposed rectifying circuit implements CMOS diode of 37.5 µm/ 130nm, W/ L ratio. Simulation results in 130nm process of proposed CMOS diode rectifier, diode connected based rectifier and diode V_{th} cancellation connected in the same harvester circuit are represented in Fig. 5. The performance of the proposed rectifier yields much higher voltage than other designs are obvious. Based on the simulation results, the harvester circuit design achieved > 1.5 V of output voltage which can be utilized purposely compatible for battery-less RC devices. The work in [18] explains the compatible configuration of RC device for the optimal efficiency.

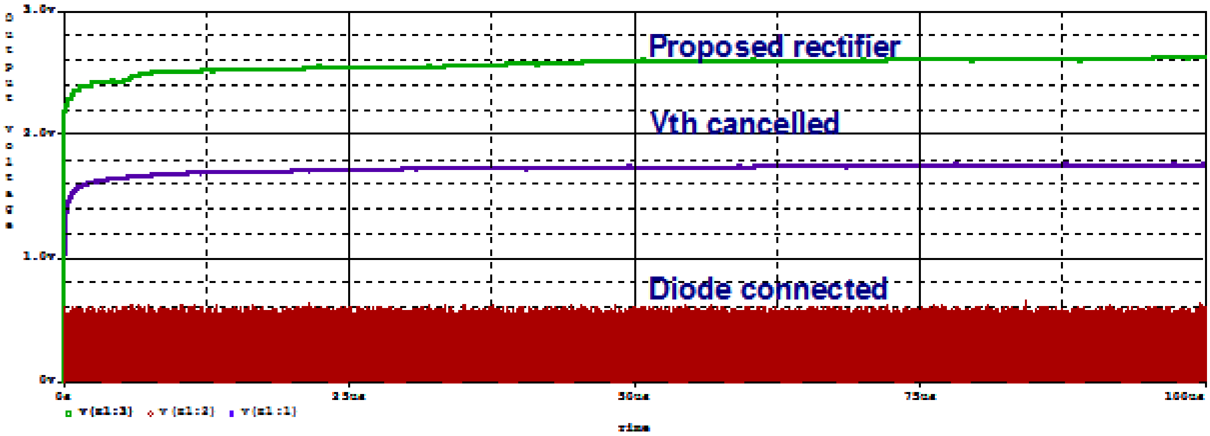

Fig. 5. DC output voltage of proposed rectifier, diode connected and Vth cancellation of rectifier in rectenna for 1M Ohm RLoad.

IV. Discussion

Simulation results for dual single-band frequency of proposed harvester system are individually designed in PSpice simulation software. With respectively single frequency operating at 1.9 GHz and 2.45 GHz, this system reaches 4.29% and 26.9% efficiency for input power of -20 dBm. However, the dual-band operating frequencies achieved 43.68% efficiency. These simulation results correspond under the same specifications indicate that the dual-band rectenna has a higher efficiency than the single-band rectenna one. The performances of this proposed design among other system designs lately published have been represented in Table II. Direct performance comparisons are impossible because those system designs drive at different frequency and different topology methods. As indicated, [9] and [19] achieved efficiency of > 50% which is show better efficiency than other designs. However, the stated designs involve in relatively high input power of > 0 dBm. Thus, this proposed design represents a better efficiency at low input power application compared among other designs.

TABLE II: Performance Comparison of Various RF Energy Harvester Techniques

Ref.[a], year	Freq.[b] (Hz)	Pin (dBm)	Vout (V)	Rload (Ω)	Eff.[c], η (%)	Rectifier method
[9], 2015	35G	8.45	2.18	1 k	67	MA4E1317
[11], 2015	490M and 860M	-18	0.7728	11 k	11.25	HSMS-2820
[10], 2016	350M	-10	1.25	10 M	n/a	180 nm CMOS
[19], 2016	2.45G	15	n/a	100 k	83.7	MOSFET
[5], 2016	915M	-8	2.72	1 M	30.95	130 nm CMOS
This work, 2017	1.9G and 2.45G	-20	2.09	1 M	43.68	130 nm CMOS

a. Reference, b. Frequency, c. Efficiency.

V. Conclusion

In this paper, dual narrow-band rectenna design based on a series CMOS diode-rectifier circuit for RF energy harvester is proposed. Simulation validation of the proposed design for RF ambient energy harvesting is presented. A high efficiency of dual specified frequency band rectenna which can effectively harvest low input power has been designed. This efficient rectenna is enhanced by co-designed dual-band receiving antenna with the perfect impedance L-match and the modified rectifier. To operate with ULP source, the energy harvester is optimized at high resistance load for optimal output power generated. Therefore the novel rectenna for RF energy harvester is capable of harvesting sufficient power from the ULP source, resulting in higher conversion efficiency.

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