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Highly Sensitive RF Energy Harvesting System for Wireless Protocol in IoT Devices

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In this paper, a co-design methodology for Radio frequency (RF) energy harvester and an ultra-low Power Management Unit (PMU) is developed in order to achieve highest system efficiency. Antenna-Converter interface model is analyzed as it plays a crucial role in order to achieve better sensitivity. Matching network realized between the interface model act as a voltage magnifier circuit as well as provides interface impedance matching. The designed system harvests energy for operating PMU whenever RF power in the environment is around -30 dBm with power conversion efficiency of 38 %. The complete schematic is simulated using Advance Design System (ADS) tool which finally generates regulated DC output voltage of 500 mV with a load current of 5 mA.

Keywords: Energy harvesting, internet of things (IoT), Radio frequency, ultra-low power, Wireless sensor node.

1. Introduction

Wireless Sensor Nodes (WSNs) are the backbone of connecting many the Internet of Things (IoT) devices, but effectively powering them is problematic due to their inherent resource constraints and accessibility issues [1]. The self-sustaining, effective, and WSNs with the ability to gather energy from the environment may be able to ease the strict and unreliable requirements for battery replacement and recharge. As a result, an essential prerequisite for ensuring the continual operation of IoT devices is an everlasting power supply, which traditional batteries cannot satisfy due to their short lifespan [2]. The continuous powering or refilling of batteries for Internet of Things devices may be possible with the help of energy harvesting from ambient sources. Wi-Fi, Bluetooth, Zigbee, and other wireless protocols that connect WSNs are frequently utilized for Internet of Things (IoT) applications. Wi-Fi is a pervasive wireless technology utilized in many Internet of Things applications today, and practically all smart devices can connect to it. However, because to its relatively high power consumption and transmission range limits the use of this technology. On the other hand, Bluetooth is a short-range wireless data network that has weak security and a sluggish data transfer rate. Because of its advantages for IoT in terms of wireless communications, power efficiency, affordability, and security, the Zigbee protocol is the protocol of choice. However, most of these wireless protocols need power supply 1-2V with few milli ampere (mA) current for their reliable operations.

Energy harvesting from many sources, including sun, wind, thermoelectricity, electromagnetic fields, and vibrational excitations, has been studied and produced using a variety of ways [3]. The wireless IoT devices may be able to continually collect energy from ambient RF signals, such as those from mobile and TV towers, Wi Fi routers, and other RF sources, thanks to features like radio frequency (RF) energy harvesting. Hence, sustainable and reliable operation of IoT enabled WSNs can be ensured with RF energy harvesters [4]. To allow IoT applications, the design and development of RF energy harvesting systems must take into account issues with higher conversion efficiency and raising voltage levels from the order of a few milli Volts (mV) to ≈ 1-2 Volts.

In that pursuit, Park J. Y. et al. [5] has demonstrated relatively high Radio frequency to DC conversion efficiency with an input RF power level of +10 dBm. However, considering +10 dBm input power is very far from practical power level available from ambient RF sources. A pragmatic design approach for RF energy harvester based on single tone power of -20 dBm showed only 18% conversion efficiency [6]. Similarly, threshold compensated RF energy harvester has been proposed in [7] for -24 dBm input power demonstrated only 16.1% of efficiency. Fig. 1 shows a typical of RF energy harvester along with generalized WSN module. This interconnected platform enables self-reliant and energy efficient IoT applications to run without replacement of batteries. A standard RF energy harvester block comprises of an antenna, matching network and RF to DC converter. In the recent past, several approaches have been proposed and demonstrated to improve the efficiency of these fundamental building blocks of RF energy harvesters.

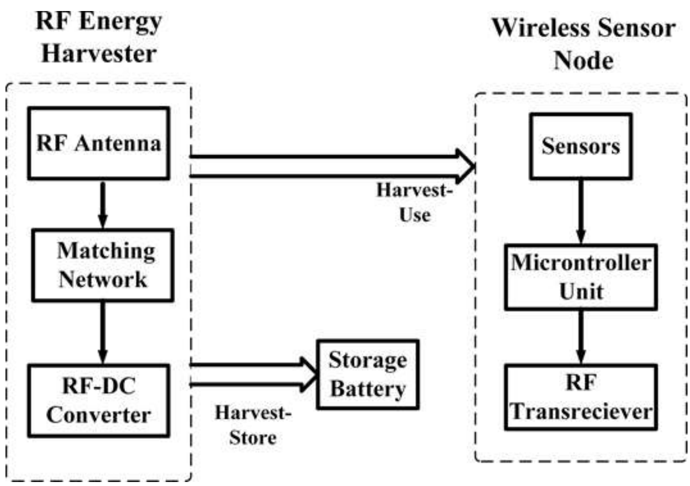

Figure 1. Schematic view of general RF energy harvesting system for powering RF Transceiver.

The DC output voltage level from RF energy converters is significantly low and not sufficient to run any real-time applications, therefore, a most common approach is to enhance the number of rectifier stages but will degrades the power conversion efficiency due to leaky Schottky diodes [8]. Hence, number of rectifier stages should be restricted to maintain adequate power conversion efficiency. An alternative approach is to employ DC-to-DC converters/boosters, but earlier reported DC-DC converter are bulkier by adding more number of discrete components for better DC output voltage level, as a result, increase in power loss and reduced conversion efficiency. For example, a ripple based switch controller using Pulse Width Modulation (PWM) involves additional circuit of post signal processor, thereby, it becomes expensive and exhibited low conversion efficiency [9]. However, recently explored DC-to-DC boosters may rise the output voltage level 1-2V and provides regulated dc output voltage with up to 100% self conversion efficiency [10, 11, 12]. In contrast with linear voltage regulator and charge pump DC-DC converter, inductor based boost converter has highest power conversion efficiency [13]. For all these converter circuits a control circuit is needed which generates constant frequency and duty cycle that drives the MOSFET switches of the boost converter circuit. For example, in literature [14], a class-C CMOS voltage-controlled oscillator supplied with 0.2 V is proposed, but it needs a bias voltage of 0.55 V at the gates.

The rest of the article is comprised as follows. Section II highlights the major contributions and how they differ from previously reported work. Section III presents the proposed energy harvester. Results from simulation and comparative analysis with prior arts are given in Section IV. Finally, Section V concludes the proposed work.

2. Proposed Rf Energy Harvester Unit

The fabricated RF-energy harvester is shown in Fig. 2. As in Fig. 4, the RF–DC conversion module shown here is an improved Villard voltage doubler circuit to obtain greater power conversion efficiency (PCE) for a given load. For the conversion process, the RF signal voltage must be greater than the threshold voltage of the MOSFETs being used. The threshold voltage and power loss brought on by a leaky mechanism are trade-offs that significantly lower the converter circuit’s power conversion efficiency (PCE). A considerable on-state channel resistance brought on by the drive-current reduction results in a significant resistive power loss, lower output dc voltage, and PCE when a transistor operates in the sub-threshold zone [17]. The RF–DC converter design flow proposed for achieving higher PCE is mentioned as follows:

- First, ULP MOSFET-based diodes eliminate the trade-off between leakage current ($I_{leakage}$) and threshold voltage (V_{TH}) that restrict traditional MOSFET based diodes in rectification process as shown in Fig. 3.

- A ULP diode is used in a low power single stage Villard voltage doubler circuit to produce a dc voltage V_{DC} that is almost twice as high as the input voltage with a fixed input voltage.

- Analysis was done to estimate the effects of capacitance values (C_1, C_2, and C_{DC}) on the frequency domain study of the voltage doubler circuit (Fig. 4).

- Finally, a voltage magnifier circuit using a matching network is created; amplifying the RF input voltage Vin to a level of 0.35 V.

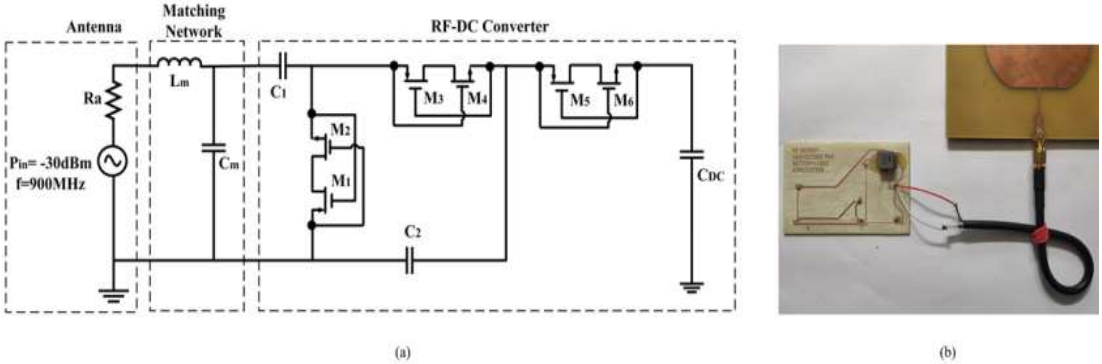

Figure 2. Overall architecture of designed RF energy harvesting system.

Capacitor C1 charges via D1 to a voltage of V_{rect} during the input voltage’s negative half-cycle. The voltage given in series with the voltage across capacitor C_1 during the positive half-cycle ($V_{C1} = V_{rect}$), charges capacitor C_2 to the output voltage ($2V_{rect}$) through D_2. A capacitor C_1 helps a capacitor C_2 charge by receiving alternating current whereas C_2 only receives direct current.

The optimized device dimensions and capacitors values for the proposed RF-DC converter using ULP diodes are as follows:

C_1 = 4.5nF, C_2 = 2.25nF, C_{DC} = 5nF

For the RF energy harvester to deliver rectified output voltage with the highest self- conversion efficiency, leakage current must be maintained to a minimum. In MOS coupled diodes, reverse bias results in leakage, which sharply lowers input power. As a result, a ULP diode is used in the recommended RF-DC converter circuit.

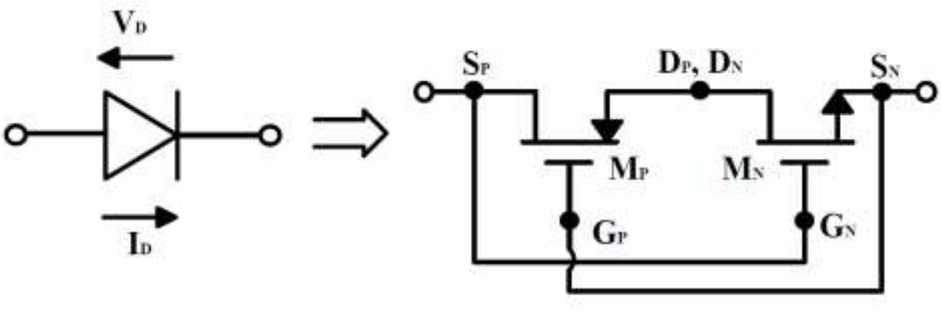

Figure 3. Representation of Ultra-low power (ULP) diode using MOSFETs [15]

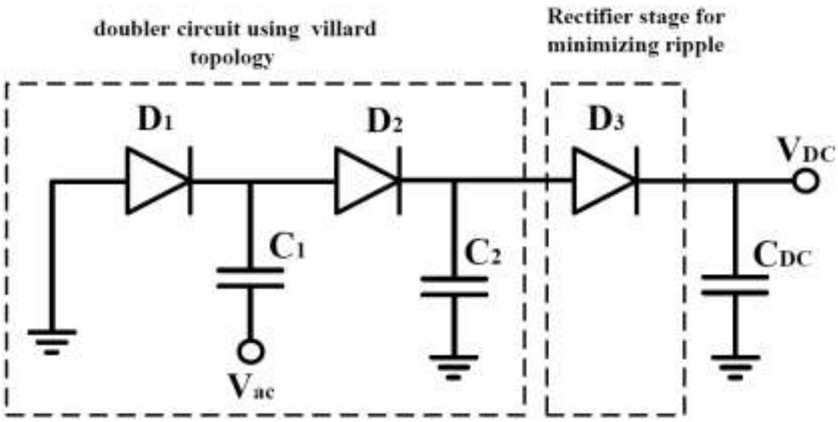

Figure 4. Proposed RF-DC converter circuit using ULP diodes.

Leakage in MOS connected diodes results in the quick decrement of input power level when reverse bias takes place. Consequently, a ULP diode based on MOSFETs (Fig. 3) that exhibits a $I_{Leakage}$=2 pA when a reverse bias voltage of -0.4 V is given to the doubler circuit through a storage capacitor (C_{DC}) in order to get rid of these harmonics and boost overall efficiency. In general, nonlinearities brought on by MOSFETs significantly enhance the harmonics in the doubler circuit. Fig. 6 shows that the output capacitor C_{DC} charged to target dc voltage of 0.5 V which is fed to the DC-DC booster circuit for voltage boosting. The capacitors (C_1, C_2 and C_{DC}) and size of the MOS devices are obtained by circuit simulation with proper tuning.

Maximum power transfer in a network needs that the equivalent impedance of source should match the equivalent load impedance connected to it. Matching of impedance between the antenna-converter interfaces is a major concern for the optimizing overall system performance as this matching network provides a passive magnification of the input RF voltage V_{in} [18]. As long as high-Quality factor (Q) components (e.g., off-chip inductors and capacitor) for impedance matching is used, power loss can be neglected but results in lower impedance transformation ratio. Whereas low-Q components in matching network is implemented for higher transformation ratio and power loss cannot be neglected. Hence a careful interface model is required to maintain the power loss and power reflection. A general 50 Ω antenna impedance has been considered which requires high conversion ratio.

The matching network adopted in this paper is exploited by on-chip inductor and capacitor with limited Q-values which offers best trade-off between power loss and the power reflection. The power reflection between the interfaces is analyzed by the significance of reflection coefficient S_{11} at converter circuit input. Lesser the value of S_{11} minimum will be the power reflection between the interfaces.

Here, total impedance offered by load is the impedance of both RF-DC Converter and DC-DC converter circuit which is shown in Fig. 4. The input impedance of the converter circuit Z_{conv} depends on the input frequency, the transconductance of MOSFETs and the capacitance value. To transfer the maximum power from antenna to converter circuit, L-type matching network is used which depends on input frequency. As stated earlier this matching network also acts a voltage magnifier circuit which provides passive magnification to the weak RF input voltage whose magnified output voltage is shown in Fig. 8.

Resistance r_d of ULP diode under forward condition,

$$r_d = \frac{g_{mp} r_{01}}{g_{mn} - g_{mp}} \quad (1)$$

where g_{mp} , g_{mn} are transconductance of pMOS and nMOS and r_{o1} is large value output impedance of MOSFET.

The overall impedance of RF-DC rectifier Z_{rect} stage is,

$$Z_{rect} = \frac{-(r_d - jX_{DC})jX_{C2} + r_d(r_d - jX_{DC} - jX_{C2})}{-(r_d - jX_{DC})jX_{C2} + 2r_d(r_d - jX_{DC} - jX_{C2})} r_d - jX_{C1} \quad (2)$$

where X_{c1} , X_{c2} and X_{DC} are reactance of capacitors C_1, C_2 and C_{DC}. Moreover,

$$A_V = \frac{V_{OUT}}{V_{IN}} = \frac{1}{2}\sqrt{1 + Q^2} \quad (3)$$

Where,

$$Q = \frac{B_m + B_{conv}}{G_{conv}} \quad (4)$$

B_m represents susceptance of matching network, B_{conv} and G_{conv} are susceptance and conductance values of converter circuit respectively.

Impedance matching analysis between antenna and the converter to obtain the voltage gain Av=100 has been done by circuit simulation in ADS tool to validate the calculated results with the following parameters of interface model.

L_m = 4 μH C_m = 0.09 nF G_{conv} = 0.014 S

B_{conv} = 0.0047 SB_m = 1.96 S

Where L_m and C_m represent inductance and capacitance value of the matching network.

3. Results and Discussions

RF energy harvesting power supply is constructed and modelled in ADS utilizing CMOS technology for the purpose of testing the proposed system. Wireless protocols in Internet of Things devices are powered by the intended power supply. The system's building blocks are each individually simulated in accordance with the design requirements. The values of inductor and capacitor are chosen in such a way that their sizes are compliant with Surface Mount Device (SMD) packages.

Fig. 5 shows the calculated and simulated reflection coefficient S_{11} between the interface. The total input impedance offered by both RF-DC converter and the DC-DC booster circuit is calculated theoretically to justify the reflection coefficient obtained by the simulation. The choice of capacitor and inductor values for matching network proposed results in minimum S_{11} of -40 dB (0.01 in magnitude).

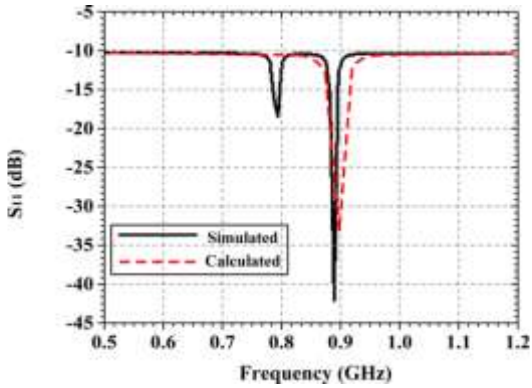

Figure 5 Reflection coefficients S_{11} of matching network between Antenna-Converter interface.

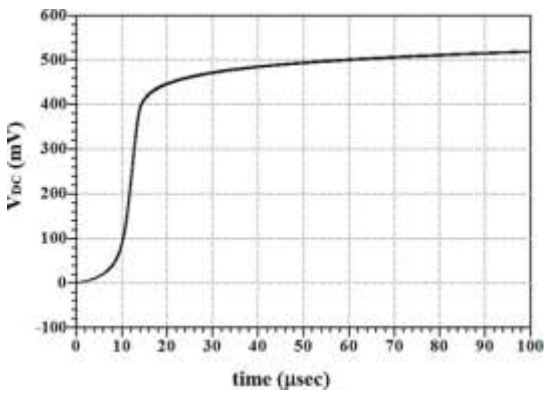

Figure 6. Simulated DC Output voltage of RF-DC converter.

The power conversion efficiency of RF energy harvester needs to be defined carefully. Here in this work, power conversion efficiency (PCE) is defined using resistive load (R_L):

$$PCE = \frac{V_{DC}^2}{R_L P_{IN}} \tag{5}$$

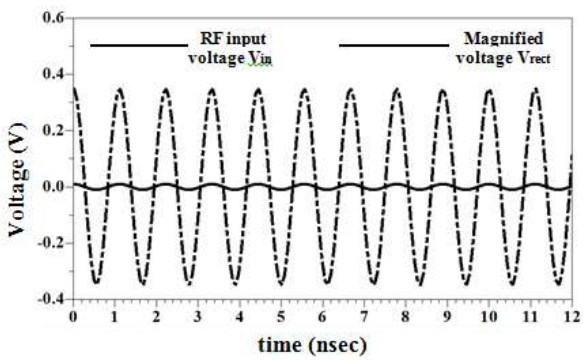

Figure 7. Magnified output voltage from matching network providing passive voltage

magnification to RF input voltage V_{in}

RF-DC converter have been simulated with different loads (RL) for a range (-35 dBm to -25 dBm) of input power from the antenna. A maximum PCE of 38 % is achieved at RL=75 kΩ from an input power Pin= -30 dBm as shown in Fig. 8 which is far better than the earlier work proposed. A rectified DC output voltage of 0.53 V shown in Fig. 6 is obtained by the RF-DC converter design from an input power level of -30 dBm at a frequency of 0.9 GHz.

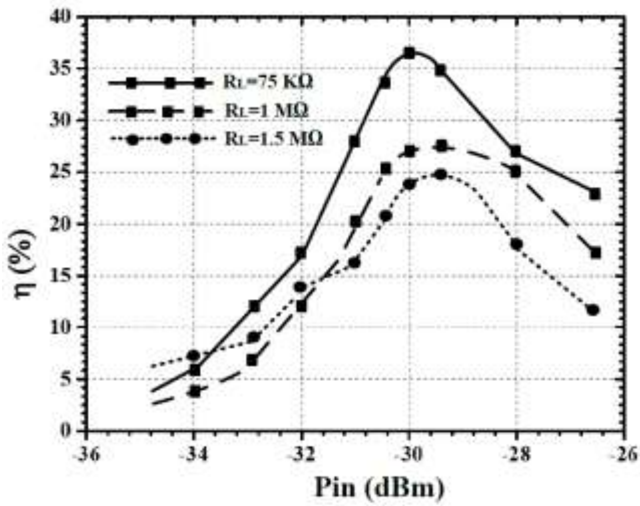

Figure 8. Measured power conversion efficiency (η) of RF energy harvester

The peak input voltage from the antenna Va is 10 mV, when this signal is fed to the impedance matching circuit which also acts as a voltage magnifier, it is then magnified up to 35 times so as to get proper threshold voltage to turn on the MOSFETs used in the RF-DC converter. The magnified output is seen to approach the saturated value between (-0.35 V to 0.35 V) as shown in Fig. 7. The magnification of the AC input signal depends on quality factor Q of the impedance matching circuit.

A. Performance Comparison with Prior Arts

The system implemented in the proposed work has reported low power converter circuits and is most power efficient among state of the art RF-DC converter and PMU circuitIn [7], 17 stages of rectifier circuit and a charge pump DC-DC converter is used to obtain 1 V dc output voltage with power conversion efficiency of only 11%. Since charge-pump dc-dc converter is associated with high static and dynamic power losses due to more number of switches than inductor based dc-dc converter and a complex control circuit is needed to control those many switches, the efficiency of this kind of dc-dc converter is not as perfect as expected. Our proposed RF-DC converter circuit uses single doubler stage and one additional rectifier stage of 38% conversion efficiency. Reference [10] uses single stage rectifier circuit and produces 1 Volt dc output voltage which is not sufficient to charge batteries of current technology. Moreover, power conversion efficiency of complete system is not mentioned in the work also. Compared with [11], the proposed system harvest 2 Volt dc output from an input power of -30 dBm which is quite smaller than input power (-14 dBm) used in [11].

4. Conclusion

A complete power supply solution for wireless protocols in IoT devices using RF energy harvesting technique is proposed. Various techniques have been provided in this paper that allows power management unit to interface with RF energy harvester. This enables Zigbee wireless protocol to operate directly from the RF energy source without the aid of a battery. The proposed system comprises of least number of chip components for higher power conversion efficiency and is compatible with current CMOS technology

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