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► **To cite this version:**

Xiaoqiang Gu, Erika Vandelle, G. Ardila, T. Vuong, Ke Wu, et al.. Environment-Aware Adaptive Energy Harvesters for IoT Applications Environment-Aware Adaptive Energy Harvesters for IoT Applications. IEEE MTT-S International Wireless Symposium, May 2019, Guangzhou, China. hal-02527550

HAL Id: hal-02527550

<https://hal.science/hal-02527550>

Submitted on 1 Apr 2020

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Environment-Aware Adaptive Energy Harvesters for IoT Applications

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Abstract—Wireless communication devices are traditionally shielded from their environment, with the purpose to operate independently from the surroundings. We propose in this work the exact opposite paradigm and demonstrate environment-aware IoT energy harvesters that enhance their operational efficiencies by adapting to their radiofrequency, vibration, temperature, and direction conditions.

Index Terms—energy harvester, environment-aware, internet of things, wireless power transmission

I. INTRODUCTION

Ubiquitous wireless sensors, actuators, and distributed computing systems are merging into the Internet of Things (IoT) to fuel the Fourth Industrial Revolution, at the dawn of the coming cyber-physical era [1, 2]. Despite the complexity and capability of the IoT ecosystem, the whole network is based on low-cost, low complexity, widespread devices that have to cope with huge hardware power restriction (aiming at batteryless operation). The major challenge is to extract energy from the thin air to fuel its operation which is described as an energy harvester.

However, such energy harvesters operating under very low power conditions are restricted by the Carnot limitation that can be expressed by the following relationship [3]:

$$\eta = \frac{1}{2} \cdot \mathfrak{R}_I^2 \cdot P_{in} \cdot R_j = \frac{q \cdot P_{in} \cdot R_j}{4 \cdot n \cdot k_B \cdot T} \quad (1)$$

where \mathfrak{R}_I , P_{in} , and R_j are current responsivity, input power, and diode nonlinear junction resistance, respectively. q , n , k_B , and T are electron charge, diode ideality factor, Boltzmann constant, and operation temperature (in Kelvin). As a consequence, the maximum efficiency is dependent on the ratio between the input power and operation temperature.

Electronic devices are usually designed and optimized based on their inner optimum operation conditions. For example, mixer diodes widely used in telecommunication are typically being driven by an LO that is 7dBm or more. But in the present case of ambient energy scavenging for IoT applications, energy increase benefits from the environment can greatly improve the nonlinear operation of the diode, resulting in enhanced efficiency performance. Accordingly, a lower temperature condition can also be beneficial to certain diode-based energy

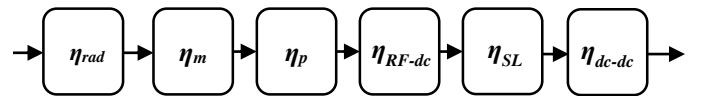
harvesters. In this work, we will show how energy harvesters adapt/react to their present environments to improve their performance. Radiofrequency (RF), vibration, direction, and temperature conditions are respectively discussed.

II. RF ENERGY AWARE

Similar to air and water, RF energy is pervasive in our daily life, to support wireless communication and parameter sensing. However, this omnipresent energy type is actually wasted if not used immediately. Thus, collecting RF energy to energize scattered low-power-consumption IoT sensors is an attractive solution, which has gained vast attention [4-6].

Our daily environment is SAR complied and thus has a low density of RF energy, which is usually below -30 dBm [7]. The diode cannot be considered as a perfect switch anymore and a new analysis approach was raised [8]. Fig. 1 (a) shows the efficiency chain of an RF energy harvester, from injecting RF signal to dc output power through various steps. Also, Fig. 1 (b) presents loss mechanisms of the RF energy harvester, corresponding to each rectifying step.

$$\eta_T = \eta_{rad} \cdot \eta_m \cdot \eta_p \cdot \eta_{RF-dc} \cdot \eta_{SL} \cdot \eta_{dc-dc} \quad (2)$$



η_{rad}	Radiation efficiency of antenna
η_m	Matching network efficiency
η_p	Parasitic efficiency
η_{RF-dc}	RF-dc conversion efficiency of nonlinear junction
η_{SL}	dc power source to load power transfer efficiency
η_{dc-dc}	dc-dc booster efficiency

(a)

III. VIBRATION ENERGY AWARE

As another form of omnipresent energy, vibration power can be found in moving vehicles, human motions, working household products, *etc.* It can be converted into AC electrical power through electromagnetic, piezoelectric and electrostatic transduction mechanisms [11]. Motivated by the efficiency calculation in (1) which indicates more input power leverages power rectifying efficiency, a hybrid RF and vibration energy harvester is proposed with prototype shown in Fig. 3 (a). The dc output increase of such a hybrid energy harvesting manner is achieved in two stages. Firstly, from the single RF energy harvester standpoint of view, the added AC power converted from vibration simply results in more dc output power, being the first stage. As can be seen from (1), energy harvesting efficiency is lifted with one more input source, which is the second stage. Therefore, as the final product of input power source multiplying rectifying efficiency, dc output power is finally obtained through a two-stage enhancement.

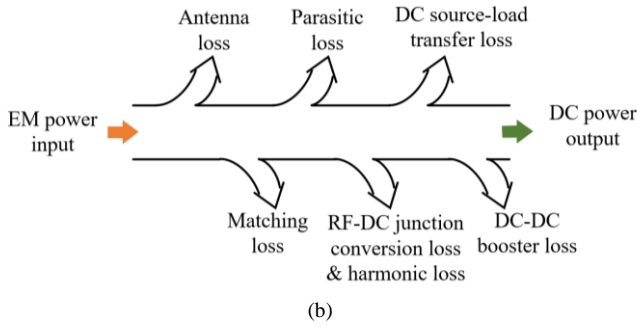
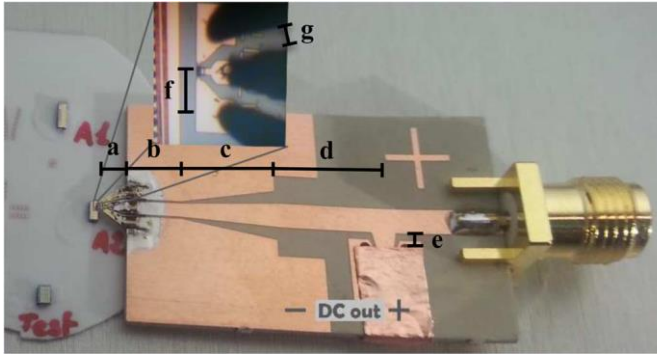
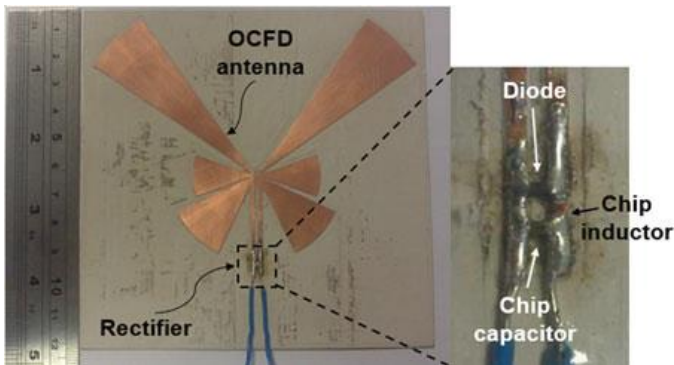


Fig. 1. (a) Efficiency chain and (b) loss mechanisms of an RF energy harvester [4].

To leverage the entire efficiency of the harvester, we can target the corresponding part. For example, the backward tunnelling diode has a stronger nonlinearity to provide higher RF-dc conversion efficiency. Therefore, an RF energy harvester (Fig. 2 (a)) built on it successfully breaks the efficiency limitation set by conventional Schottky diodes [9]. Whereas, to alleviate matching loss issue, an RF energy harvester with matching network eliminated has been presented in Fig. 2 (b). Expression (1) also gives a clue that a larger input power level would lead to higher efficiency performance, which will be addressed in detail afterwards.

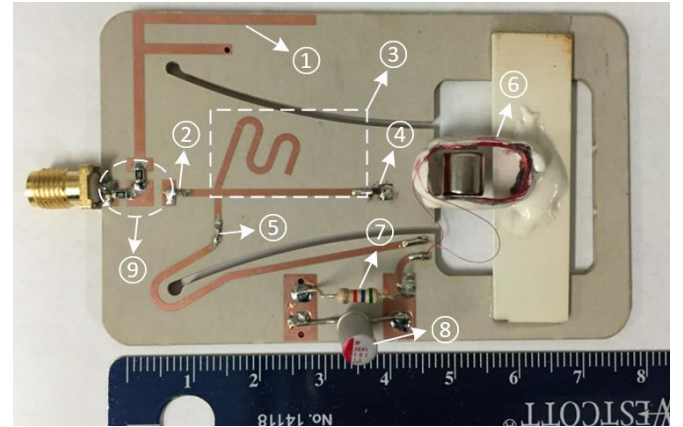


(a)

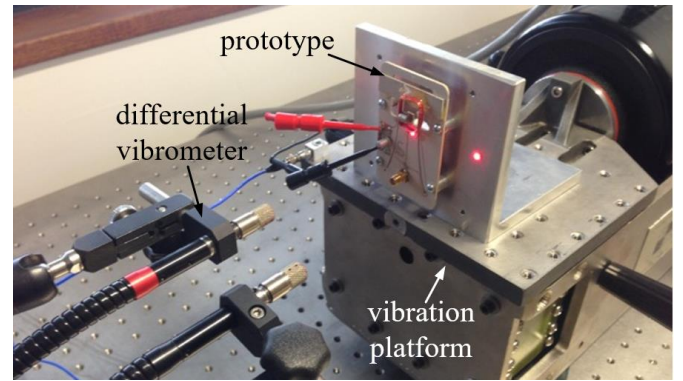


(b)

Fig. 2. (a) Backward tunnelling diode-based RF energy harvester [9] and (b) RF energy harvester with matching network eliminated [10].



(a)



(b)

Fig. 3. (a) Experimental prototype of the integrated RF and vibration energy harvester [12] and (b) measurement setup [13].

The experimental prototype was tested using a vibration platform. Measured results demonstrate that dc output power of the hybrid RF and vibration energy harvester is 1.97 times

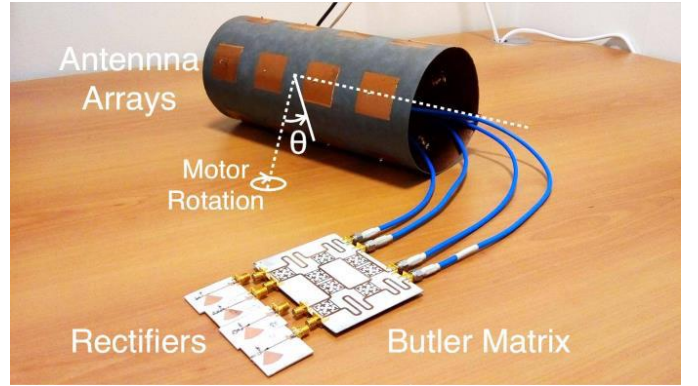
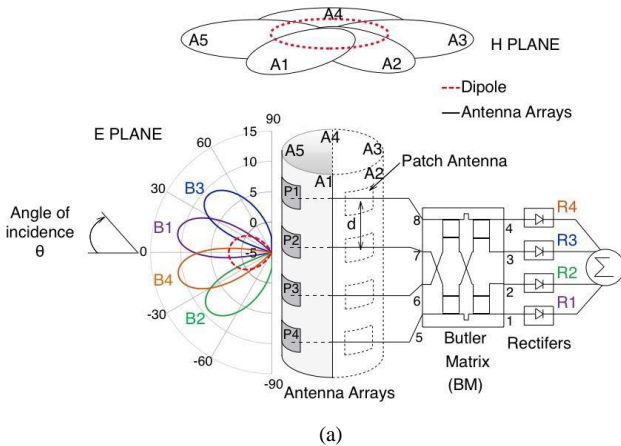
larger with diode HSMS-2850 at both input power levels of -40 dBm, compared with the traditional single RF energy harvester. Besides the dc output enhancement, such a hybrid energy harvester has a strong resilience, capable of working with access to only either power source or both of them. A similar idea to collect both RF and vibration energy has also been reported in [14].

IV. COMMUNICATION DIRECTION AWARE

The recent evolution of wireless communications via cellular networks, Wi-Fi, TV broadcasting and Wireless Sensor Network (WSNs) has transformed our environment into a giant resource of RF energy, suitable for supplying continuous power to electronics devices. Most of this electromagnetic power is instantaneously unused and can only be recycled by an energy harvester disposed with the right position. Indeed, aside from the design of efficient energy transceivers for low-power operation, the orientation of the harvester with respect to the RF emitter is equally crucial to optimally collect electromagnetic waves. Because the angles of arrival of the ambient RF signals on the harvester are unknown and time-varying, they conventionally impose rectifying antennas (rectennas) with low gain and omnidirectional properties. As a consequence, only a limited quantity of energy can be recycled. This is even more critical with such low-power levels, as the harvester efficiency is proportional to the RF power entering the rectifier, which is given, for a direction of arrival (θ_i, ϕ_i) , by:

$$P_{in}(\theta_i, \phi_i) = S(\theta_i, \phi_i) \cdot D(\theta_i, \phi_i) \cdot \eta_{rad} \cdot \frac{\lambda_0^2}{4\pi} \quad (3)$$

where $S(\theta_i, \phi_i)$ is the power density at the angle of arrival of the RF signal and $D(\theta_i, \phi_i)$ is the directivity of the antenna at the angle (θ_i, ϕ_i) .



(b)

Fig. 4. (a) Scheme and (b) experimental prototype of the multi-directional RF energy harvester composed of passive beam-forming networks [15].

In order to optimize the collection of RF power, the direction of arrival of the incident signals can be estimated before the energy harvesting process. For the sake of energy restriction, multiple linear antenna arrays associated to passive Beam-Forming Networks (BFNs) have been presented in Fig. 4 to produce a high gain rectenna with optimal angular coverage [15]. As a result, a multi-directional rectenna with multiple DC outputs is obtained. Each rectifier shows a high rectification efficiency for a specific direction of arrival, as shown in Fig 5.

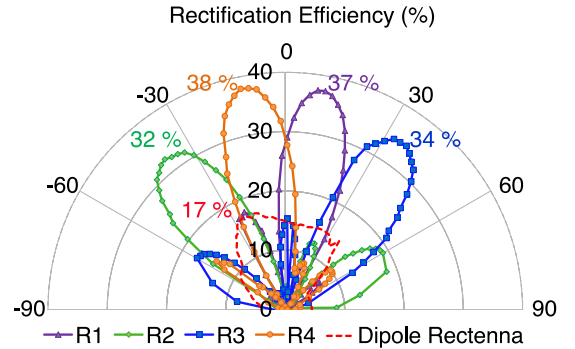


Fig. 5 Measured rectification efficiency (%) as a function of the angle of incidence of a RF signal of power density $S = 0.45 \mu W \cdot cm^{-2}$ in the E-plane of the multi-directional RF energy harvester and of a dipole rectenna [15].

V. TEMPERATURE AWARE

Operation temperature conditions are always considered to ensure the consistent reliability of electronics. Special design considerations associated with temperature need to be taken into account. For example, datasheets of diodes usually demonstrate their performance results under various temperature conditions. A higher temperature is found to be harmful to a p-channel MOSFET voltage multiplier, especially in a low power range [16]. Whereas, based on the efficiency calculation in (1), harvesting efficiency is inversely proportional to the temperature when the parasitic effect is not considered. Thus, certain temperature condition can be

beneficial for ambient power harvesters. Experimental prototypes based on diode SMS7630 and HSMS-2850 are fabricated and tested. Measurement and simulation results of both harvesters at the input power of -40 dBm versus temperature are shown in Fig. 6. Each harvester has its own optimum temperature to deliver the best harvesting efficiency. Noticeably, the SMS7630-based harvester has its optimum temperature at 15°C according to measurement results. And the enhancement of power conversion efficiency at this temperature over room temperature (25°C) and summer season (40°C) are 13.7 % and 105 %, respectively.

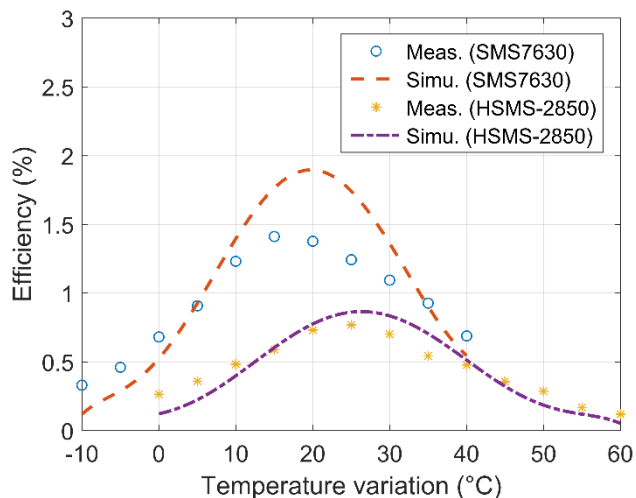


Fig. 6. Comparisons of measured and simulated PCE results of SMS7630 and HSMS-2850 diodes-based rectifiers at -40 dBm in a temperature range of -10°C to 60°C [17].

CONCLUSION

Based on theoretical analysis of efficiency performance of energy harvesters for IoT applications, this work addresses the possibilities of increasing input power level and optimizing temperature to obtain more dc output. Then, it presents how ambient energy harvesters can be designed to adapt to certain environmental conditions to enhance its operation.

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