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► **To cite this version:**

Carlos Lorenz, Simon Hemour, Weiqun Liu, Adrien Badel, Fabien Formosa, et al.. Hybrid Power Harvesting for Increased Power Conversion Efficiency. *IEEE Microwave and Wireless Components Letters*, 2015, 25 (10), pp.687-689. <10.1109/LMWC.2015.2463229>. <hal-04559889>

HAL Id: hal-04559889

<https://hal.science/hal-04559889v1>

Submitted on 25 Apr 2024

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Hybrid Power Harvesting for Increased Power Conversion Efficiency

Carlos H. P. Lorenz, *Student Member, IEEE*, Simon Hemour, *Member, IEEE*, Weiqun Liu, Adrien Badel, Fabien Formosa, Ke Wu, *Fellow, IEEE*.

Abstract— This work presents a cooperative power harvesting scheme, collecting power from two or more independent ambient energy sources into a single non-linear component. It is shown that the interaction of uncorrelated signals in a nonlinear device can greatly improve the conversion efficiency of the harvester. This letter proposes and studies a hybrid power harvester working with both microwave radiation and mechanical vibration excitations. Up to 6 dB gain on the harvested power is obtained for excitations in the range of maximum -40 dBm input power, when compared to a single excitation and standalone harvester working at the same input power level.

Index Terms — Hybrid energy harvesting, mechanical vibration, microwave power transmission, Schottky diodes, rectifier, rectenna.

I. INTRODUCTION

The development of the internet of things (IoT), smart cities and smart houses is expected to rely on networks of dozens to millions of interconnected electronic devices and apparatus. Powering all of these devices and apparatus through cables or batteries may become an unpractical or even impossible task as some of them may be installed in inaccessible places, or too small to hold a battery, not to mention the huge quantity of those scattered elements.

As every new generation of transistor becomes more power efficient, these distributed devices will become less power hungry. Koomey's law [1] crystalizes this trend, predicting that the total energy needed per computing operation halves roughly each 18 months. Thus, in a few years, the hundreds of computations necessary for the ubiquitous/embedded sensors will require only a couple of nano joule [1, 2]. This would make microwave power harvesting a possible source of power for these distributed network devices and apparatus.

Ambient microwave power harvesters have been the subject of many recent publications. However, η_{Total} , the total

harvester RF to DC power conversion efficiency, remains usually below 10% [3] at power levels below -30 dBm, as found in ambient energy harvesting applications [4].

Harvesting from multiple sources to increase the total power has already been considered [5, 6]. Niotaki *et al.* [6] presented a very interesting topology, combining DC power from solar and RF harvesting, however no efficiency improvement from energy combination has been reported to date. This letter evaluates a collaborative conversion of power using different sources, namely mechanical vibration and microwave radiation. The powers of both sources are combined using a single diode, operating in such a way that the system efficiency is increased and the topology is simplified.

II. INCREASING THE CONVERSION EFFICIENCY

Using small signal theory, the diode's voltage-current relationship may be written in a Taylor series around the 0V bias operation point [7]:

$$I_{Rj}(V_j) = I_s \cdot \left[\frac{V_j}{N \cdot V_T} + \frac{V_j^2}{(N \cdot V_T)^2 2!} + \dots + \frac{V_j^n}{(N \cdot V_T)^n n!} \right] \quad (1)$$

where I_{Rj} is the current flowing through the diode's nonlinear junction resistance; V_j is the voltage over the diode's junction; I_s is the diode's saturation current; N is the diode's ideality factor, V_T is the thermal voltage constant and n the order of the Taylor series. Assuming a voltage applied to the diode's junction, composed by two sinusoidal signals, corresponding to two different ambient energy transducers with angular frequencies equal to ω_1 and ω_2 , and amplitudes equal to A and B , one can write:

$$V_j = A \cdot \cos(\omega_1 t) + B \cdot \cos(\omega_2 t) \quad (2)$$

For signals exhibiting a very small swing around the 0V bias point, one can keep only the first and second terms of equation (1) as a good approximation. Substituting (2) into (1) and applying some trigonometric manipulations, one can isolate the DC component of the resulting current, I_{dc} , and the current in each angular frequency, $I_{j\omega_1}$ and $I_{j\omega_2}$. Using these current components together with (2), the power absorbed by the diode junction at each of these frequencies, $P_{j\omega_1}$ and $P_{j\omega_2}$, may be calculated as follows,

$$I_{dc} = I_s \cdot \frac{A^2 + B^2}{4 \cdot N^2 \cdot V_T^2} \quad (3)$$

Manuscript received Feb 09, 2015; revised Apr 09, 2015 and May 30, 2015; accepted Jun 15, 2015. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada (NSERC) and CREATE PERSWADE Training Program.

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The authors would like to thank Benedict Besner and Isabelle Nowlan, for allowing the use of the acoustics laboratory installations, and also the technicians in Poly-GRAMES research center.

$$P_{j\omega 1} = \frac{I_s \cdot A^2}{2 \cdot N \cdot V_T} \quad (4)$$

$$P_{j\omega 2} = \frac{I_s \cdot B^2}{2 \cdot N \cdot V_T} \quad (5)$$

The sinusoidal signal to DC power conversion efficiency at the diode's non-linear junction, η_{AC-DC} [3], can then be found, being described by (6). R_{j0} is the diode's zero-bias junction resistance, R_s is the diode's series resistance and R_L is the load's resistance. This equation gives the ratio of the total power reaching the diode's junction that is converted into DC power. As it can be seen from this equation, η_{AC-DC} is directly proportional to the total power that is absorbed by the diode's junction.

$$\eta_{AC-DC} = \frac{P_{DC}}{P_{j\omega 1} + P_{j\omega 2}} \quad (6)$$

$$= (P_{j\omega 1} + P_{j\omega 2}) \cdot \left(\frac{R_{j0}}{2 \cdot N \cdot V_T} \right)^2 \frac{1}{R_{j0} + R_L + R_s}$$

In other words, (6) indicates that the collaboration of different energy sources brings the operation point of the rectifier to a higher efficiency region. This increase in the efficiency has already been documented in multi-tone low power microwave power harvesting, as shown in [8].

III. PROTOTYPE AND MEASUREMENT RESULTS

The constructed prototype consists of a collaborative harvester, composed by a microwave signal harvester and a mechanical vibration harvester. It was optimized for excitations at the -50 dBm to -30 dBm power range. For these power levels, one can assume the two harvested powers as two sinusoidal signals arriving at the diode's junction, so the small signal approximation previously made remains valid.

The microwave rectifier operates at 2.1 GHz, and was built using a SMS7630-061 Schottky diode on a 15 mil Rogers RT/Duroid 5880 substrate. A parallel topology was chosen along with a 5.1 k Ω load, to which the DC power is delivered. This load value was chosen to optimize the source to load DC power transfer, and has a value near the diode's R_{j0} [3]. An electromagnetic cantilever type mechanical vibration harvesting system, with low DC impedance and resonant frequency at 33 Hz was added in series with the DC current path (Figure 1). In order to reduce the low-frequency mechanical harvester losses over R_L , a 100 μ F capacitor, $C_{decoupling}$, was placed in parallel with R_L .

The cantilever was excited by a shaker and monitored by an accelerometer, while the RF input was connected to a calibrated signal generator. In order to measure the power provided by the mechanical harvester to the system, the voltages at its terminals and over $R_L/C_{decoupling}$ were monitored by an oscilloscope. The DC power supplied to the load was calculated using the DC component of the voltage over R_L .

The system was simulated using Keysight ADS Harmonic Balance. A sweep of the two input signals was done to generate a matrix of data. The vibration acceleration can be directly related to the power supplied by the mechanical

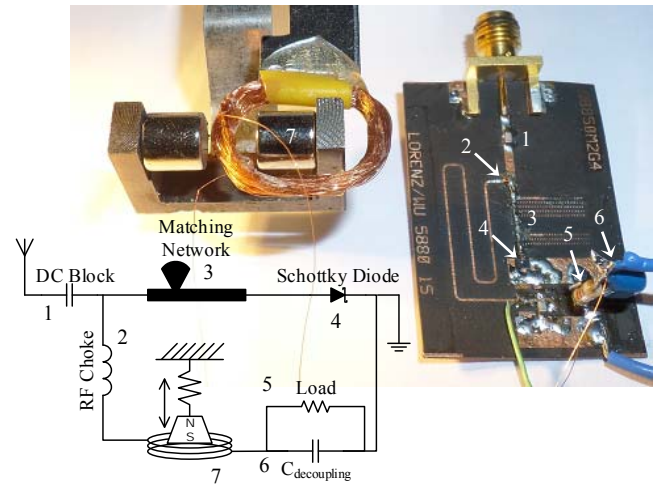


Figure 1 - Picture and scheme of the built prototype, combining both Vibration and Microwave power harvesting.

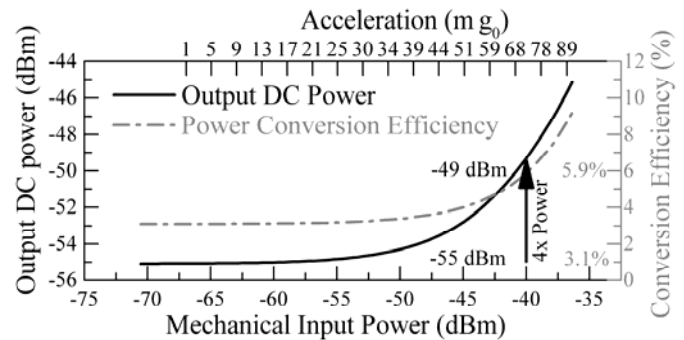


Figure 2 - Simulated DC power delivered to the load, for a constant -40 dBm RF input power, as a function of the Mechanical input power. The top X axis shows the acceleration needed to obtain the corresponding input power from the cantilever transducer, and the right Y axis shows η_{AC-DC} (6).

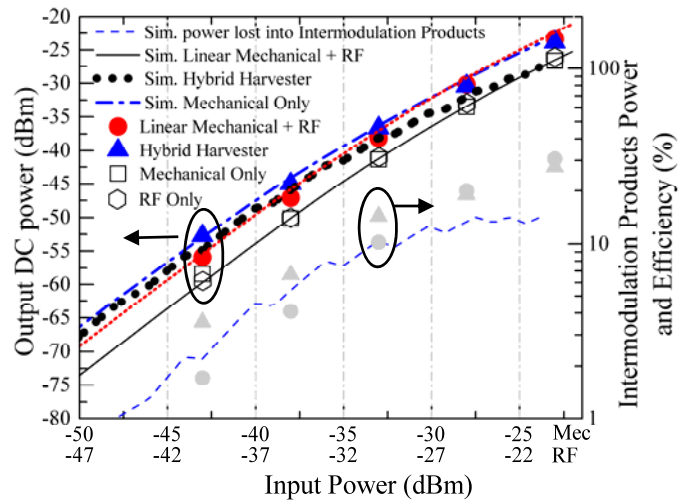


Figure 3 - Comparison between the harvesters working only with mechanical excitation, only RF excitation or in hybrid mode, with both excitations applied at the same time. Scattered symbols (measurements) and lines (simulation) were added for comparison, the light grey symbols show the equivalent measurements power conversion efficiency. The percentage of the input power converted into intermodulation products is also shown as a dashed line.

harvester. Figure 2 shows the simulated output power for a constant -40 dBm input RF power using a lossless matching network, and varying input mechanical power. The output

power is multiplied by a factor of 4 when the two input signals reach the same amplitude, meaning that the total efficiency is doubled, as expected from (6). The acceleration amplitude near this point, 70 mg, is equivalent to the one found at an external window near to a busy street [9].

In Figure 3, simulation and measurement results are used in a comparison between the harvested powers when a single excitation is applied, and when both excitations are applied. An additional curve showing the direct sum of the harvested power with single excitation is given to ease the comparison. As nearly half of the input RF power is lost in diode parasitic components and matching network insertion losses (IL), the RF input power axis was shifted by 3dB to align the excitations where the magnitude of the power arriving at the diode's junction is equivalent for both sources. This approximation is valid while the diode's non-linear junction maintains a value near R_{j0} , for higher powers the decrease in R_{j0} will result in a lower IL and diode parasitic losses [3], and matching network retuning may be necessary.

A 6 dB increase in the total power harvested by the hybrid strategy was obtained, when compared to the single source harvesting. This gain is verified up to nearly -35 dBm input RF power. Above this threshold, the excitation cannot be considered as being small-signal anymore, and intermodulation products at the combination of the two excitation frequencies start to be generated by the non-linear diode junction. This power is then lost on parasitic effects or re-radiated by the antenna. The percentage of the total input power that is converted into intermodulation products, as a function of the input power, is shown in Figure 3.

The efficiency gain obtained using the hybrid harvesting, η_{Gain} , is shown in Figure 4. Equation (7) describes η_{Gain} , where P_{DC_RF+MEC} is the recovered DC power using the hybrid

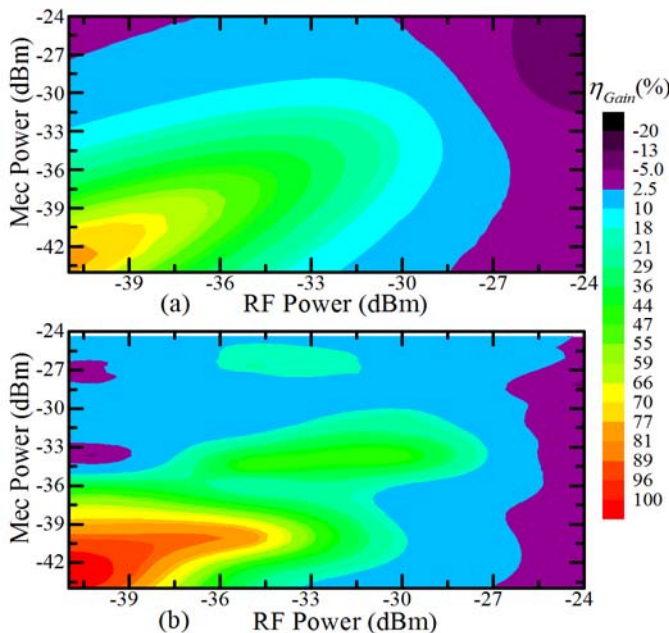


Figure 4 - Comparison between (a) simulated and (b) measured efficiency gain, η_{Gain} . The color scale indicates the rapport between the DC power harvested by the hybrid harvester (P_{RF+MEC}), over the added DC power that would be recovered if each source was harvested by a separated circuit, multiplied by 100.

approach, with both excitations applied at the same time, while P_{DC_RF} and P_{DC_MEC} are the recovered DC powers for separate excitations.

$$\eta_{Gain} = \frac{P_{DC_RF+MEC}}{P_{DC_RF} + P_{DC_MEC}} \cdot 100 \quad (7)$$

The agreement between the simulation and the measurement demonstrates the relevance and the fine understanding of the proposed approach. The gain in the recovered power reaches nearly 100% for input power levels below -40 dBm, decreasing when the power increases. For stronger input power levels, near -24 dBm, losses start to appear due to intermodulation products generation.

IV. CONCLUSION

This work has successfully demonstrated the increase in power harvesting efficiency at power levels below -30 dBm, usually found in ambient power harvesting applications, by the use of Collaborative Hybrid Power Harvesters.

The Power Harvester proposed by this work uses two different power sources to excite a single rectification circuit, increasing the overall harvesting efficiency at low power levels. An example was presented, of a collaborative hybrid power harvester of mechanical vibration and microwave radiation, where output power gains up to nearly 100% were observed for -40 dBm and lower input powers, in accordance to the small signal theory presented in the beginning of this letter. Even though the proposed prototype uses these two power sources, the authors propose that other alternate signal harvesters could be combined to obtain a similar result.

The proposed hybrid technique presents another advantage over the separated power harvesting schemes, as the delivered DC power is already combined at the rectifying element. No extra circuitry is needed to combine both DC outputs. Hence diminishing eventual power losses that would occur during this process, simplifying the circuit and reducing its cost.

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