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Dual-Band Ambient UHF Energy Harvesting with Tunable Π-Matching Network for Ultra-Low-Power Edge Nodes in IoT

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Abstract

This work addresses the design of an energy harvesting system for dual-frequency operation at 1.8 and 2.4 GHz. With the purpose of optimizing the harvesting of the available electromagnetic energy, a tunable Π-impedance-matching network is included aiming to compensate the eventual mismatch between the RF-front-end (antenna) and the RF-back-end (rectifier and load). In this regard, the impact of the Π-matching network on the harvested DC power is comprehensively analysed. For an ambient input power of -20 dBm (10 μW), the proposed dual-band wireless energy harvesting system is able to provide an induced voltage >50 mV, paving the way to the deployment of battery-free ultra-low-power edge nodes in the Internet of Things arena.

1 Introduction

The omnipresent sensing and computing paradigm that has originated the so-called Internet of Things (IoT) aims to interconnect a myriad of physical objects wirelessly; nevertheless, how to provide an eco-friendly energy solution to power many of these devices remains a significant challenge. In this regard, ambient radiofrequency (RF) wireless power is increasing every day with the number of applications and devices and, in particular, in mobile communications, providing an ubiquitous potential energy source. Recycling it for non-mainstream applications becomes a potential target [1]. In this framework, rectifying diodes are very attractive nonlinear devices for transforming electromagnetic RF signals into practical DC power, in order to, e.g., feeding ultra-low-power sensors or actuators.

Across different investigations about ambient RF power density in core areas, streets, roads, and highways, the most represented frequency spectrum ranges from 400 to 2700 MHz, covering Wi-Fi, mobile telecommunications and Bluetooth. According to [2], GSM/LTE850 and LTE700 offer optimal opportunities for recycling RF energy in downtown areas with high population density (particularlly, the study was performed in Montreal - Canada).

Nevertheless, the RF power level available in the environment is uncontrollable and can be unpredictably altered by factors such as position, orientation, or even weather conditions. These aspects are crucial for wireless energy harvesting (WEH) systems, as the level of captured power supply alters the efficiency and sensitivity of the rectifier [3].

In this work, a rectenna-based WEH system is in-depth analyzed to determine the influence of the available input power, the RF impedance matching network (IMN) and the load on its efficiency. Moreover, a design including a tunable IMN, able to auto-tune the matching if external factors alters the RF-back-end, is presented. This concept, which was recently introduced to increase the dynamic range in power detectors [4], may be exploited to optimize the power harvested as a function of the received power or, as we propose here, to dynamically shift the WEH working frequency to leverage the eventual maximum available power in a determined band.

This work is organized as follows. Section 2 introduces the WEH concept, together with the circuit topology and its design, while Section 3 focuses on the development of a tunable IMN, aiming at adapting the system to receive the maximum power either at 1.8 GHz or at 2.4 GHz. Next, the system efficiency and the induced DC voltage are evaluated as a function of unpredictable factors in WEH such as the input power and optimum load resistance in Section 4. The main conclusions are drawn in Section 5.

2 RF wireless energy harvesting system

This section analyzes how the RF input power influences the final rectified DC power that ultimately feeds the load in the WEH system shown in Fig. 1. The RF-to-DC efficiency is defined as follows [5],

$$\eta = \frac{P_{DC,R_L}}{P_{\text{in}}} \tag{1}$$

where P_{DC,R_L} is the power delivered to the load, and P_{in} is the antenna available power.

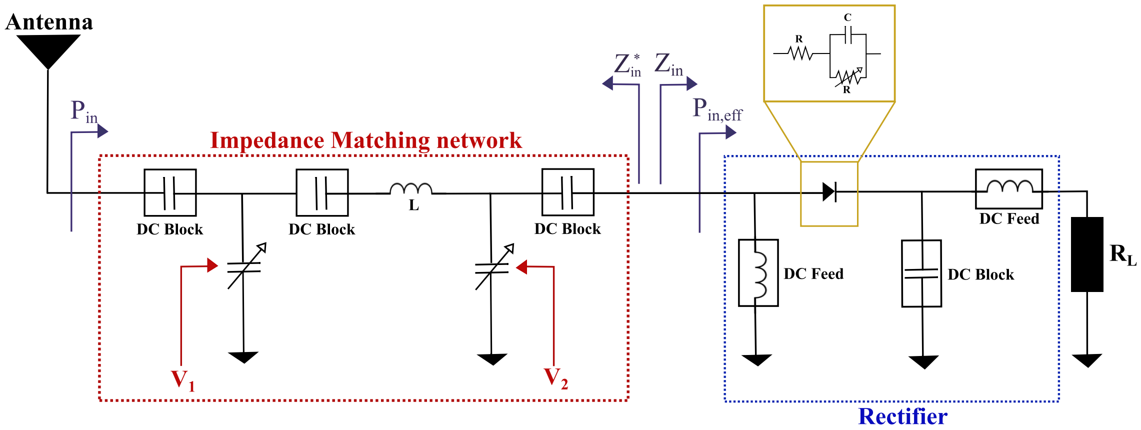


Figure 1. Topology of the conceived harvester, including the four main blocks of the system: antenna, tunable IMN, rectifier and load (R_L). The work focuses on the analysis of the tunable Π-type IMN, comprising two shunt varactors, and the zero-bias rectifier, consisting in a series Schottky diode (both framed within dashed boxes).

In terms of the X-parameters [6], the maximum achievable efficiency of the rectifier, η^m, can be evaluated as a function of the effective input power, $P_{\text{in,eff}}$, as:

$$\eta^m = \frac{P_{DC,R_L}}{P_{in,eff}} = \frac{(X^{FI})^2 R_L}{P_{in}(1-|HS_{1,1}|^2)} \quad (2)$$

Here, X^{FI} is the induced DC current and $HS_{1,1}$ is the one-port active (Hot) S-parameter. The $P_{in,eff}$ term would correspond to P_{in} provided that the system was fully matched to the RF-back-end, so that all the captured power was delivered to the rectifier.

As drawn by eq. (2), the value of the load resistance (R_L) is critical to optimize the rectified power. However, the DC power generated by the nonlinear behavior of the diode junction is dissipated by the load resistance along with the diode itself, and the problem is optimized provided that the load resistance is equal to the junction resistance of the rectifier [5]. Nevertheless, the load resistance affects the induced voltage and, therefore, to the large-signal operation point (LSOP) of the diode, giving rise to a non-trivial self-consistent problem.

As for the RF part of the circuit, the rectifier input impedance (i.e., without considering the IMN) depends on the effective input power delivered to the diode ($P_{in,eff}$), as the rectifier generates a self-bias, also dependent on the load resistance. So that, the non-linear LSOP will be shifted from the initial zero bias behavior to the originated self-bias. In this context, ideally, the IMN circuit should be able to optimize the WEH system depending on the input power and frequency, i.e., $P_{in,eff} = P_{in}$.

3 Tunable impedance matching network

The IMN should ensure the maximum power transfer between the antenna and the rectifier. In addition, depending on the environment, the input RF power level may vary; to counteract this effect, our proposal is to adapt the working frequency to select the band with the highest power level, thus modifying the IMN to optimize the power transfer to the nonlinear device. For this purpose, a tunable Π-network, formed by two shunt varactors and a series inductor (see Fig. 1), is employed to match the impedance of the rectifier (from the point in between the blue and red dashed boxes in Fig. 1 towards the load) to the input impedance (from the point in between the blue and red dashed boxes in Fig. 1 towards the antenna) [7]. For the Π-network, Skyworks SMV1234 varactors together with a $L = 3$ nH coil have been considered.

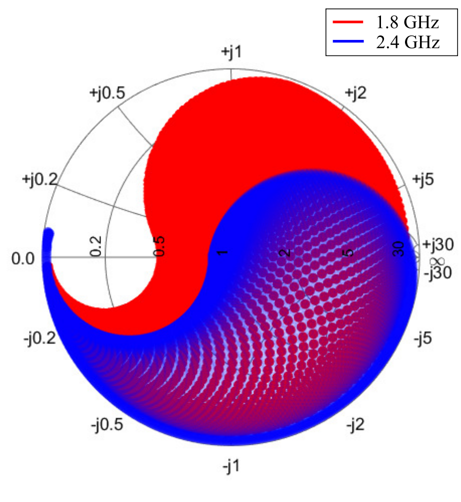


Figure 2. Adaptive impedance range using the Π-Matching network presented in Fig. 1 for both design frequencies: 1.8 GHz (red) and 2.4 GHz (blue).

Figure 2 shows the range of impedances that the designed Π-network can match. The varactors are operated in reverse bias in the range betweeen 0 and 15 V. As the input impedance of the loaded rectifier depends on the operating

Frequency GHz	Z_{in} Ω	$HS_{1,1}$ dB
1.8	30.37 -j378.28	-12.15
2.4	20.48 -j282	-7.64

Table 1. Diode input impedance and hot reflection coefficient at the design frequencies.

frequency, Figure 2 show the available range of matchable impedances at the two operating frequencies considered, 1.8 and 2.4 GHz, respectively.

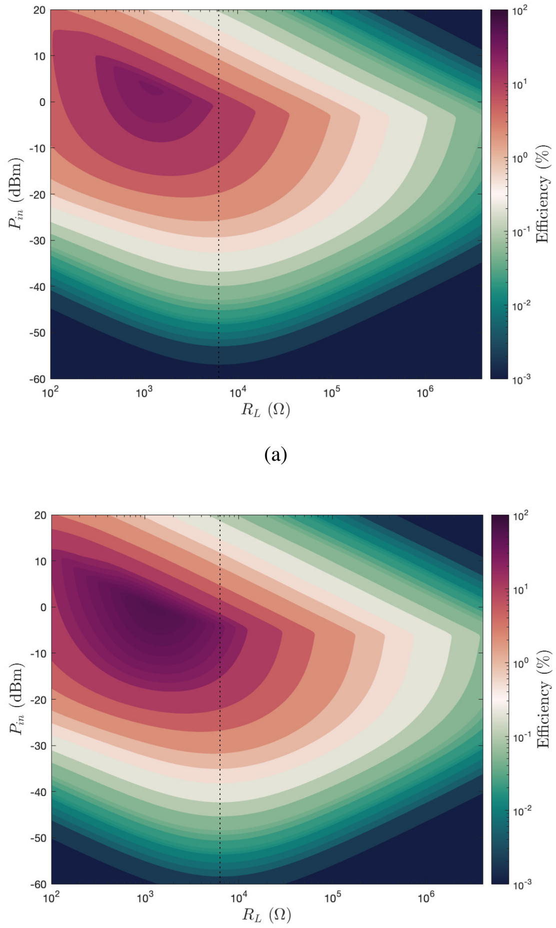
4 Design details and results

With the aim of designing an ambient WEH system able to operate at dual band, we choose a target input effective power of -40 dBm and undertake the optimization of η^m as a function the load resistance, by means of eq. (2). Regardless of the input frequency (1.8 or 2.4 GHz), the load resistance that maximizes the achievable efficiency at dual band operation is 6.25 kΩ.

Once the load resistance has been chosen, the IMN needs to be designed. Table 1 collects the specific input impedance of the RF-back-end, Z_{in}, together with the active reflection coefficient $HS_{1,1}$ attained at the input of the IMN, which guarantees an ad-hoc RF matching at dual band. Despite the significant value of the optimal input reactance, a reasonable matching is achieved at both design frequencies.

Figure 3 depicts the results achieved for the efficiency as a function of the load resistance and the input power, P_{in}, considering the inclusion of the tunable IMN. The design value of R_L is highlighted with a vertical dashed line in Fig. 3: its perfect fit with the maximum efficiency at the target input power of -40 dBm demonstrates the validity of the design process. What is more, it results suitable for a broad input power range, what is crucial for a practical ambient scenario. In this regard, the efficiency of the system for low input levels ranging from -40 dBm to -20 dBm roughly achieves values between 0.2% and 10%. At higher power levels, the efficiency of the WEH system could reach values of 30 and 57% for input powers of 3 and -2dBm, though the load resistances should be shifted to the range of 1 to 1.5 kΩ, at 1.8 GHz and 2.4 GHz, respectively. These results are comparable with state-of-the-art harvesters optimized to operate at a single frequency [8].

To put into context the role of the RF matching, Figure 4 shows a comparison of the achieved efficiency of the complete dual-band WEH system, loaded with the optimum R_L, for two scenarios: matching through the proposed variable matching network (VMN), and perfect matching. As can be seen, the dual-band efficiency for low-input levels, achieved by employing the VMN, is very close to the ideal case (the inset in Fig. 4 zooms in the efficiency around -40 dBm input power levels), showing a noticeable drop for high input power levels given that the VMN cannot synthethise the required impedance. It should be emphasized though that



(a)

(b)

Figure 3. Efficiency ($P_{DC,R_L}/P_{in}$) at (a) 1.8 GHz and (b) 2.4 GHz as a function of the input power of the device and the load impedance. The optimum load resistance at -40 dBm is highlighted with a vertical dashed line.

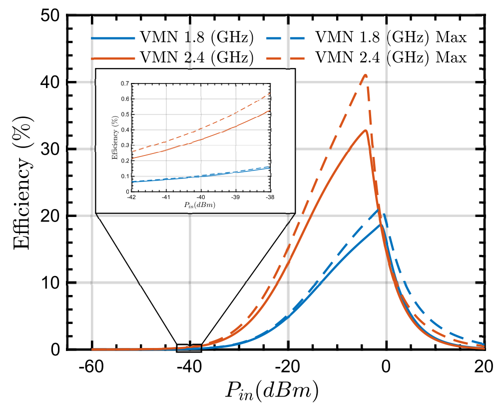


Figure 4. Efficiency as a function of the system input power, ideal and employing the Π-matching network, for 1.8 and 2.4 GHz.

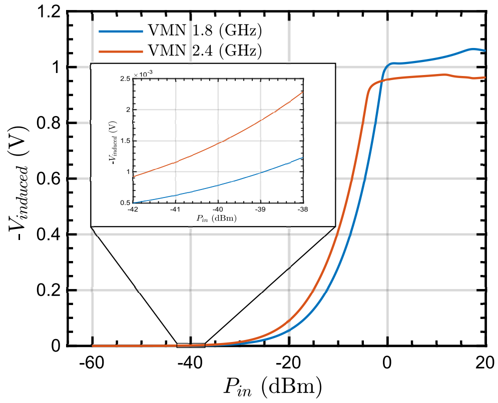


Figure 5. Induced voltage at network load, R_L, as a function of system input power, for 1.8 and 2.4 GHz.

high input power levels are not of real interest in an ambient scenario, and therefore the impact of this degradation is low for harvesting purposes. Also, as observed in Fig. 2, as the VMN at 2.4 GHz covers a smaller area of the Smith chart than at 1.8 GHz, the difference between the perfect matching and the matching through the VMN is larger at 2.4 GHz than at 1.8 GHz.

Aiming at drawing the specific harvested DC biases, Fig. 5 shows the induced voltage at R_L as a function of the input power of the dual-band WEH system. The induced voltage increases, and hence does the DC power, up to $\sim$0.9 V for high-power input stimulus. From this point, the exponential growth trend of the induced voltage changes, flattening out, reaching a quasi-stable value of induced voltage. This behavior is originated due to the self-biasing effect of the rectifier, by shifting from the initial nonlinear zero-bias operation to a more linear LSOP at the self-biasing induced voltage.

5 Conclusion

This work presents an analysis of a dual-band wireless energy harvesting system, exploiting a tunable Π-matching network formed by two shunt varactors and an inductor. The design allows frequency selective reconfiguration based on the indoor-outdoor needs, e.g. working in the GSM and Wi-Fi bands, achieving conversion efficiencies close to the ideal rectifier behavior (i.e., the one that would be achieved under perfect conjugate adaptation). The concept is potentially applicable in higher power circuits, such as detectors, where the input impedance variation is significantly higher, allowing input impedance matching as a function of the large-signal power. In particular, for an ambient input power of -20 dBm , the proposed dual-band wireless energy harvesting system shows a promising efficiency ranging from 5% to 13% that would allow the future deployment of battery-free ultra-low-power edge nodes of the Internet of Things.

Acknowledgements

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