Rectifier Design Challenges for RF Wireless Power Transfer and Energy Harvesting Systems

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Abstract. *The design of wireless power transfer (WPT) and energy harvesting (EH) solutions poses different challenges towards achieving maximum RF-DC conversion efficiency in these systems. This paper covers several selected challenges when developing WPT and electromagnetic EH solutions, such as the design of multiband and broadband rectifiers, the minimization of the effect that load and input power variations may have on the system performance and finally the most optimum power combining mechanisms that can be used when dealing with multi-element rectifiers.*

Keywords

Wireless power transfer, energy harvesting, rectifier, rectenna, Schottky diode, multiband rectifier, broadband rectifier, wideband rectifier

1. Introduction

Wireless power transfer (WPT) and energy harvesting (EH) solutions are receiving a lot of attention towards providing autonomy to a wide variety of sensors and devices. These self-sustainability properties allow implementing concepts such as the Internet of Things (IoT), smart cities and smart buildings to name a few. However both WPT and EH solution synthesis pose several design challenges that need to be addressed towards achieving an optimum performance.

In the case of electromagnetic EH the amount of available power from a selected RF energy source may be variable and unpredictable. This is why several solutions where it is possible to harvest from more than one frequency band have been proposed in the literature [1–11]. These solutions are based on the use of multiband rectifiers or in the combination of the DC outputs of several single band rectifiers. In [3], [5] dual band electromagnetic energy harvesting is proposed where the energy is collected from two different RF frequency bands, while in [1, 2, 4] triple band EH is considered. Some other works focus on broadband electromagnetic EH [7–11] where the energy is collected from a selected range of continuous frequencies.

A common challenge for both WPT and EH is the fact that due to the nonlinear nature of the rectifying devices the performance of rectifier circuits in terms of RF-DC conversion efficiency get easily affected by variations in the input power level and also in the output load. In order to minimize the effect these variations have on the overall performance some authors have considered using several rectifying branches [11] each one optimized to operate at a different input power level. Other works combine the use of a JFET transistor and a Schottky diode to synthesize a rectifier that can operate for both large and small input powers levels [13]. Some other works propose the use of resistance compression networks (RCN) in order to minimize the variations in power and load that reach the rectifying element [14, 15].

Other challenge in designing rectifier circuits for WPT and EH is the use of arrays of either antennas or rectenna elements. The selection of either one of the options depends on the amount of power that is being received and the rectifying element selected. One challenge in designing these arrays is the DC power combining mechanism of the rectifier outputs. Some works have covered this topic [16–18] showing results on how the optimum load varies depending of the type of DC power combination performed, series, parallel or combined.

In this paper, some of the previously mentioned solutions towards addressing the challenges in WPT and EH solutions are covered in more detail. In Sec. 2, a state of the art review of existing multiband and broadband designs of rectifiers is presented and an example of a broadband rectifier is explained. In Sec. 3, the design of a rectifier using RCN is presented for minimizing the effect that load and input power variations have on the rectifier performance. Section 4 focuses on the design of a rectenna array and how the DC outputs can be combined towards maximizing the RF-DC conversion efficiency and how the optimum load is different depending on the type of combination performed (series/parallel) as well as on the angle of arrival of the RF incoming signal.

2. Multi-band/Broadband Rectifiers

As previously mentioned, a key goal in rectenna and rectifier design is to maximize the RF-DC conversion efficiency. One alternative is to perform a multiband or broadband design for the rectifier circuit. This is important if one is considering to perform electromagnetic EH from different broadcast transmissions that operate at different frequencies.

Table 1 shows several state of the art results regarding multiband rectifier designs [1–5] showing efficiencies in the order of 15% for –20 dBm input power for dual band rectifiers [5] where a single diode is used and efficiencies in above 25 % for triple band rectifiers with –15 dBm input power where a dedicated branch for each frequency is considered [2].

Table 2 shows several state of the art results regarding broadband rectifier design [7–11]. The design in [10] is capable of harvesting in the 2–18 GHz frequency band with efficiencies of 20% for 15 dBm input power at 3 GHz using a single diode rectifier in a 64 element array configuration. The design in [8] uses a 5-stage charge pump circuit to obtain efficiencies >30% for 18 dBm input power.

The challenge in designing ultra-wideband rectifiers is of fundamental nature. A rectifier circuit is a capacitive load, with an equivalent circuit which consists of a shunt resistor in parallel with a shunt capacitor. The equivalent circuit elements are nonlinear in nature and depend on the input power, output load as well as the circuit topology of the rectifier [19]. The minimum reflection coefficient that can be achieved using a lossless network to obtain broadband impedance matching over a desired frequency band is bound by the theoretical limit obtained in the work of Bode and Fano [20]. In [19], a wideband rectifier with an octave bandwidth is proposed where a matching network based on a non-uniform transmission line is used. A photo of the rectifier is shown in Fig. 1 and the results in terms of RF-DC conversion efficiency versus frequency are depicted in Fig. 2. A measured efficiency of more than 60% was obtained for 10 dBm input power in the 470 MHz to 860 MHz frequency band.

Reference	Frequency of operation (MHz)	Topology	Pav (dBm)	Efficiency (%)	RL (Ohm)	Vdc (mV)	No. elements
[1]	900, 1800, 2400	Full wave rectifier	1.76	60 at 900 MHz 47 at 1760 MHz 33.5 at 2.45 GHz	6300	2381 at 900 MHz 2100 at 1760 MHz 1774.8 at 2.45 GHz	1
[2]	900, 1800, 2400	Three charge pump branches	–15	45 at 900 MHz 46 at 1800 MHz 25 at 2.45 GHz	50000	0.82 at 900 MHz 0.85 at 1800 MHz 0.62 at 2.45 GHz	1
[3]	915, 2450	Single diode rectifier	–11 at 915 MHz –13.5 at 2.45 GHz	4.7 at 915 MHz 56.2 at 2.45 GHz	2200	200 at 915 MHz 313.5 at 2.45 GHz	1
[4]	900, 1800, 2400	Single series diode	27	~50 at 900MHz, 1800 MHz, 2.4 GHz	50	~250 mV at 900 MHz, 1800 MHz, 2.4 GHz	1
[5]	850, 1850	Single series diode	–20	15 at 850 MHz 15 at 1850 MHz	2200	57.4 at 850 MHz 57.4 at 1850 MHz	1
[5]	850, 2450	Single series diode	–20	18 at 850 MHz 10 at 2.45 GHz	2200	46.9 at 850 MHz 62.9 at 2.45 GHz	1
[6]	791, 1570, 2340	Single series diode	–10	~40 at 791 MHz, 1570 MHz, 2340 MHz	1470	~242 at 791 MHz, 1570 MHz, 2340 MHz	1

Tab. 1. Comparison of different multiband rectifier design.

Reference	Frequency of operation	Topology	Pav (dBm)	Efficiency (%)	RL (Ohm)	Vdc (mV)	No. elements
[7]	[2.41-2.47] GHz	Single shunt diode	–20	24.3	1800	70	1
[8]	~ [800-1000] MHz	5 stage charge pump circuit	18	31.8	200	6000	1
[9]	[600-1150] MHz	Class F-1 amplifier based	40	>60	34	521.5	1
[10]	[2-18] GHz	Single diode	[–17…+15] at 3 GHz	[0.1-20] at 3 GHz	100	[2.5-790] at 3 GHz	64
[11,19]	[470-860] MHz	Single diode	10	>60			1

Tab. 2. Comparison of different broadband rectifier design.

Fig. 1. Broadband rectifier operating in the 470–860 MHz frequency band.

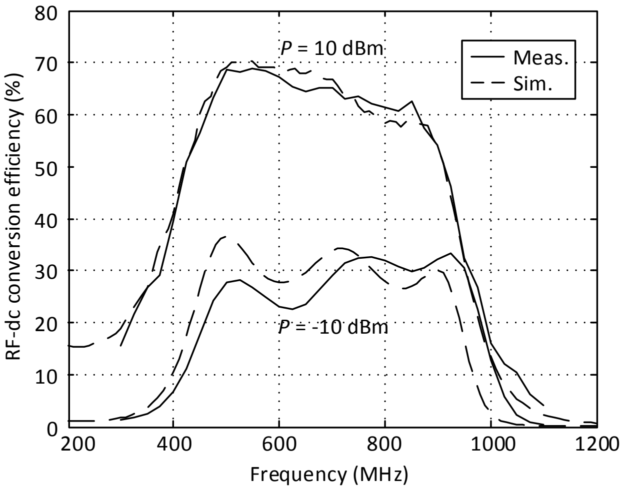

Fig. 2. RF-DC conversion efficiency versus frequency for the broadband rectifier of Fig. 1 [19].

3. Rectenna Arrays and DC Power Combining

It is well known that there exists an optimum load in a rectifier circuit that maximizes its RF-DC conversion efficiency. This optimum load depends on several parameters, namely the available input power, the signal characteristics as well as rectifier circuit topology [21]. It is possible to set the value of the optimum load by using a rectenna array and connecting the various rectifier DC outputs in series or parallel combinations [16–18]. When designing rectenna arrays there is a trade-off between designing antenna subarrays where each sub-array feeds one rectifier or creating a full rectenna array where one antenna feeds one rectifier. The first one first combines the RF power and the DC outputs and the second one combines all the DC rectifier outputs. The target is always to maximize the RF-DC conversion efficiency.

Figure 3 shows a 2 × 2 rectenna array designed to operate at 2.4 GHz. The rectenna elements consisted of a shorted circular slot antenna, an impedance matching network and a series Shottky diode rectifier.

The value of the optimum load resistance was investigated for different topologies for the combination of the rectifiers DC outputs but also for different angles of incidence of the incoming continuous wave (CW) signal. The results are shown in Fig. 4 where it can be seen that agreeing with other existing studies in the literature [16–18], the optimum load is increased when a series rectifier connection is formed, whereas it is reduced when a parallel connection is used.

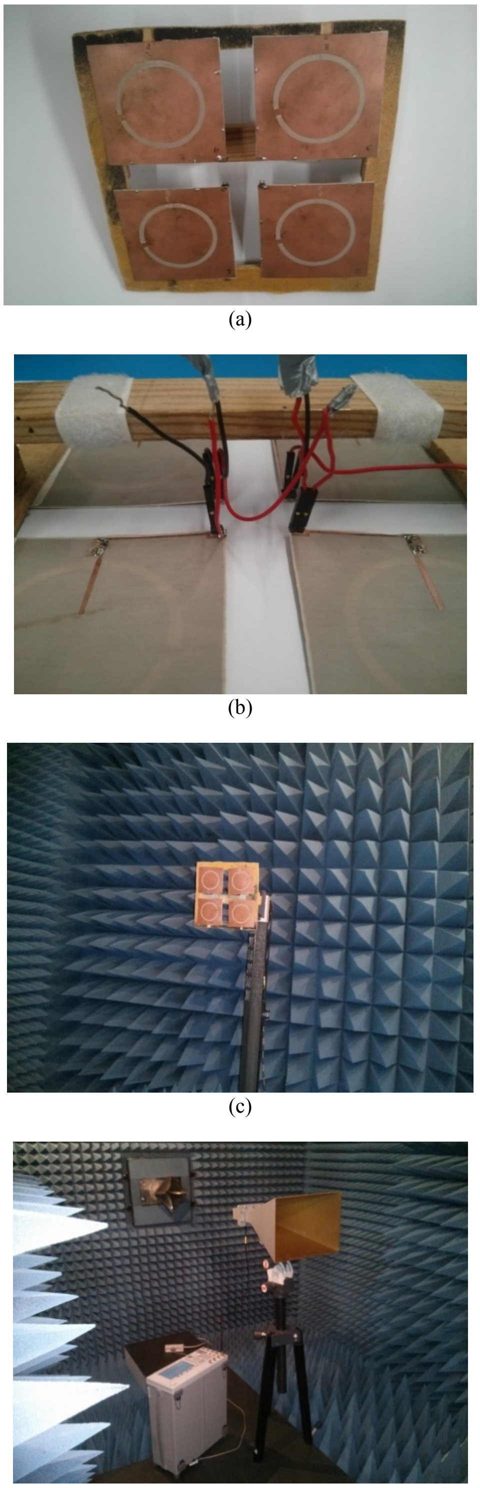

Fig. 3. Rectenna array: a) fabricated prototype antenna side, b) fabricated prototype rectifier side, c) receive rectenna array setup in an anechoic chamber, d) transmitter setup exciting the rectenna array.

The study performed versus the direction of the incoming wave shows that the optimum load is also dependent on this direction due to the existing mutual coupling among the antenna elements. For the rectenna array in Fig. 3 the optimum load increases as the angle of incidence deviates from broadside.

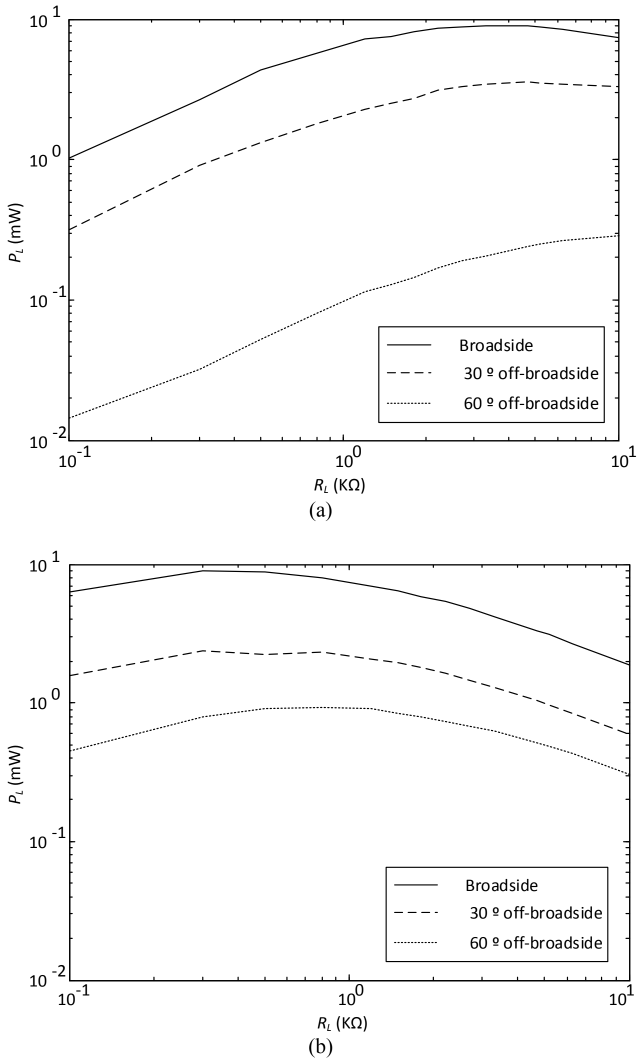

Fig. 4. Rectenna array output DC power versus the output load resistance for different incoming wave angle of incidence relative to broadside: (a) series connection of the rectifier outputs, b) parallel connection of the rectifier outputs.

4. Load/Input Power Variations in Rectifier Circuits

The RF-DC conversion efficiency in a rectifier circuit may be affected by variations in the input power level and in the output load resistance. This means when designing a rectifier it is of key importance to minimize the effect these variations will have on the rectifier performance by selecting a rectifier architecture that is insensitive to power and load changes. In [22] a method to improve the dynamic range in rectifier circuits was proposed. This method makes use of two branches, such as in a Doherty topology used in power amplifier design, to achieve efficiencies above 50% in an input power level range from –7 dBm to 16 dBm. In [14] a resistance compression network (RCN) is used to keep a high RF-DC conversion efficiency versus a large range of output load values. The RCN is formed by two parallel branches which have 2 identical variable loads

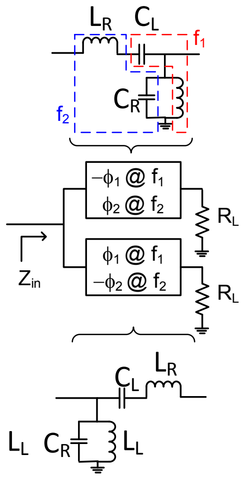

Fig. 5. Dual band RCN used in the rectifier design in [15]. Parallel connection of two branches which include identical copies of the variable load and reactive networks introducing a properly designed and opposite phase at the two desired operation frequencies.

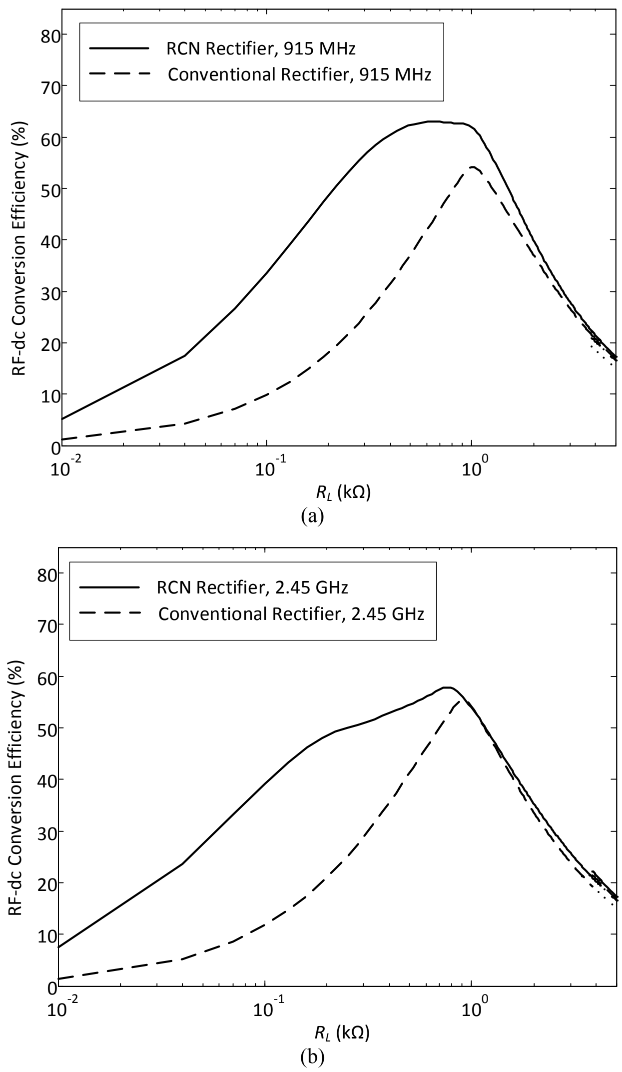

Fig. 6. Dual band RCN based rectifier [15]. RF-DC conversion efficiency versus output load compared to a conventional dual band rectifier: (a) 915 MHz, (b) 2.45 GHz.

connected in series with some reactive elements that introduce opposite phase response in the two branches at the desired operation frequency. More recently, in [15] a dual band RCN based rectifier circuit has been proposed where the reactive element networks consist of dual band bandpass filters sections. These dual band bandpass sections are formed by a series and a shunt LC section. The opposite phase response in the two branches is obtained by using the same network but reversing the node where it is connected to the varying load [14, 15]. The schematic representation of the dual band RCN based rectifier in [15] is shown in Fig. 5 and its RF-DC conversion efficiency is compared to the efficiency of a conventional dual band rectifier in Fig. 6, showing a higher efficiency over a wider range of load values. As it can be seen, it is possible to obtain improved performance in terms of insensitivity to load variations by sacrificing circuit complexity introducing additional circuit branches and rectifier elements.

5. Conclusions

In this paper a review of some of the existing challenges in WPT and EH solutions have been presented. More specifically, this paper has shown how the use of multi-band and broadband rectifiers can be used to maximize the amount of harvested power, how RCN based rectifiers can minimize the effect that load variations have on the RF-DC conversion efficiency and how the output load can be tailored to maximize the RF-DC conversion efficiency in rectenna arrays by selecting the DC power combining topology (series/parallel).

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