ANALYSIS OF SCALABLE RECTENNA CONFIGURATIONS FOR HARVESTING HIGH FREQUENCY ELECTROMAGNETIC AMBIENT RADIATION

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Abstract: Low power microwave energy harvesting rectennas have been simulated from 0.1 to 100 GHz. Comparison of previously published configurations, and selection between two widely used Schottky diodes and one promising commercially available Schottky diode, has been performed to evaluate efficiency across the range of frequencies. Analysis from our results give, for the first time, a clear explanation as to why a series rectification is more efficient than a shunt configuration for frequency scalable rectennas, finally clarifying previous inconclusive results from the literature. Conversion efficiencies around 7% have been accomplished by a single detector series configuration at 60 GHz and an input power of 0 dBm. Alternate simulations with other configurations, such as a voltage doubler, have been analyzed, demonstrating that they can provide a higher voltage than a series configuration.

Keywords: rectenna, RF energy harvesting, RF to dc conversion, dual antenna, high frequency rectification

INTRODUCTION

The numerous applications of wireless sensor networks (WSN) have made this challenging area of technology potentially a very profitable one. Defence-related applications motivated the initial research in this field. However, this technology was soon adapted to civil applications ranging from industrial sensing, to home automation and healthcare.

Even though WSNs have been evolving, powering them has been a crucial limiting factor. Several energy sources have been explored, such as small wind turbines, solar cells, MEMS-based generators, and thermal gradient generators [1]. In many of these cases, the energy sources are not always accessible, and so, microwave power collection has been considered as an alternative way of producing direct current (dc) power.

Wireless energy can be harvested to provide a dc source with a rectifying antenna, also known as a rectenna. The basic rectenna design consists of an antenna that acts as a transducer for harvesting electromagnetic radiation, an impedance matching stage, and a diode to rectify the signal. Different rectennas have been designed since the 1950s. Recent and successful attempts have been published by Hagerty *et al.* [2] and Salter *et al.* [3], where rectenna arrays working from 2.45 to 18 GHz and 1 mm^3 rectennas have been presented respectively. Different configurations and devices have been used extensively by many research groups, but no clear explanation has been given as to why a certain device or configuration has been chosen. The aim of this paper is to present a consistent and thorough analysis of RF detectors and basic rectenna designs as the basis for future low power and dual high frequency rectennas across a range of frequencies.

RF DETECTOR SELECTION

To start the rectenna design, millimetre-wave Schottky diodes were selected, based on the open literature and on commercially available alternative devices. Schottky diodes were selected for rectification purposes because of their shorter transit time when compared to p-n diodes and transistors, and for their low turn-on voltage as well. This low turn-on voltage is required because the diode will not operate with bias and consequently will not operate in the steepest region of the I V curve. Therefore, Schottky diodes that are able to operate with zero bias are needed for low power, high frequency rectification.

From the open literature, the HSMS-2850 and the SMS7630 Shottky diodes were selected for their zero bias characteristics and their already proven performance from 0.8 to 5 GHz [2]. The MZBD-9161 GaAs beamlead detector was selected because of its comparable performance to the previously described diodes and its flat detection response from 1 to 110 GHz. The important characteristics of these diodes are presented in Table 1.

Device	C_j [pF]	R_s [Ω]	R_v [kΩ]	L_p [nH]	C_p [pF]
SMS7630	0.14	20	5000	0.7	0.11
HSMS-2850	0.18	25	8000	2	0.08
MZBD-9161	0.035	20	3000	0.3	0.011

Table 1. Small-signal characteristics for Schottky diodes

SIMULATION SETUP

Low power microwave energy harvesting rectennas were simulated from 0.1 to 100 GHz, in order to compare previously published configurations and to select a semiconductor device that would achieve a higher conversion efficiency. Analysis from our results give, for the first time, a clear explanation as to why series rectification is more efficient than a shunt configuration for frequency scalable rectennas, finally clarifying previously inconclusive results from the literature.

Rectification is inherently a large-signal operation and therefore assuming a constant value of R_s (*i.e.* a linearised model) is invalid. In addition, junction capacitance is very important at high frequencies [2]. For these reasons, the large signal harmonic balance (HB) simulation tool from Agilent ADS was chosen to simulate rectenna designs at different frequencies and input powers levels.

The antenna was simulated using its equivalent Thevenin circuit with a single tone power source and source resistance [4]. The source resistance represents the input impedance of the antenna, which has to match the impedance of the rectifying circuit to ensure maximum power transfer. An initial 50 Ω impedance was selected for the antenna, because it is an industry standard reference value for antennas and transmission lines. The available power density for signals around 0.8 to 2.45 GHz are around 0.0002 to 1.5 μW/cm^2, with an average of 0.27 μW/cm^2 [5]. A half-wave square patch antenna for 2.45 GHz has an area of 36 cm^2. Thus, for a power density of 0.27 μW/cm^2 that is being received by a 36 cm^2 antenna, the available power is 9.72 μW or -20 dBm. If a WiGig or WiHD router is to be used as the energy source, the FCC and IEEE 802.11n standards indicate that if the transmitted power is +27 dBm, the maximum gain of the antenna can be +27 dBi. For calculating the available power at 60 GHz the power link budget and free space loss equations shown in Equations 1 and 2 were used. The available power at the receiving antenna is calculated, using a gain of 32 dBi, as the one designed by Menzel *et al.* [6]. In this case we consider the fade margin loss to be zero because the transmitter and receiver will be in direct line of sight, as suggested by the manufacturers of the routers. The available power at 60 GHz with the previous stated characteristics is 0 dBm at a distance of 8 m. Therefore, during simulations power values were swept between -40 to 0 dBm.

$$P_{Rx} = P_{Tx} + G_{Tx} + G_{Rx} - L_{fs} - L_M \tag{1}$$

$$L_{fs} = 20\log\left(\frac{4\pi D}{\lambda}\right) \tag{2}$$

Where P_{Rx} and P_{Tx} are the received and transmitted power, G_{Rx} and G_{Tx} are receiver and transmitter antenna gain, L_M is fade margin, L_{fs} is free space loss, and D is the distance from transmitter to receiver. Once the rectifying devices, antenna equivalent, and input power were selected, HB simulations were performed for different rectenna configurations. For every power, frequency values from 0.1 to 100 GHz were swept with different resistive loads. With each simulation, the optimum load resistance was selected and an input L-matching network was designed.

The first problem to solve was to understand why a series configuration is better or worse than a shunt configuration. Circuits presenting both configurations are shown in Figures 1.(a) and 1.(b).

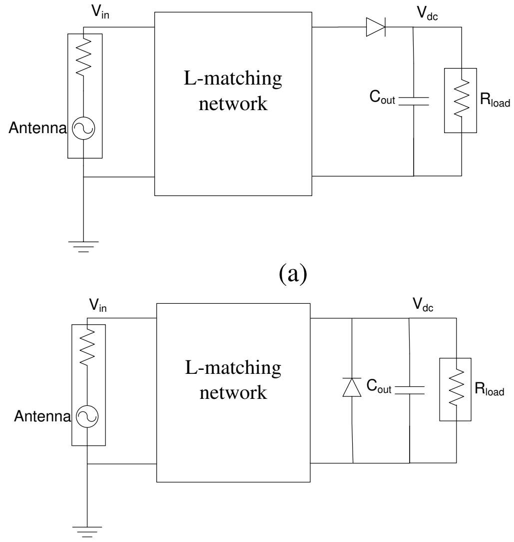

Figure 1. (a) Series rectenna; and 1.(b) shunt rectenna configurations with impedance matching network.

Many designs have stated that the series configuration is the best [7], [8], but others have stated differently [9], [10]. No one has given a clear explanation of why one is better than the other; therefore, a consistent analysis of both configurations was necessary to clarify this issue.

SIMULATION RESULTS

To ensure that all the different simulations were compared on the same basis, all configurations were tested with and without a good impedance match for each frequency, power, and load selected. To optimize the rectenna, the load that gave the highest conversion efficiency without an impedance match was selected as the optimal value. After this, the impedance seen from the antenna was measured and used to design the L-matching network. Finally, output dc power, conversion efficiency, and mismatch loss were calculated. Equation 3 and 4 [11] show the equations for conversion efficiency and mismatch loss or mismatch efficiency.

$$\eta = \frac{output\ dc\ power}{available\ input\ RF\ power} \tag{3}$$

$$\eta_{mismatch} = 1 - |\Gamma|^2 \tag{4}$$

Where Γ is the voltage-wave reflection coefficient. Figure 2 shows the simulation results for the *LC* impedance-matched series configurations at an input RF power of -20 dBm. The HSMS-2850 presented the highest conversion efficiency for 0.1 GHz to 1 GHz, the SMS7630 for 1 to 10 GHz, and the MZBD-9161 presented the highest efficiency between 10 to 100 GHz. For all diodes, frequencies, and powers, the impedance matched rectenna had a $\eta_{mismatch}$ close to 100%, compared to the unmatched rectenna which had a $\eta_{mismatch}$ below 86%.

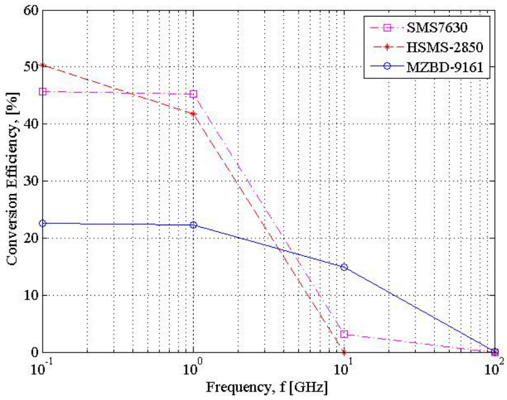

Figure 2 Conversion efficiency of an impedance-matched series configuration rectenna.

In Figure 3 the simulation results of an impedance-matched series rectenna configuration is presented, highlighting that the MZBD-9161 shows great potential for high frequency applications. The impedance-matched series configuration achieved the highest conversion efficiency for all swept powers and frequencies. The highest conversion efficiency at 2.45 GHz was 33.86%, with the impedance-matched SMS7630 in a series configuration with a 3250 Ω load. The best conversion efficiency at 60 GHz was 6.83%, with the impedance matched MZBD-9161 in a series configuration and a 300 Ω load. Similar results to a recent publication from Costanzo *et al.* [12] were found at 2.45 GHz, using the SMS7630, thus proving to be one of the best zero bias detectors for frequencies near 2.45 GHz. Furthermore, similar sensitivity results to Song *et al.* [13] were obtained at 100 GHz with a dc output voltage of 93 mV per 1 mW of input RF power.

The correlation of Figure 3 and Table 1 indicate that the junction capacitance and its relationship with the output capacitor is the crucial factor in determining the optimal configuration. A good approximation of the impedance, seen from the antenna, can be calculated using the small-signal equivalent diode model presented in Figure 4 [14]. It is important to note that only the load values around the optimal selected loads could be matched using realistic component values, thus the value of R_{load} could not be increased. The value of R_{load} was selected, as previously discussed, because its value together with the diode impedance was near the normalized centre of the Smith chart, making it easy to achieve an impedance match with a simple L-network.

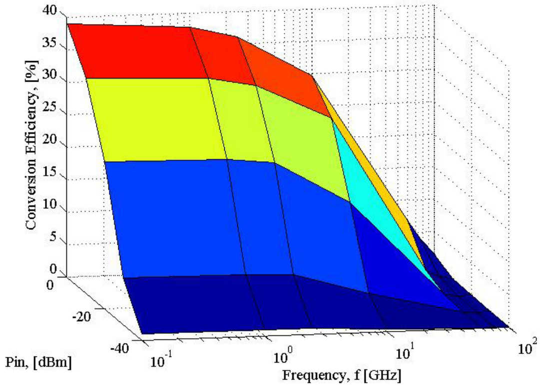

Figure 3 MZBD-9161 impedance matched series configuration results.

With a series configuration, the value of $C_j(V)$ dominates the circuit's impedance, as long as $C_{out}>C_j(V)$, and thus C_{out} has little or no effect on the matching circuit. This allows C_{out} to be large enough to provide a ripple-free output voltage. In contrast, C_{out} must be less than 1 pF to achieve a good impedance -match with a shunt configuration as C_{out} appears in parallel with C_j and C_p. However, C_{out} is too small to provide a ripple-free dc voltage to the load.

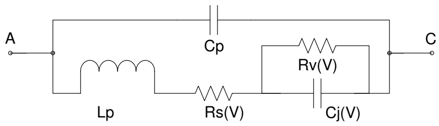

Figure 4 Small-signal Schottky diode model. C_p parasitic capacitance, L_p parasitic inductance, $R_s(V)$ parasitic series resistance, $R_v(V)$ video junction resistance, $C_j(V)$ junction capacitance.

Once the zero bias diode detector was selected to work at high frequencies, and the basic rectenna configurations were analyzed and simulated, other configurations were compared against the series impedance-matched configuration using the MZBD-9161 at 60 GHz. For frequencies around 2.45 GHz, different configurations have already been tested. Therefore, for configuration comparison, 60 GHz input signals, as transmitted by WiGig routers, were used to provide a new input at a frequency not previously tested before. The first configuration that was compared was the voltage doubler, since it has been widely used with success in other designs [3].

When comparing the voltage doubler with the series configuration at -10 and 0 dBm, the voltage increased more than 35%, whilst the conversion efficiency decreases by more than 12%. The impedance matching is easier because the impedance of both diodes is in parallel. Nevertheless, it does not provide an impedance that could work efficiently without the matching network.

Another configuration was tested with two

MZBD-9161 connected in series, to have a double series rectenna, as used by Akkermans *et al.* [15]. It was found that whilst adding diodes in series decreased the conversion efficiency and voltage output, $\eta_{mismatch}$ could be increased when no matching network was used.

CONCLUSION

Simulation setup and results have highlighted a few of the difficulties in rectenna design. Due to the low level of available power, at frequencies around 2.45 GHz and especially at 60 GHz, concurrently harvesting energy at these two frequencies will provide an advantage for single frequency rectennas. A consistent analysis was performed in selecting a detector device that could work at frequencies above the 2.4 GHz ISM band. An extensive comparison of the selected detectors in different configurations was performed and a clear frequency range for each device was established. The MZBD-9161 Schottky diode showed good performance even under zero bias operation and will be used on frequency scalable rectennas. This will be the foundation for future applications for wireless sensors operating at 2.45 and 60 GHz, such as WiFi and WiGig. Conversion efficiencies from around 33% and 6% can be expected for input power levels of -20 and 0 dBm at 2.45 and 60 GHz, respectively. An important breakthrough was achieved by understanding why a series configuration is better than a shunt configuration. By performing a complete analysis of how the different elements of the diode's model behave at different frequencies, the operation at high frequencies was predicted. In addition, key benefits of each configuration were highlighted.

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