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# Circuit Model of Rectennas Array for Estimating Microwave Energy Harvesting in Presence of Mutual Coupling Between Elements

Tristan FOUGEROUX<sup>1\*</sup>, Alexandre DOUYERE<sup>1</sup>, Pierre Olivier LUCAS DE PESLOUAN<sup>1</sup>, Nour Mohammad MURAD<sup>1</sup>, Shailendra OREE<sup>2</sup> and Jean-Lou DUBARD<sup>3</sup>

<sup>1</sup> Energy-Lab, Faculty of Science, University of La Reunion, 97744 Saint Denis, Cedex 9, France

<sup>2</sup> Department of Physics, Faculty of Science, University of Mauritius Reunion, 80837, Mauritius

<sup>3</sup> Université Côte d'Azur, CNRS, LEAT, 930 route des Colles, 06903 Sophia Antipolis, France

\*tristan.fougeroux@gmail.com

**Abstract** — Based on measurement results, this paper proposes a circuit model for an array composed of  $N$  rectennas at 2.45GHz in the ISM band. More precisely, the estimation of the power harvested is carried out using an equivalent circuit composed only of passive elements. The model is developed for a rectennas array based on DC series combiner topology. In applications targeting the provision of power to low consumption WSN components, the model's predictions can be used to determine the required number of rectennas to power an electronic circuit autonomously. Examples are given to illustrate the use of this model.

## I. INTRODUCTION

Wireless Power Transmission techniques are the subject of considerable interest with the rapid development of mobile devices and expansion of ubiquitous computing, including the IoT. According to analysis of Business Insider Intelligence [1], there will be more than 41 billion IoT devices by 2027, up from about 8 billion in 2019. Against this backdrop, the scope of energy harvesting from the environment, particularly electromagnetic energy, is very promising [2].

Energy harvesting is the process of collecting and capturing ambient energy and its conversion to electricity in order to meet the needs of low-power electronic circuits and thereby make new things possible [3]. This solution relieves users from the expense, inconvenience and pollution resulting from frequent replacement of batteries. One possible implementation of this technology is using a rectifying antenna (rectenna) to convert electromagnetic energy into DC electricity. However, despite the existence of a large number of electromagnetic emitters in a typical urban environment, mainly assigned to communications, power densities remain relatively small ( $1\mu\text{Wcm}^{-2}$ ) depending on the frequency bands [4]. The average level of the electric field is, indeed, less than  $1\text{Vm}^{-1}$  on the different radio frequency bands [5]. Therefore, in practical energy harvesting systems, several rectennas may be interconnected in the form of an array to increase DC output power. This is called DC-combining configuration in which the outputs of the rectennas are combined in series, in parallel or in a hybrid manner [6].

In the study [7], the intended application is to design compact rectenna systems for powering wireless communicating devices, in which the main constraint is the short distance between elements. This work is based on a Thevenin equivalent circuit model for a rectennas array. This model is used as an

energy harvesting estimation tool. As in [8], our approach is empirical and the nonlinear equations to estimate the harvested energy are derived from experimental measurements. However, in our study, these equations consider electromagnetic couplings between rectennas.

## II. IMPROVING THE CIRCUIT MODEL OF THE RECTENNA ARRAY

The process employed to estimate the energy harvesting performance of a  $N$  elements rectennas array starts with designing one rectenna for a given frequency, a given substrate, a given load and measurement of its performance. Secondly, a coarse estimation of the global DC power harvested for  $N$  non-interacting rectenna elements is done and the error is evaluated with respect to measurements. The experimental setup is composed of a linearly polarized biquad antenna ( $G \approx 10\text{dBi}$ ) operating at 2.45GHz with a constant 25dBm feeding power. The distance between the transmitting antenna and the receiving rectennas array is fixed to 2 meters. We assume that the power received by each rectenna is identical.

For simplicity, we assume that uniform coupling exists, meaning that every array element has an identical environment. Thus, for every element, mutual coupling effects are identical and we model them with passive elements that depend on the number of rectennas  $N$ . Depending on the layout of the rectennas in the design of the array, two types of mutual electromagnetic coupling may appear and are modeled by two nonlinear resistances. For the design of a  $N_H \times 1$  elements array, only horizontal coupling is present, modeled by a resistance  $R_{CH}$ . In case of a  $N_H \times N_V$  elements array, additional vertical couplings appear, modeled by an additional resistance  $R_{CV}$ . They are described in the following subsections.

### A. Modeling of the horizontal mutual coupling

The first mutual coupling term is due to interactions between horizontally adjacent rectennas. We start by deriving the value of the equivalent resistance  $R_{CH}$  from measurements. More precisely, we represent  $R_{CH}$  using a quadratic polynomial equation as a function of the load resistance  $R_L$ . The polynomial coefficients found are expressed as linear functions of  $N = N_H \times 1$ .  $R_{CH}$  is then given for  $N > 1$  by:

$$R_{CH} = (\alpha \cdot R_L)^2 + \beta \cdot R_L + \gamma \quad (1)$$

with  $\alpha = (-117N + 215) \cdot 10^{-9}$ ;  $\beta = -0.022N + 0.237$  and  $\gamma = -443N + 240$ .

### B. Modeling of the vertical mutual coupling

Similarly, the derivation of the second resistor  $R_{CV}$  is performed. This resistor has a negligible impact for  $N = N_H \times N_V$  less than 10 and generally has less impact on array performance because the antennas are more distant. Using a quadratic interpolation, the expression of  $R_{CV}$  is then obtained for  $N > 9$  as:

$$R_{CV} = (\alpha_1 \cdot R_L)^2 + \beta_1 \cdot R_L + \gamma_1 \quad (2)$$

with  $\alpha_1 = (-43N + 417) \cdot 10^{-9}$ ;  $\beta_1 = -0.0255N + 0.098$  and  $\gamma_1 = 2078N - 16611$ .

The results generated using this enhanced model for arrays with different numbers of elements are presented in the next section.

## III. RESULTS AND DISCUSSION

The simulated and measured collected DC power regarding the number of rectennas are represented in figure 1. Despite a more significant error for the 9 x 2 elements array and loads between 1k $\Omega$  and 50k $\Omega$  the error between measurements and simulations for each array is small with a minimum of 0.5% and a maximum of 2.5% for  $P_{max}$  at the optimal  $R_{load}$ . These results show a good agreement and allow to validate the proposed model. To estimate the microwave energy that could be harvested under the same experimental conditions, we propose to extrapolate these results to larger rectennas arrays as illustrated in figure 2.

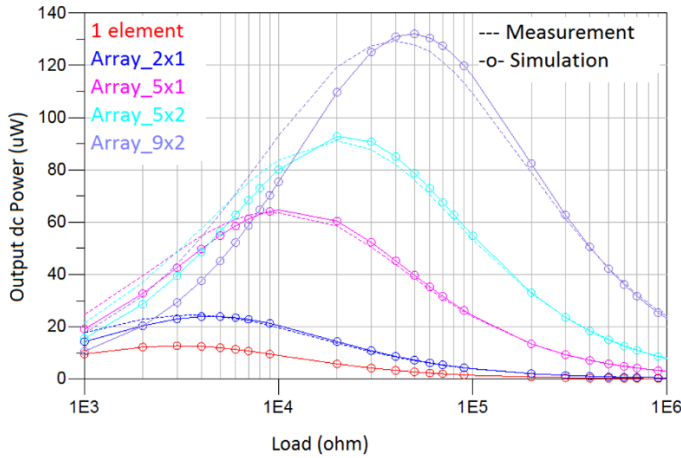


FIGURE 1. MEASUREMENT AND SIMULATION OUTPUT DC POWER VS LOAD

Figure 2 displays the operating point (load impedance, number of rectennas and power harvested) of an application in a power range [0.1 $\mu$ W, 200 $\mu$ W] and for a maximum of 50 rectennas with  $N_V \leq 2$ . One can observe an asymptotic DC output power limit for the considered loads. As an example, we use this chart to predict the number of rectennas required in two applications with  $R_{load} = 1M\Omega$  [9] and  $2M\Omega$  [10] respectively. The first application is an ultra-low power status led which consumes 4.5 $\mu$ W (3V, 1.5 $\mu$ A). The chart shows that an array of 13 rectennas is needed to power the led application. The second

one is a digital thermometer which consumes 9 $\mu$ W (3V, 3 $\mu$ A) and can show temperature on an LCD display. To power this device, an array of 11 rectennas is sufficient. Also, the surface area of rectennas array as a function of the number of rectenna is added and is related to the output DC power.

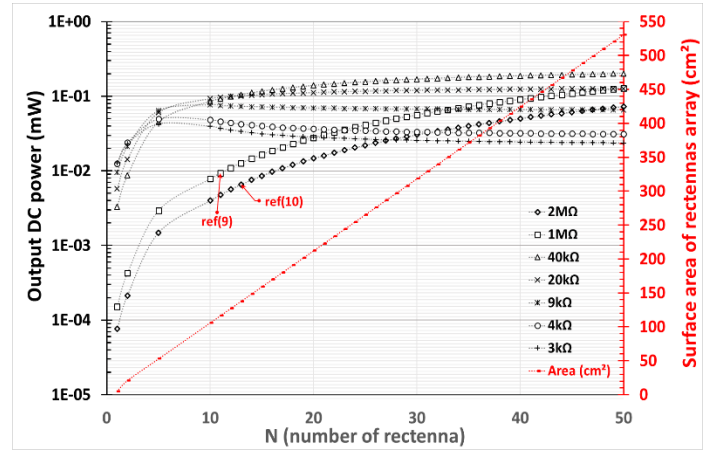


FIGURE 2. POWER AND SURFACE AREA OF RECTENNAS ARRAY VS NUMBER OF RECTENNA FOR VARIOUS LOAD VALUE

## IV. CONCLUSION

Using a passive circuit model, an estimate of DC power delivered by a rectennas array was obtained. The proposed model considers the mutual electromagnetic coupling between rectennas. It is suitable to arrays composed of an arbitrary number  $N = N_H \times N_V$  of rectennas with  $N_V \leq 2$ . Comparisons with experimental results validate the accuracy of the model.

## ACKNOWLEDGMENT

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