Comparative Performance of Algorithmic Techniques for Optimizing Dual-Band Rectifier

Maria S. Papadopoulou
ELEDIA@AUTH, School of Physics
Aristotle University of Thessaloniki
Thessaloniki, Greece
mpapa@physics.auth.gr

Achilles D. Boursianis
ELEDIA@AUTH, School of Physics
Aristotle University of Thessaloniki
Thessaloniki, Greece
bachi@physics.auth.gr

Argyrios Chatzopoulos
Dept. of Information and Electronic Eng.
International Hellenic University
Sindos, Greece
ahatz@ihu.gr

Panagiotis Sarigiannidis
Dept. of Electrical and Computer Eng.
University of Western Macedonia
Kozani, Greece
psarigiannidis@uowm.gr

Spyridon Nikolaidis
ELEDIA@AUTH, School of Physics
Aristotle University of Thessaloniki
Thesssaloniki, Greece
snikolaid@physics.auth.gr

Sotirios K. Goudos
ELEDIA@AUTH, School of Physics
Aristotle University of Thessaloniki
Thessaloniki, Greece
sgoudo@physics.auth.gr

***Abstract*—Radio Frequency (RF) energy harvesting (EH) is a technique to replenish the source of wireless sensor networks (WSNs). Also, many interdisciplinary fields in the Internet-of-Things (IoT) era use RF-EH, like precision agriculture, biomedical, and robotics. Over the years, various designs have been presented in the literature operating in multi- or wide-band frequencies. Usually, a designed system is optimized using specific goals and optimization parameters to obtain maximization in power conversion efficiency (PCE). In this work, a dual-band RF rectifier system that resonates in the Wi-Fi frequency bands of 2.45 GHz and 5.8 GHz is presented. The proposed system is optimized using four optimization techniques, namely the Gradient algorithm, the Minimax algorithm, the Simulated Annealing, and the Genetic algorithm. A set of comparative results is presented to assess the performance of each technique and to obtain the feasible solution of the proposed design. Numerical results demonstrate that a 42.8% efficiency is achieved, having a 16 dBm input power and a 1.7 kΩ output resistance load.**

***Index Terms*—RF energy harvesting, rectenna, impedance matching, optimization technique, genetic algorithm, rectifier, wireless sensor network**

I. Introduction

In the last years, the ever-increasing development of mobile devices and wireless sensor networks (WSNs) turned the attention of scientists to energy harvesting (EH) and wireless power transfer (WPT) techniques. The number of radiofrequency (RF) sources is continuously increasing. The RF-EH aims to turn ambient RF energy into usable DC voltage to power electronics or charge batteries. It is a promising solution to extend battery life or reduce waste when employed in battery-less low-power WSNs. Many interdisciplinary application fields in the Internet of Things (IoT) era use RF energy harvesting, such as precision agriculture [1], [2], biomedical engineering [3], robotics [4], while new applications are constantly emerging.

An RF-EH system usually consists of a receiving antenna or an array, an impedance matching network (IMN), an RF-to-DC rectifier, a power management unit (PMU), and an output load (Fig. 1). The antenna resonates and harvests the ambient RF energy at specific frequency bands. Usually, an impedance matching network is applied to adjust the impedance between the antenna and the RF-to-DC rectifier. The matching network is also responsible for minimizing the power loss due to impedance mismatches and transferring the maximum power to the rectifying circuit [5]. The RF-to-DC rectifier converts the captured AC signal into output DC voltage. One of the key performance factors of an RF-to-DC rectifier is the power conversion efficiency (PCE). Finally, the PMU is responsible for improving the efficiency of the DC-DC converter.

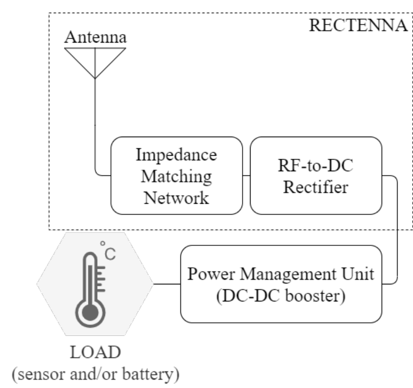

Fig. 1. Typical topology of an RF-EH system.

A critical point in designing an RF-to-DC rectifier is the design aspects of the IMN to minimize the reflection loss and maximize the power conversion efficiency [6]. The matching between the impedances of a source A and a load L is attained when the impedances Z_A and Z_L have the below relation:

$$Z_A = Z_L^* \tag{1}$$

where "*" denotes the complex conjugate number, Z_A the source impedance, and Z_L the load impedance. There are two approaches to design an IMN; by using lumped elements, such as resistors, inductors, and capacitors, or by applying distributed elements (microstrip lines). Whichever approach the designer chooses, he must apply optimization techniques to achieve the maximum PCE.

In [7], the authors presented a triple-band rectifier operating in the frequency bands of GSM-900, GSM-1800, and UMTS-2100. They optimized the size of the impedance matching circuit by adjusting its distributed components (transmission lines and stubs), as well as its lumped ones (inductors) to achieve an acceptable matching in the impedance. In [8], the authors designed a rectifier operating at 5.81 GHz. The authors proposed an iterative method to call the API handle of the impedance matching tool and optimize the performance of their design by reconfiguring the matching goal. In [9], the authors proposed a microstrip-based rectifier consisted of a voltage-doubler circuit and utilizing two Zero-Bias Schottky diodes. The rectenna model was co-simulated and optimized. In [10], the authors designed an impedance matching circuit for a rectifier at 2.45 GHz. The system was optimized using performance goals and optimization parameters to obtain a maximum PCE.

Generally speaking, the optimization process is a complex procedure. It is essential how and which optimization method is applied to achieve maximum performance. In this paper, we determine the optimum IMN in a dual-band operation design, by utilizing four optimization algorithms that are intrinsically available in the ADS environment (Advanced Design System (ADS), ©Keysight Technologies 2000-2021). We present the comparative results and obtain a feasible solution for the proposed design. The remainder of the paper is structured as follows. Section II describes the RF-EH system and the proposed dual-band rectifier. Section III presents the four optimizers of the ADS software briefly. Section IV displays the simulation results and concludes with the optimum solution. The PCE of the system is calculated and a comparison between the two best approaches is presented. Finally, in Section V, some concluding remarks are outlined.

II. Energy Harvesting System

A. Rectenna

The antenna and the rectifier are composing the so-called rectifying antenna (rectenna), Fig. 1. The rectifier module is the key module of the rectenna system. The antenna captures the RF electromagnetic radiation, whereas the rectifier converts the input AC power into output DC voltage. The overall PCE strongly depends on the rectifier's performance. An IMN is applied to adjust the impedance between the antenna and the RF-to-DC rectifier, thus maximizing the PCE.

B. RF-to-DC Rectifier

The RF-to-DC system is one of the core components of the rectenna. A diode with fast switching characteristics is mandatory to achieve high PCE. Received power signal levels that are transmitted by the ambient RF energy sources are usually low. Therefore, the turn-on voltage of the utilized diode must be smaller than the maximum voltage produced by received signals. The Schottky diode, having a relatively low substrate leakage and forward voltage, is commonly used in rectifier design [11]. In this work, the Avago HSMS-286C diode, which features a maximum forward voltage V_F of 350 mV, a typical capacitance C_T of 0.25 pF, and a frequency range between 915 MHz and 5.8 GHz, has been selected.

The next decision step is the selection of the topology. In our work, we utilize the Dickson voltage-doubler (Fig. 2) by exploiting the characteristic of mitigating the parasitic capacitances between the different stages at the transitional nodes [12]. The rest of the IMN is completed by four capacitors C_i (i = 1, 2, 3, and 4) of 100 pF and various conductor lines. The IMN, Fig. 3, adjusts the input impedance between the antenna and the RF-to-DC rectifier, thus achieving the maximization of the PCE, and obtaining the maximum DC output [6]. There are two techniques when designing an IMN; the use of lumped or distributed elements in the proposed design. In this work, we utilize the design of the IMN with distributed (microstrip line) elements. The proposed circuit is designed on an FR-4 substrate (substrate thickness: 1.6 mm, relative permittivity: 4.4, dielectric loss tangent: 0.02, copper foil thickness: 35 μm).

We consider an antenna port of impedance $Z_A = 50\Omega$. The RF-to-DC PCE versus the AC RF signal (P_{in}) at the input port is usually the reference point for the evaluation of the system's performance. Fig. 3 portrays the geometry of the proposed IMN of the dual-band rectifying module. Z_{in} is the total impedance of the IMN and the rectifier. Also, P_{inav} is the available power at the input of the IMN. The variations of the rectifier's input impedance, as the RF input power is modified, results in the use of the Large-Signal S-Parameter simulation tool of the ADS environment. Finally, we compute the efficiency of the overall circuit as a function of the incident RF input signal.

C. Output Load

One of the key factors that affect the performance of the electronic circuits is the output load. Generally speaking, when the resistance value of the output load falls into a specific range, the performance of the corresponding circuit increases. On the contrary, when the output load value diverges from this range, the circuit's performance decreases. In RF EH systems, the selection of the optimal value for the resistance output load is rather complex and depends on the number of the applied

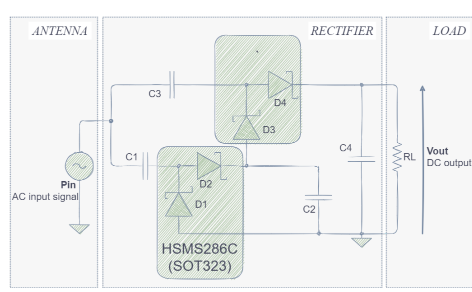

Fig. 2. Two-stage Dickson voltage-doubler topology.

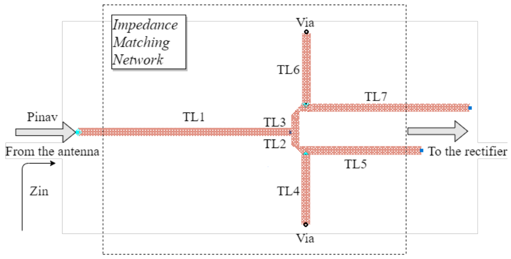

Fig. 3. Geometry of the proposed impedance matching network (IMN).

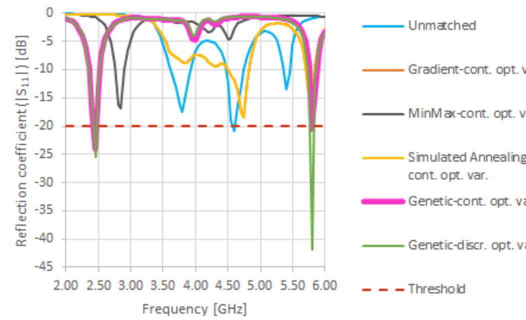

Fig. 4. The magnitude of the reflection coefficient of the proposed rectifier as a function of frequency (Pin = 0 dBm).

stages and the various types of the utilized nonlinear devices. Therefore, a preliminary fast-swiping method for the resistance output load is applied to assess the impact of its value on the designed circuit.

D. Optimization

Optimization techniques are useful tools for scientists to find a feasible or an optimal solution to the given optimization problem [13]. It is a complex process of setting several parameters to satisfy predefined performance goals (optimization criteria). Generally speaking, optimizers compare computed and desired outputs at each iteration, and update the position vector (current solution to the optimization problem) to obtain new results (at the next iteration) that are likely to be closer to the desired. Maximum and/or minimum acceptable values are set to define the limits of an optimization goal. ADS environment has many integrated optimizers for different design problems. Each optimizer applies a specific search method and an error function to achieve the desired outputs. In this paper, we utilize the following optimizers: Gradient, Minimax, Simulated Annealing, and Genetic.

III. Numerical Results

A. Optimizer Setup

The voltage-doubler input impedance for the dual-band design is calculated by utilizing the S-parameters simulator tool of the ADS environment. The derived values prior to the optimization (unmatched rectifier) are $34.703 - j*409.314$ and $17.744 - j*119.464$ at $2.45GHz$ and $5.8GHz$, accordingly. We also consider an antenna port of 50Ω. The IMN is a two-branch circuit with shorted-stubs. The number of iterations is set to 100. Also, six decision variables (IMN length and width of TL1, TL4, and TL6 microstrip lines) of the proposed design are included in the optimization process. We consider continuous optimization variables for all the optimizers. Additionally, we apply optimization for discrete variable change by 0.1 mm only for the genetic optimizer. The rest of the parameters of the proposed design are unaltered during the optimization process.

B. Optimizers Comparison

Fig. 4 illustrates the reflection coefficient (S_{11} magnitude) of the proposed RF-to-DC rectifier as a function of the frequency. From the presented results we can deduce that the genetic algorithm (GA) achieves acceptable results at the two frequencies of interest. The proposed RF-to-DC design exhibits a dual-band frequency operation. In detail, GA with continuous optimization variables achieves -24.2 dB at 2.45 GHz and -20.5 dB at 5.8 GHz, whereas GA with discrete optimization variables by 0.1 mm achieves -25.5 dB and -41.9 dB, accordingly. Table I shows the optimized values of microstrip lines TL1, TL4, and TL6.

C. Power Conversion Efficiency

The RF-to-DC PCE (%) of the proposed design is computed by

$$P_{DC} = V_{DC}^2/R_L = V_{out}^2/R_L \tag{2}$$

$$PCE = P_{DC}/P_{inav} * 100 \tag{3}$$

where V_{out} is the DC output voltage, P_{inav} is the electromagnetic energy available at the input of the IMN, and R_L is the output load resistance. The design procedure takes into account the harmonic balance optimization that is available in the ADS environment to maximize the PCE (%) of the proposed circuit. Fig. 5 portays the RF-to-DC PCE (%) as a function of the output resistance $R_L(\Omega)$, for the genetic optimizer with discrete optimization variables. From the displayed graphs, we can deduce that the proposed RF-to-DC circuit attains a maximum performance of 42.8% when a two-tone signal is applied, the input power is equal to 16 dBm, and the output load is 1.7 $k\Omega$. Fig. 6 illustrates the PCE versus frequency for discrete optimization variables for an output load of 1.7 $k\Omega$. We can observe that the proposed RF-to-DC circuit attains a PCE over 30% at 2.45 GHz and 5.8 GHz for input power greater than 8 dBm.

IV. Conclusion

In this work, a dual-band RF-to-DC rectifier that operates at 2.45 GHz and 5.8 GHz is proposed. The system is optimized using four intrinsic optimization algorithms (gradient, minimax, simulated annealing, and genetic) that are available in the ADS environment. We consider continuous optimization variables for all the above optimizers. Moreover, discrete optimization variables with a step of 0.1 mm for the genetic optimizer are also considered. The comparative results indicate the outperformance of the genetic optimization

TABLE I
PHYSICAL DIMENSIONS OF THE MICROSTRIP LINES (LENGTH/WIDTH VALUES ARE EXPRESSED IN MILLIMETERS).

	Optimization					
	Unmatched	**Gradient**	**Minimax**	**Sim. Annealing**	**Genetic**	**Genetic (discrete)**
TL1	20.0/ 0.4	20.000/ 0.702	21.043/ 0.806	20.006/ 0.714	24.2857/ 1.29768	25.0/ 1.2
TL4	6.0/ 0.4	6.000/ 2.717	8.488/ 0.404	6.000/ 2.619	15.7878/ 2.33383	16.6/ 1.9
TL6	6.0/ 9.5	6.000/ 2.085	12.189/9.499	6.000/ 2.073	17.8356/ 6.5816	17.8/ 6.3

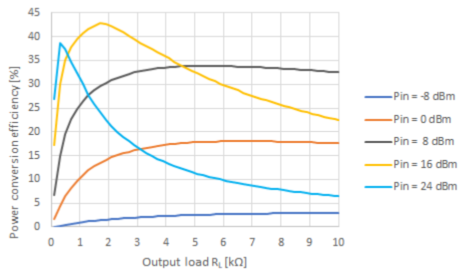

Fig. 5. Power conversion efficiency [%] as a function of the output load $R_L[k\Omega]$ for the two-tone signal of the proposed circuit (P_{in} varies from -8 dBm to 24 dBm with a step of 8 dBm, GA is considered with discrete optimization variables).

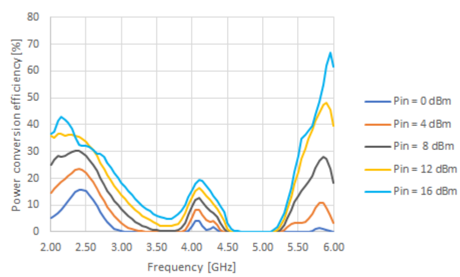

Fig. 6. Power conversion efficiency [%] as a function of the frequency [GHz] for an output load $R_L = 1.7k\Omega$ (P_{in} varies from 0 dBm to 16 dBm with a step of 4 dBm, GA is considered.

algorithm against the other utilized algorithmic techniques. The overall system exhibits improved characteristics compared to the initial unmatched circuit in terms of its resonance at the frequencies of interest. Also, numerical results show that the optimized design reaches an efficiency of 42.8% for a two-tone input signal of 16 dBm and an output load of 1.7 $k\Omega$. Future work includes the assessment of more complex RF-to-DC rectifier systems by utilizing various optimization techniques, such as swarm intelligence or human-based algorithms, and the experimental validation of the proposed design.

REFERENCES

[1] A. D. Boursianis, M. S. Papadopoulou, P. Damantoulakis, A. Karampatea, P. Doanis, D. Geourgoulas, A. Skoufa, D. Valavanis, C. Apostolidis, D. G. Babas, K. B. Baltzis, T. N. Kaifas, K. Siozios, S. Siskos, T. Samaras, K. Siakavara, S. Nikolaidis, S. K. Goudos, A. Liopa-Tsakalidi, P. Barouchas, I. Kasimis, G. Kalamaras, D. Merkouris, G. Perrakis, C. Tsirogiannis, A. Gotsis, and K. Maliatsos, "Advancing rational exploitation of water irrigation using 5g-iot capabilities: The arethou5a project," in *2019 29th International Symposium on Power and Timing Modeling, Optimization and Simulation (PATMOS)*, 2019, pp. 127–132.

[2] A. D. Boursianis, M. S. Papadopoulou, A. Gotsis, S. Wan, P. Sarigiannidis, S. Nikolaidis, and S. K. Goudos, "Smart irrigation system for precision agriculture—the arethou5a iot platform," *IEEE Sensors Journal*, vol. 21, no. 16, pp. 17 539–17 547, 2021.

[3] F. F. Zulkifli, J. Sampe, M. S. Islam, M. A. Mohamed, and S. A. Wahab, "Optimization of rf- dc converter in micro energy harvester using voltage boosting network and bulk modulation technique for biomedical devices," in *2015 IEEE Regional Symposium on Micro and Nanoelectronics (RSM)*, 2015, pp. 1–4.

[4] D. Bonilla Licea, S. A. Raza Zaidi, D. McLernon, and M. Ghogho, "Improving radio energy harvesting in robots using mobility diversity," *IEEE Transactions on Signal Processing*, vol. 64, no. 8, pp. 2065–2077, 2016.

[5] B. Li, X. Shao, N. Shahshahan, N. Goldsman, T. Salter, and G. M. Metze, "An antenna co-design dual band rf energy harvester," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 60, no. 12, pp. 3256–3266, 2013.

[6] C. R. Valenta and G. D. Durgin, "Harvesting wireless power: Survey of energy-harvester conversion efficiency in far-field, wireless power transfer systems," *IEEE Microwave Magazine*, vol. 15, no. 4, pp. 108–120, 2014.

[7] S. Shen, C.-Y. Chiu, and R. D. Murch, "A dual-port triple-band l-probe microstrip patch rectenna for ambient rf energy harvesting," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 3071–3074, 2017.

[8] Q. Zhang, J.-H. Ou, Z. Wu, and H.-Z. Tan, "Novel microwave rectifier optimizing method and its application in rectenna designs," *IEEE Access*, vol. 6, pp. 53 557–53 565, 2018.

[9] A. Afyf, M. A. Sennouni, L. Bellarbi, A. Achour, and N. Yaakoubi, "Enhanced rf energy harvester for power efficient internet-of-things wireless sensors," in *2018 6th International Conference on Multimedia Computing and Systems (ICMCS)*, 2018, pp. 1–6.

[10] A. Gupta, U. Pattapu, and S. Das, "High efficiency low power series diode rectifier design," in *2018 3rd International Conference on Microwave and Photonics (ICMAP)*, 2018, pp. 1–2.

[11] A. D. Boursianis, M. S. Papadopoulou, S. Koulouridis, P. Rocca, A. Georgiadis, M. M. Tentzeris, and S. K. Goudos, "Triple-band single-layer rectenna for outdoor rf energy harvesting applications," *Sensors*, vol. 21, no. 10, 2021. [Online]. Available: https://www.mdpi.com/1424-8220/21/10/3460

[12] M. A. Abouzied and E. Sánchez-Sinencio, "Low-input power-level cmos rf energy-harvesting front end," *IEEE Transactions on Microwave Theory and Techniques*, vol. 63, no. 11, pp. 3794–3805, 2015.

[13] A. D. Boursianis, M. S. Papadopoulou, M. Salucci, A. Polo, P. Sarigiannidis, K. Psannis, S. Mirjalili, S. Koulouridis, and S. K. Goudos, "Emerging swarm intelligence algorithms and their applications in antenna design: The gwo, woa, and ssa optimizers," *Applied Sciences*, vol. 11, no. 18, 2021. [Online]. Available: https://www.mdpi.com/2076-3417/11/18/8330