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# Design of a Compact Line-of-Sight Rectenna for Wireless Power Transfer Systems

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**Abstract**—This paper presents the design of a compact line-of-sight rectenna system for wireless power transfer and energy harvesting applications. The proposed rectenna consists of a highly-directive Vivaldi microstrip antenna and a voltage doubler rectifier circuit assembled in the same double-sided copper fiberglass substrate. To achieve the established requirements for the antenna, a mixed optimization process is proposed by using alternately two techniques: Particle Swarm and Covariance Matrix Adaptation Evolution Strategy. In addition, to limit the rectifier output current, a buffer circuit is proposed to interface the rectifier output and the load. Finally, the proposed methodology and the designed rectenna are numerically and experimentally characterized, and the obtained results confirm the system's capacity to power low-consumption loads.

**Index Terms**—optimization, rectennas, Vivaldi antenna, wireless power transmission, wireless sensor network.

## I. INTRODUCTION

The recent, rapid, and widespread growth of wireless communications, coupled with the availability of low-consumption electronic devices, has spurred the creation, development, application, and expansion of various technologies and concepts, such as smart cities, the Internet of Things (IoT), and 5G applications. At the core of these advancements lies the utilization of Wireless Sensor Networks (WSNs). However, as these technologies continue to improve, the number of nodes (sensors) within each network increases, posing challenges for replacing or recharging batteries and connecting electrical cables to power these networks. To address the pressing need for energy supply in these low-consumption loads, extensive research has been conducted on different energy harvesting technologies.

Since Wi-Fi systems currently dominate wireless communication, the electromagnetic radiation within this frequency band presents an attractive alternative for powering WSN nodes. Among the various technologies explored for harvesting

Wi-Fi energy, rectennas, i.e., miniaturized microstrip antennas connected to microwave rectifier circuits, have emerged as the most commonly used method. Rectennas are especially suitable for powering WSNs as they can seamlessly integrate into the distributed sensor structure, reducing costs, maintenance requirements, and environmental impact.

While research has made significant progress in employing rectennas for wireless energy transmission [1]–[4], the limited availability of electromagnetic energy in the environment, even in direct line-of-sight applications between transmitter and receiver antennas, poses a challenge in collecting substantial power values. Consequently, researchers have explored different strategies and techniques to enhance the power-handling capabilities of these systems. Notable approaches include using various antenna types, dielectric substrates, and optimized rectifier circuit designs.

In this study, we present the design of a comprehensive line-of-sight rectenna system capable of powering low-consumption sensors. The proposed system comprises a high-gain transmitter and receiver antennas, as well as a compact and efficient rectifier circuit. The key innovation of this work lies not only in the novel topology proposed for the rectenna but also in utilizing a mixed optimization process to fulfill the established requirements for the antenna design. By leveraging this approach, we aim to maximize the efficiency and effectiveness of the rectenna system, paving the way for improved wireless energy transmission and empowering the seamless operation of low-consumption devices in various applications.

## II. RECTENNA DESIGN

The rectenna proposed in this study comprises a microstrip antenna based on the Vivaldi topology chosen for its ability to achieve high directivity values. This antenna design ensures focused and efficient energy reception. Additionally, the rectenna incorporates a voltage doubler circuit, which enhances the

overall efficiency of the energy conversion process. The rectifier circuit minimizes circuit complexity by employing a minimal number of non-linear devices, simplifying design and implementation.

Both components were constructed using a double-sided copper fiberglass substrate known as FR4 to ensure consistency and compatibility between the antenna and rectifier. This substrate offers favorable electrical characteristics, making it suitable for the rectenna design. With a thickness of  $t = 1.5$  mm and characterized relative electric permittivity  $\epsilon_r = 4.3$  and loss tangent  $\delta = 0.01$ , this substrate provides mechanical stability while maintaining the desired electrical properties.

The Vivaldi antenna geometry was designed and optimized by using Computer Simulation Software (CST<sup>®</sup>) to achieve at the same time a low reflection coefficient  $S_{11} < -20$  dB and maximum gain in the range from 2.4 GHz to 2.5 GHz. To accomplish these goals, a mixed optimization process was employed, utilizing two techniques in an alternating manner: Particle Swarm Optimization (PSO) and Covariance Matrix Adaptation (CMA) Evolution Strategy, as depicted in Fig. 1.

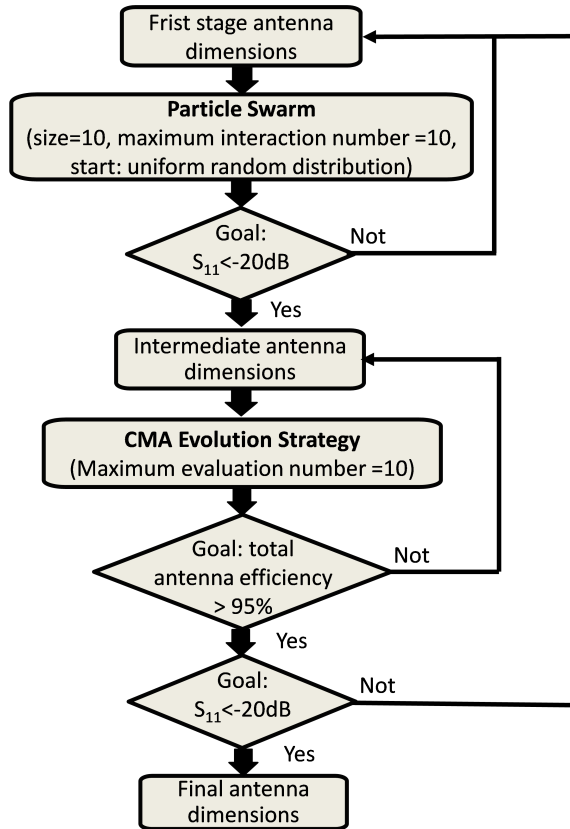


Fig. 1. Proposed optimization process. It combines the Particle Swarm (PSO) algorithm in an initial stage with its solution used as an initial parameter for Covariance Matrix Adaptation (CMA) Evolution Strategy optimization.

PSO was selected as the initial optimization technique due to its simplicity and fast convergence properties. It strikes a balance between exploration, allowing for the search for new solutions, and exploitation, refining promising solutions. This

makes PSO well-suited for the early stages of optimization. The results obtained through PSO serve as the initial values for the subsequent optimization using CMA, which is a more robust and effective global search algorithm employed in the latter stages of optimization. It ensures the attainment of a globally optimal solution by avoiding local optima. By combining the strengths of both PSO and CMA, the desired performance targets can be achieved with fewer evaluations, making the optimization process more efficient and effective.

With its seamless transition from PSO to CMA, this combined optimization approach facilitates attaining the desired antenna characteristics while minimizing computational effort. This innovative methodology optimizes the Vivaldi antenna design, delivering exceptional performance in terms of low reflection coefficient and maximum gain within the specified frequency range. Finally, the final topology of the optimized antenna is shown in Fig. 2(a).

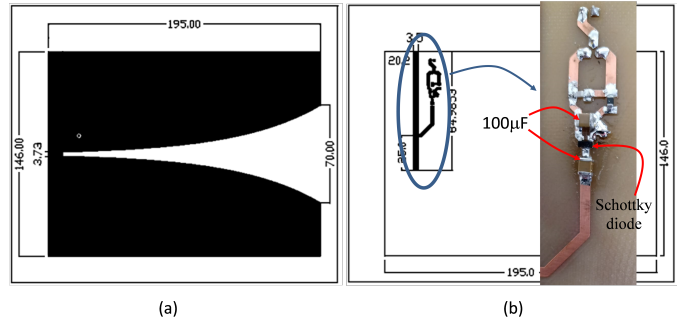


Fig. 2. Proposed rectenna based on the Vivaldi topology: (a) front-side view with antenna dimensions and (b) back-side view with prototyped rectifier circuit.

The design of the rectifier circuit focused on its operation within the WLAN bandwidth. To ensure compatibility with this frequency range, Schottky diodes SMS7630 were utilized. However, these non-linear components introduce a notable sensitivity to load and input power variations. The proposed rectifier circuit is a variation of a voltage-multiplier rectifier and incorporates two  $100 \mu\text{F}$  capacitors, as depicted in Fig. 2(b). Notably, this work introduces an innovative buffer circuit, which acts as an interface between the rectifier circuit and the load. The buffer circuit consists of a FET BS270, two  $100 \mu\text{F}$  capacitors, one  $10 \text{ pF}$  capacitor, one  $15 \text{ F}$  supercapacitor, one  $22 \mu\text{H}$  inductor, and two Schottky diodes. Its primary function is to protect the rectifier circuit by limiting the output current, as it behaves as a high-impedance load.

The rectifier circuit parameters were optimized by using the Advanced Design System (ADS<sup>®</sup>) software to achieve optimal performance. This optimization aimed to match the input impedance as closely as possible to a nonreactive  $50 \Omega$  at  $2.45\text{GHz}$ , considering an input power of  $P_{in} = -10$  dB and a high impedance load of  $820 \Omega$ . This careful parameter optimization ensures the rectifier circuit operates efficiently and effectively within the desired frequency range while maintaining compatibility with the target load conditions.

### III. RESULTS

To verify the design of both the microstrip antenna and the rectifier circuit, they underwent individual characterization processes. This approach allowed for a comprehensive assessment of their performance. The results obtained from numerical simulations and experimental measurements conducted at the 2.45GHz frequency are presented in Table I and visually depicted in Fig. 3 and Fig. 4, respectively. The comparison between the measured and simulated performance parameters, specifically  $S_{11}$ , and gain, reveals a close correlation, thus validating the proposed design. The obtained results demonstrate that the actual performance aligns with the expected behavior, reinforcing the accuracy and reliability of the design approach.

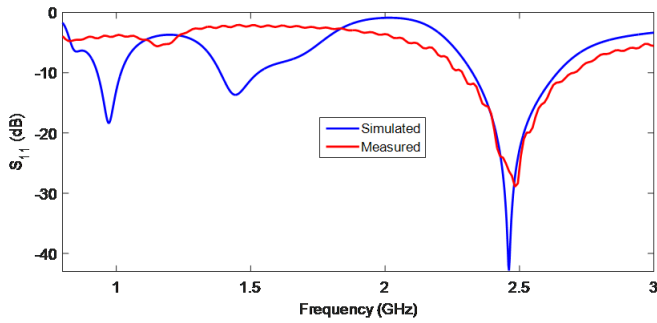


Fig. 3. Simulated and measured results for the reflection coefficient of the designed Vivaldi microstrip antenna ( $S_{11}$  parameter).

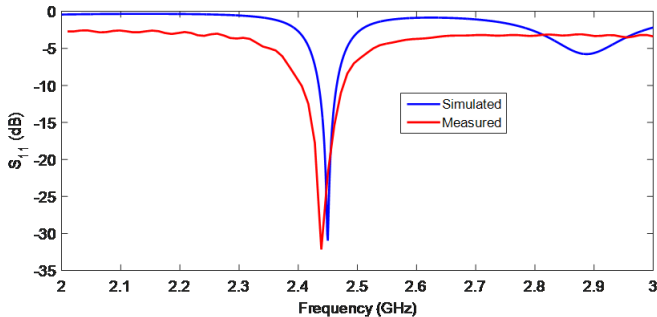


Fig. 4. Simulated and measured results for the proposed rectifier circuit's reflection coefficient ( $S_{11}$  parameter).

To assess the performance of the proposed rectenna, an experimental setup was conducted involving the positioning of the rectenna at varying distances  $d$  from an identical Vivaldi antenna, as depicted in Fig. 2(a). It's important to note that the transmitter antenna used for this evaluation was similar to the rectenna but did not have a rectifier circuit on its backside. The transmitter antenna was powered by a signal generator adjusted to deliver a power of 26 dBm at a frequency of 2.45 GHz. Meanwhile, an 820  $\Omega$  resistive load was connected to the output of the buffer circuit.

The measured power values obtained at the load are presented in Fig. 5, illustrating the harvested power by the rectenna at different distances. Notably, at a distance of 90 cm,

the rectenna successfully harvested approximately 850  $\mu$ W of power. This power level is substantial enough to meet the energy requirements of low-consumption loads, such as Wireless Sensor Networks (WSNs) [5,6]. The harvested voltage can be directly utilized to power sensor nodes or, more optimally, stored in a supercapacitor for subsequent delivery to the load in predetermined cycles controlled by a microcontroller circuit.

The experimental results underscore the rectenna's capability to capture and harvest energy effectively, validating its suitability for powering low-consumption devices. By efficiently harnessing the power from the transmitter antenna and implementing energy storage mechanisms, the rectenna system demonstrates its potential to provide a reliable and sustainable power supply for various wireless sensor applications.

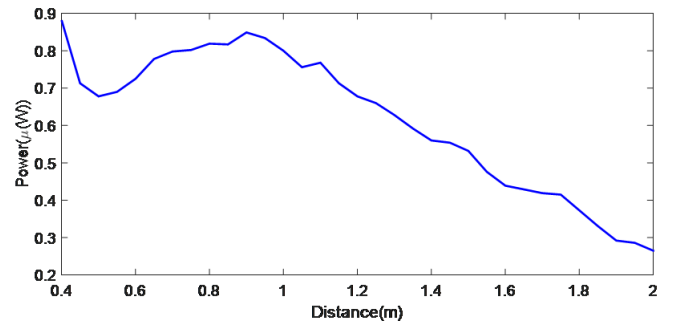


Fig. 5. Received power measured at the output of the rectifier circuit as a function of the distance from the transmitter antenna.

### IV. CONCLUSION

This paper presented a comprehensive study on the design and performance evaluation of a rectenna system for wireless energy harvesting. The proposed rectenna, consisting of a Vivaldi antenna and a voltage doubler circuit, was carefully optimized and characterized using advanced simulation tools and experimental measurements. The results demonstrated the achievement of a low reflection coefficient and high gain within the desired frequency range. Incorporating a FET BS270 buffer circuit enhanced the rectifier's robustness and protected it from high-impedance loads.

The rectenna performance was further evaluated through distance-dependent power harvesting experiments, showcasing its ability to capture energy from a transmitter antenna efficiently. The harvested power levels were sufficient for supplying low-consumption loads such as Wireless Sensor Networks (WSNs). Therefore, the proposed rectenna system offers promising prospects for powering a range of low-consumption devices, enabling energy autonomy and reducing reliance on traditional power sources.

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