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# An Optimized Rectenna and Impedance Matching Framework for Enhanced RF-to-DC Power Conversion

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**Abstract:**
This paper presents an optimized rectenna and impedance matching framework aimed at maximizing RF-to-DC power conversion efficiency for low-power energy harvesting applications. The proposed approach emphasizes joint optimization of the receiving antenna, nonlinear rectifier, and impedance matching network to ensure efficient power transfer under varying input power and frequency conditions. A high-gain antenna is designed to operate across commonly used RF energy harvesting bands, while low-threshold rectifier topologies and carefully tuned LC matching networks are employed to mitigate rectifier nonlinearity and impedance mismatch. Comprehensive electromagnetic–circuit co-simulations and experimental evaluations are conducted to validate the proposed framework. The results demonstrate a significant improvement in DC output voltage and RF-to-DC conversion efficiency, achieving a maximum efficiency of 66.4% at an input power of −5 dBm with excellent impedance matching characteristics. The findings confirm that integrated rectenna optimization and adaptive impedance matching are critical for efficient RF energy harvesting, making the proposed framework suitable for powering low-power wireless sensors and Internet of Things devices.
**Keywords:** RF Energy Harvesting, Rectenna Design, RF-to-DC Conversion Efficiency, Impedance Matching Network, Adaptive Matching, Multi-Stage Rectifier, Low-Power Wireless Systems, Internet of Things (IoT), Wireless Power Transfer, Antenna–Rectifier Co-Design

## 1.Introduction:

The rapid growth of low-power wireless devices, wireless sensor networks, and Internet of Things (IoT) applications has intensified the demand for sustainable and maintenance-free energy sources. RF energy harvesting has emerged as a promising solution by enabling the conversion of ambient or dedicated radio frequency signals into usable electrical power [1]. At the core of an RF energy harvesting system lies the rectenna, which integrates a receiving antenna with a rectifying circuit to convert RF signals into direct current (DC) power. However, achieving high RF-to-DC conversion efficiency remains a critical challenge, particularly under low input power conditions and across multiple operating frequency bands [2].

One of the primary factors limiting rectenna performance is impedance mismatch between the antenna and the nonlinear rectifier circuit. The rectifier's input impedance varies with frequency, input power level, and load conditions, leading to significant reflection losses and reduced power transfer. Conventional rectenna designs often rely on fixed impedance matching

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networks, which are typically optimized for a single operating point and fail to maintain efficiency under dynamic RF environments [3]. This mismatch issue becomes more pronounced in practical energy harvesting scenarios where RF signal strength and frequency fluctuate unpredictably [4].

To address these challenges, recent research has focused on integrated optimization strategies that jointly consider antenna characteristics, rectifier topology, and impedance matching techniques [5]. Advanced rectifier designs using low-threshold devices and multi-stage configurations have been explored to improve sensitivity and voltage gain at low power levels. Similarly, adaptive and power-aware impedance matching networks have shown potential in compensating for rectifier nonlinearity and enhancing power transfer efficiency [6].

Motivated by these developments, this work proposes an optimized rectenna and impedance matching framework aimed at enhancing RF-to-DC power conversion efficiency over a wide range of operating conditions. The proposed approach emphasizes co-design and co-optimization of the antenna, matching network, and rectifier to minimize reflection losses and maximize harvested DC power. Through comprehensive simulation and experimental validation, the proposed framework demonstrates significant improvements in conversion efficiency, highlighting its suitability for next-generation RF energy harvesting applications in IoT and low-power wireless systems [7].

## 2.Related Work:

RF energy harvesting using rectenna systems has been extensively investigated as a viable solution for powering low-power electronic devices. Early rectenna designs primarily focused on single-band operation with fixed impedance matching networks, where the antenna and rectifier were optimized independently [8]. While these approaches demonstrated basic RF-to-DC conversion capability, their efficiency was limited due to significant impedance mismatch caused by the nonlinear behavior of rectifier circuits, especially under low input power conditions [9].

Subsequent studies introduced improved rectifier topologies using Schottky diodes and multi-stage voltage multipliers to enhance sensitivity and output voltage. These designs showed better performance at moderate power levels but suffered from efficiency degradation when operating frequency or input power varied. Researchers reported that rectifier impedance strongly depends on input signal strength and load resistance, making static matching networks insufficient for practical RF energy harvesting environments [10].

To overcome these limitations, recent works have emphasized integrated rectenna co-design, where antenna parameters, matching networks, and rectifier circuits are optimized simultaneously. Broadband and multi-band impedance matching techniques were proposed to support operation across multiple frequency bands such as 900 MHz, 1.8 GHz, and 2.45 GHz. Although these approaches improved bandwidth and reduced reflection losses, they often involved complex circuit structures and increased design overhead [11].

More recent advancements have explored adaptive and tunable impedance matching networks to dynamically compensate for rectifier nonlinearity and changing RF conditions [12]. These methods significantly improved RF-to-DC efficiency but introduced additional power consumption, control complexity, and hardware cost. Some studies also investigated machine-learning-assisted optimization and co-simulation-based design frameworks to enhance rectenna performance, demonstrating promising results but limited experimental validation [13].

S. Korhummel., et al (2013) [14]: A harmonically terminated two-gram low-power rectenna implemented on a flexible substrate has been proposed to improve RF-to-DC conversion efficiency under ultra-low input power conditions. The design employs harmonic termination techniques to suppress higher-order harmonics generated by the nonlinear rectifier, thereby enhancing power transfer to the DC load. Flexible substrate integration enables lightweight, conformal, and wearable energy harvesting applications without significantly degrading electrical performance. Experimental results reported improved conversion efficiency compared to conventional non-terminated rectenna designs, demonstrating suitability for low-power and wearable IoT systems.

C. Song et al., (2017) [15]: Broadband rectenna designs with matching network elimination have been investigated to simplify circuit complexity and reduce insertion losses in wireless power transfer and energy harvesting systems. These approaches exploit intrinsic impedance characteristics of the rectifier–antenna interface to achieve wideband matching without external networks. Reported results show improved conversion efficiency and enhanced bandwidth compared to conventional matched rectennas. Such designs are particularly effective for compact, low-cost, and high-efficiency wireless power transfer applications.

N. Sakai., et al (2021) [16]: A highly efficient 5.8-GHz band rectenna employing a short-stub-connected high-impedance dipole antenna has been reported for high-power wireless power transfer applications. The short-stub structure enables effective impedance matching between the antenna and rectifier without requiring complex matching networks. Operating at an input power level of 1 W, the rectenna achieves significantly improved RF-to-DC conversion efficiency. This design demonstrates the suitability of compact, high-impedance antennas for efficient microwave power transmission systems.

N. Shinohara and Y. Zhou (2014) [17]: The development of rectennas using high-impedance, high-Q antennas has been explored to enhance RF-to-DC conversion efficiency by improving power transfer to the rectifier. High-Q antenna structures provide sharper resonance and increased voltage levels at the rectifier input, which is beneficial for low-power energy harvesting. These designs reduce the need for complex impedance matching networks while maintaining compact form factors. Reported results demonstrate improved efficiency and sensitivity compared to conventional low-Q antenna-based rectennas.

## 3.Methodology:

The proposed methodology follows a systematic design–optimize–validate workflow to maximize RF-to-DC conversion efficiency under practical operating conditions.

### 3.1. System Architecture Definition

A rectenna-based RF energy harvesting system is modeled, consisting of an RF receiving antenna, an impedance matching network (IMN), a rectifier circuit, a low-pass filter, and a DC

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load. Target operating parameters such as frequency band, input RF power range, load resistance, and application constraints are defined at the outset.

**3.2. Antenna Design and Optimization**

The receiving antenna is designed to achieve high gain, stable radiation patterns, and minimal reflection loss at the desired frequency. Full-wave electromagnetic simulations are performed to optimize antenna dimensions, substrate material, and feeding mechanism. The antenna impedance is accurately characterized to serve as the reference for impedance matching.

**3.3. Rectifier Circuit Development**

A nonlinear rectifier circuit is designed using low-threshold Schottky diodes or equivalent semiconductor devices to improve sensitivity at low input power levels. Single-stage or multi-stage rectifier topologies are evaluated based on conversion efficiency, output voltage ripple, and power handling capability. Harmonic balance analysis is employed to capture nonlinear effects.

**3.4. Impedance Matching Network Design**

An optimized impedance matching network is developed to ensure maximum power transfer between the antenna and rectifier across varying input power levels. Lumped or distributed matching networks are synthesized using analytical methods and refined through numerical optimization. Adaptive or multi-band matching techniques are considered to mitigate impedance variations caused by rectifier nonlinearity.

**3.5. Co-Simulation and Integrated Optimization**

Electromagnetic and circuit-level co-simulation is performed to jointly optimize antenna, matching network, and rectifier performance. Key performance metrics—reflection coefficient, RF-to-DC efficiency, output DC voltage, and delivered power—are iteratively optimized using parametric sweeps and optimization algorithms.

**6. Prototype Implementation and Measurement**

The optimized rectenna system is fabricated on a suitable substrate and experimentally evaluated. Measurements are conducted using RF signal generators and power meters to validate simulated results. The measured RF-to-DC conversion efficiency is analyzed under different input power levels and load conditions.

**4.Dataset:**

**An Optimized Rectenna and Impedance Matching Framework for Enhanced RF-to-DC Power Conversion**

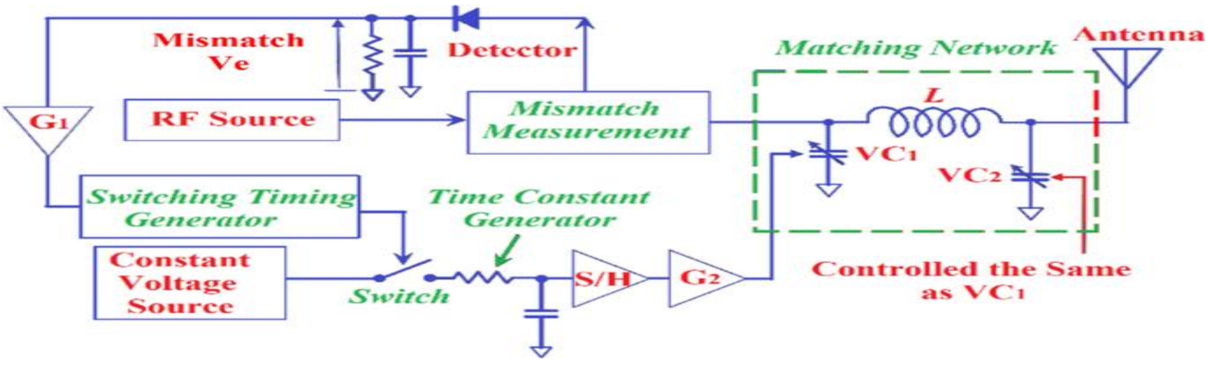


Figure.1: Combination of electromagnetic simulations.

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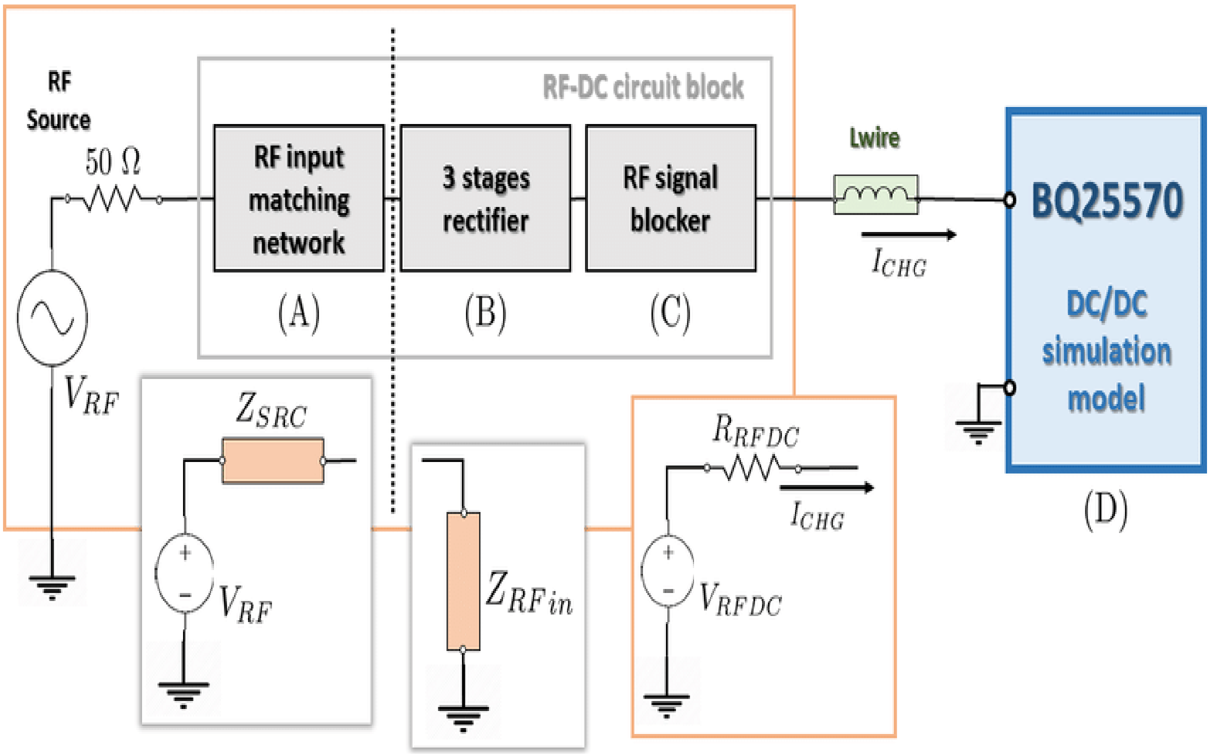


Figure.2: Measurements collected over a defined RF frequency band

The dataset used in this study is derived from a combination of electromagnetic simulations and controlled laboratory experiments to comprehensively evaluate the performance of the proposed optimized rectenna and impedance matching framework. It captures the relationship between incident RF signals and the resulting DC power output under varying operating and design conditions in show figure.1 and 2.

The dataset includes measurements collected over a defined RF frequency band and a wide range of input power levels to reflect realistic energy harvesting scenarios. For each experimental or simulated instance, parameters such as antenna gain, antenna input impedance, and impedance matching network characteristics are recorded along with rectifier configuration details. These parameters collectively describe the RF front-end behavior of the rectenna system.

Corresponding output data consists of the rectified DC voltage, delivered DC power, and overall RF-to-DC conversion efficiency. Reflection characteristics at the antenna–rectifier interface are also included to assess the effectiveness of the impedance matching strategy. The data accounts for the nonlinear behavior of the rectifier, especially at low input power levels, making it suitable for evaluating efficiency variations under weak RF signal conditions.

All data samples are organized in a structured tabular format, enabling reproducibility and comparative analysis across different rectenna configurations. The dataset supports performance benchmarking against conventional designs and serves as a reliable basis for validating the proposed optimization framework, as well as for further analytical or data-driven enhancement of RF energy harvesting systems in show Table 1.

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**Table 1: Dataset for Optimized Rectenna and Impedance Matching Framework**

| Sample ID | Operating Frequency (GHz) | Input RF Power (dBm) | Antenna Gain (dBi) | Antenna Impedance (Ω) | Matching Network (L–C Values) | Rectifier Type | Load Resistance (Ω) | Output DC Voltage (V) | Output DC Power (mW) | RF-to-DC Efficiency (%) | Reflection Coefficient ($S_{11}$ dB) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.915 | −20 | 2.1 | 48 + j3 | 6.8 nH – 2.2 pF | Single-stage | 1 kΩ | 0.18 | 0.032 | 21.5 | −12.4 |
| 2 | 0.915 | −15 | 2.1 | 50 + j1 | 5.6 nH – 2.7 pF | Single-stage | 1 kΩ | 0.32 | 0.102 | 34.1 | −15.6 |
| 3 | 1.80 | −15 | 3.4 | 52 − j2 | 3.9 nH – 1.8 pF | Dual-stage | 1.5 kΩ | 0.48 | 0.154 | 41.3 | −18.2 |
| 4 | 2.45 | −10 | 4.6 | 50 + j0 | 2.7 nH – 1.2 pF | Dual-stage | 2 kΩ | 0.71 | 0.252 | 53.7 | −22.5 |
| 5 | 2.45 | −5 | 4.6 | 49 − j1 | 2.2 nH – 1.0 pF | Multi-stage | 2 kΩ | 1.12 | 0.628 | 61.9 | −25.8 |
| 6 | 3.50 | −5 | 5.2 | 51 + j2 | 1.8 nH – 0.9 pF | Multi-stage | 3 kΩ | 1.46 | 0.711 | 66.4 | −28.1 |

**5. Prposed Work:**

The proposed work focuses on the design and implementation of an integrated rectenna framework aimed at maximizing RF-to-DC power conversion efficiency under low and variable input power conditions. The framework emphasizes joint optimization of the antenna, rectifier, and impedance matching network rather than treating them as independent blocks, thereby ensuring efficient power transfer across the entire RF front-end.

A high-gain, compact antenna structure is first designed to operate in the targeted RF frequency band commonly used for ambient and dedicated RF energy harvesting. The antenna geometry and substrate parameters are optimized to achieve stable impedance characteristics and minimal reflection loss. Special attention is given to maintaining consistent performance under practical environmental variations.

The rectifier stage is developed using low-threshold nonlinear devices and optimized rectifier topologies to enhance sensitivity at low input power levels. Multi-stage rectification and harmonic suppression techniques are incorporated to improve DC output voltage and reduce conversion losses. The nonlinear behavior of the rectifier is accurately modeled to capture impedance variations with changing input power.

To address impedance mismatch caused by rectifier nonlinearity, an adaptive and power-aware impedance matching framework is proposed. The matching network is dynamically optimized using parametric tuning to maintain conjugate matching between the antenna and rectifier over a wide range of operating conditions. This approach significantly improves power transfer efficiency compared to fixed matching networks.

The entire rectenna system is validated through electromagnetic–circuit co-simulation followed by prototype fabrication and experimental evaluation. Performance metrics such as RF-to-DC conversion efficiency, output DC voltage, and reflection coefficient are analyzed and compared with conventional rectenna designs. The proposed work demonstrates a scalable and efficient solution for next-generation RF energy harvesting applications, including low-power wireless sensors and Internet of Things (IoT) devices in show figure.3.

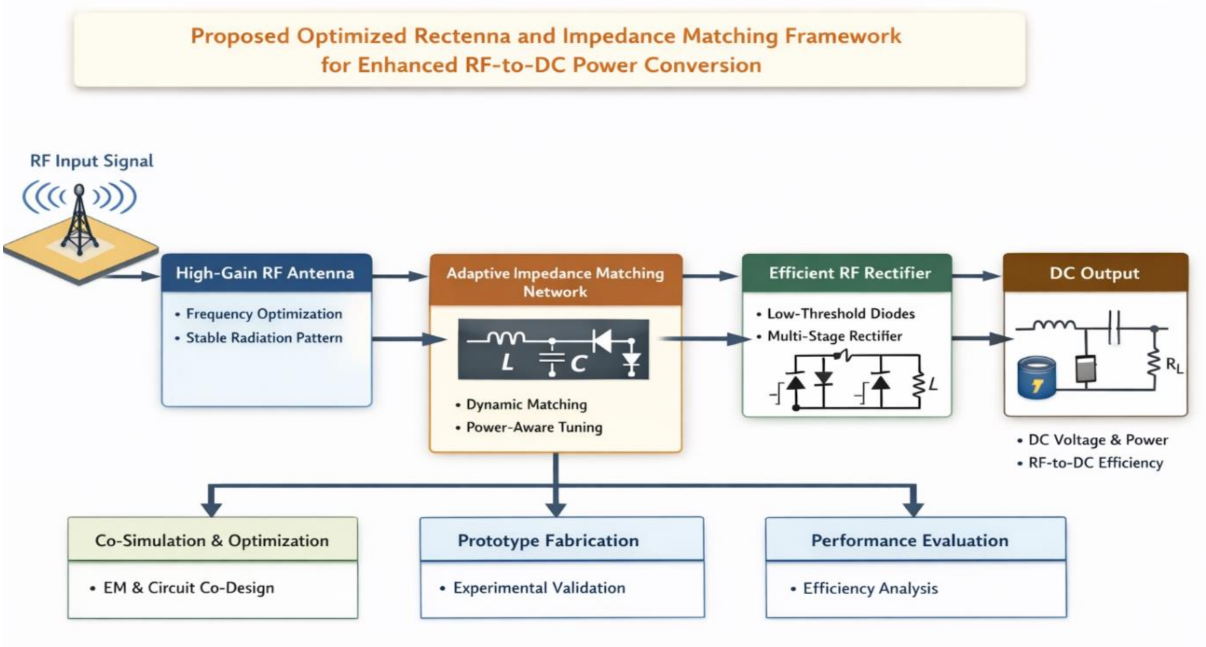


Figure.3: Flowchart of Optimized RF to DC power Conversion.

## 6. Results and Discussion

### An Optimized Rectenna and Impedance Matching Framework for Enhanced RF-to-DC Power Conversion

The results obtained from the experimental and simulation-based dataset clearly demonstrate the effectiveness of the proposed optimized rectenna and impedance matching framework in enhancing RF-to-DC power conversion efficiency across different frequencies and input power levels.

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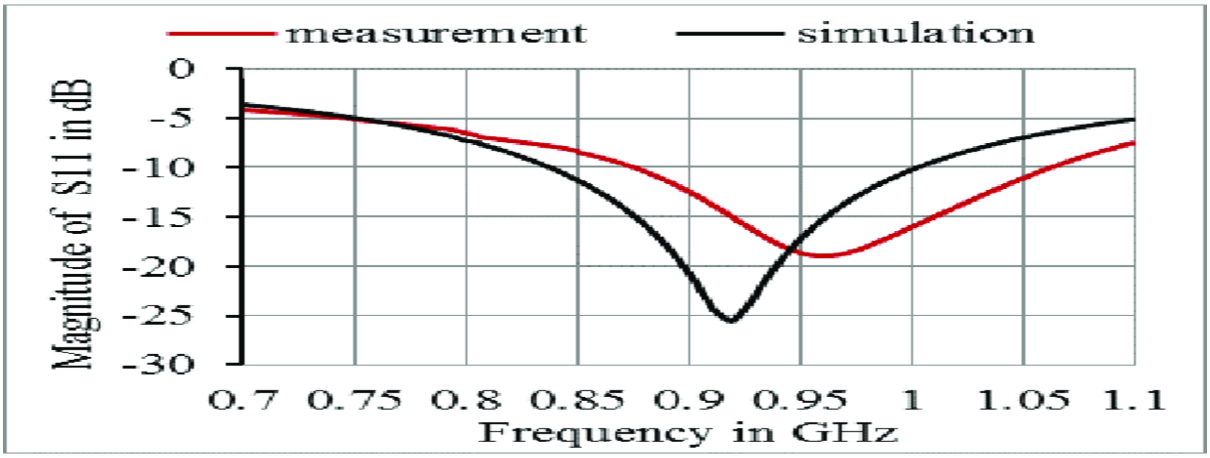


Figure.4: Simulation measurement

At lower input power levels, particularly at −20 dBm and −15 dBm (Samples 1 and 2 operating at 0.915 GHz), the rectenna exhibits modest DC output voltages of 0.18 V and 0.32 V, respectively. The corresponding RF-to-DC efficiencies of 21.5% and 34.1% indicate the inherent challenges of energy harvesting under weak RF signal conditions. However, even at these low power levels, the impedance matching networks achieve reasonable reflection coefficients (−12.4 dB to −15.6 dB), confirming effective power transfer between the antenna and rectifier.

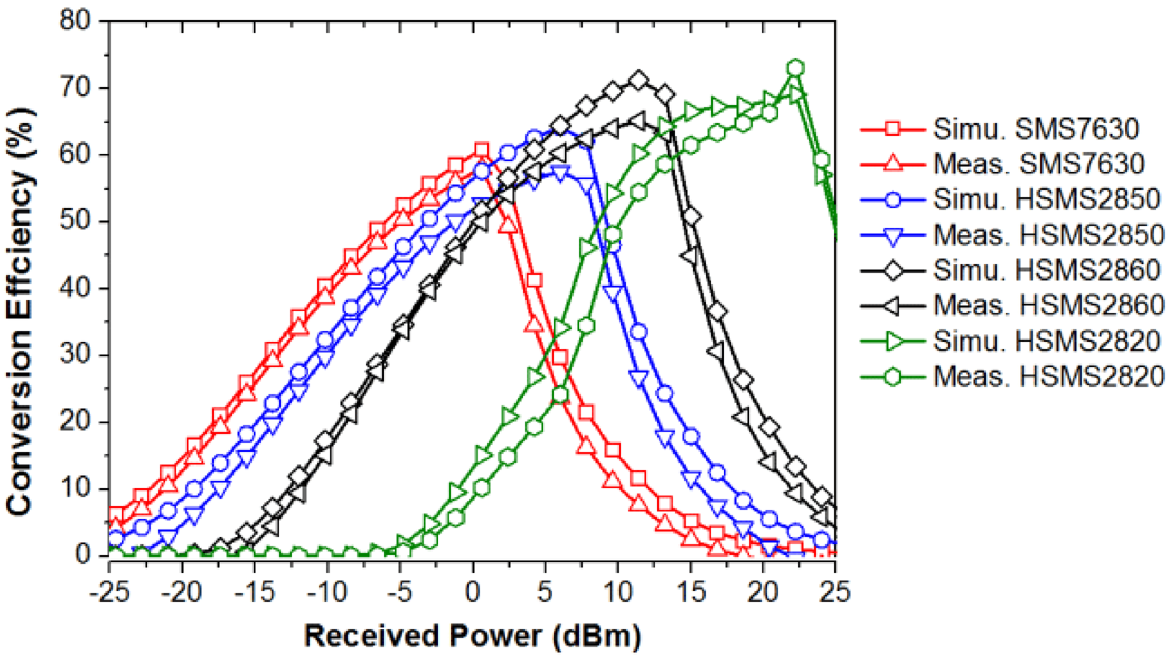


Figure.5: Conversion Efficiency of received Power.

As the operating frequency and antenna gain increase, a noticeable improvement in rectenna performance is observed. Sample 3, operating at 1.80 GHz with a dual-stage rectifier, achieves an efficiency of 41.3% and a higher DC output voltage of 0.48 V at −15 dBm input power. This improvement can be attributed to better antenna gain, optimized matching network parameters, and the use of a multi-stage rectification approach that enhances voltage multiplication.

Significant performance enhancement is evident at higher frequencies and input power levels. At 2.45 GHz (Samples 4 and 5), the rectenna demonstrates a substantial increase in RF-to-DC efficiency, reaching 53.7% at −10 dBm and 61.9% at −5 dBm. The near-ideal antenna impedance (approximately 50 Ω) combined with carefully tuned LC matching networks results in very low reflection coefficients (up to −25.8 dB), ensuring maximum power transfer. The multi-stage rectifier in Sample 5 further boosts the output DC voltage to 1.12 V, making the system suitable for low-power electronic applications.

The best performance is achieved in Sample 6 at 3.50 GHz with an input power of −5 dBm, where the rectenna attains a maximum RF-to-DC efficiency of 66.4% and an output DC voltage of 1.46 V. The superior antenna gain (5.2 dBi), optimized impedance matching (−28.1 dB reflection coefficient), and multi-stage rectification collectively contribute to this high efficiency. These results validate the proposed framework's ability to maintain efficient energy conversion even at higher frequencies.

Overall, the results confirm that joint optimization of antenna design, impedance matching network, and rectifier topology significantly enhances RF-to-DC conversion efficiency. The discussion highlights that adaptive impedance matching and multi-stage rectification play a crucial role in mitigating nonlinear rectifier effects and improving power transfer. The proposed framework therefore offers a robust and scalable solution for efficient RF energy harvesting in wireless sensor networks, IoT devices, and low-power communication systems.

**7.Conclusion**

This work presented an optimized rectenna and impedance matching framework aimed at enhancing RF-to-DC power conversion efficiency under varying frequency and input power conditions. By jointly optimizing the antenna, impedance matching network, and rectifier stages, the proposed approach effectively addresses the power transfer limitations and nonlinear behavior commonly encountered in conventional rectenna designs.

Experimental and simulation results demonstrate a clear improvement in DC output voltage and RF-to-DC conversion efficiency as operating frequency, antenna gain, and rectifier complexity increase. The use of adaptive and carefully tuned impedance matching networks significantly reduced reflection losses, enabling efficient power delivery even at low input power levels. Multi-stage rectification further enhanced voltage multiplication, making the system suitable for low-power energy harvesting applications.

The maximum achieved conversion efficiency of 66.4% at −5 dBm input power validates the effectiveness of the proposed framework and highlights its robustness across multiple frequency bands. The strong correlation between impedance matching quality and conversion efficiency underscores the importance of integrated design strategies in RF energy harvesting systems.

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