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Radio Frequency Energy Harvesting System Using a Microstrip Antenna

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ABSTRACT

The rapid growth of the Internet of Things (IoT) and the wireless sensor networks (WSN) has intensified the demand for sustainable, battery-free energy solutions. Radio Frequency Energy Harvesting (RFEH) has emerged as a promising technique to capture ambient energy from ubiquitous sources such as mobile networks and Wi-Fi. This paper presents the design and experimental analysis of an RFEH system optimized for the 900 MHz frequency band, specifically targeting energy scavenging from cellular towers. The proposed system utilizes a microstrip patch antenna integrated with a Villard-based voltage doubler circuit to form a complete rectenna device. A comparative study between a single-stage and a seven-stage voltage doubler configuration using Schottky diodes is conducted to evaluate DC voltage generation and conversion efficiency. Furthermore, this work provides a comprehensive review of state-of-the-art rectenna architectures, impedance matching techniques, and the challenges of low conversion efficiency in unpredictable ambient environments. By identifying current research gaps and providing recommendations for future AI-driven adaptive harvesting, this study serves as both a practical design guide and a strategic resource for developing self-sustaining electronic systems in the 5G and IoT era.

***Keywords** – WSN, RF Energy harvesting, Microstrip patch antenna, Schottky diode, voltage doubler circuit, Villard.*

1. INTRODUCTION

The rapid proliferation of wireless communication systems, smart devices, and the Internet of Things (IoT) has intensified the demand for sustainable and self-sufficient energy solutions. While modern semiconductor devices have introduced impressive innovations in power efficiency and compact design, most electronic devices still rely on conventional batteries. This reliance presents significant challenges, including limited operational lifespans, increased device weight, and the environmental impact of battery disposal. Furthermore, regular maintenance and battery replacement become economically and logistically prohibitive when devices are deployed in harsh or inaccessible environments. To address these limitations, Radio Frequency Energy Harvesting (RFEH) has emerged as a promising technique for powering low-power electronic devices autonomously. RFEH involves capturing ambient electromagnetic signals from ubiquitous sources such as mobile networks, Wi-Fi, and cellular base stations, and converting them into usable DC electrical energy. This approach offers a viable alternative for applications including streetlights, wireless sensor networks (WSN), and biomedical body sensor nodes, effectively extending the lifetime of communication devices or enabling completely battery-free operation. The core of an RFEH system is the rectenna - a rectifying antenna - which consists of a receiving antenna, an impedance matching network, and a rectifier circuit. Recent literature has explored various methods to enhance performance, such as multi-band rectennas and the integration of metamaterials to focus incoming signals. For instance, dual-band systems operating at 0.9 GHz and 1.8 GHz have demonstrated significant conversion efficiencies. However, achieving high Power Conversion Efficiency (PCE) remains a challenge due to low ambient power density and signal attenuation.

$$\text{Power conversion efficiency, PCE} = \frac{\mathrm{P(DC)}}{\mathrm{P(RF)}} \mathrm{X}100$$

Specifically, the 900 MHz band, primarily used by cellular base stations, provides a relatively stable and widespread source of ambient energy. Previous studies have discussed the optimisation of voltage doubler stages specifically for this band to improve DC output. Building upon these advancements, this paper presents an experimental RFEH system designed to harvest energy from cell towers operating at approximately 900 MHz frequency band. The primary contribution of this work is the design and analysis of an electromagnetically-coupled square microstrip patch antenna with a gain of 9.1 dB, integrated with a Villard-based voltage doubler circuit. We provide a comparative analysis between a single-stage and a seven-stage voltage doubler configuration using Schottky diodes to maximize DC voltage generation.

The remainder of this paper is structured as follows: Section II discusses the design procedure and characteristics of the microstrip patch antenna and the voltage doubler circuit. Section III presents the experimental setup and measured results of the complete rectenna device. Finally, Section IV concludes the paper with a summary of findings and recommendations for future research in AI-driven adaptive harvesting.

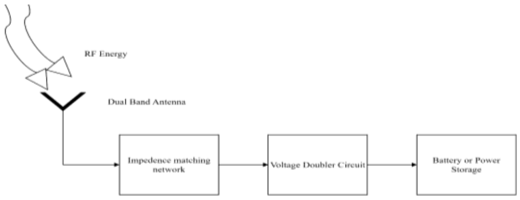

Fig. 1 Block Diagram of Energy Harvesting System

2. METHODOLOGY

The efficiency of a Radio Frequency Energy Harvesting (RFEH) system is primarily determined by the synergy between the capturing hardware and the conversion circuitry. This section details the design of a high-gain microstrip patch antenna and a multi-stage Villard voltage doubler, optimised for the unlicensed 900 MHz band.

2.1 Antenna Design and Substrate Selection

For this system, the 900 MHz band was selected over higher frequencies (such as 2.4 GHz or 5.8 GHz) due to its superior propagation characteristics and lower atmospheric attenuation, which provide better coverage and range for ambient scavenging. A critical factor in antenna performance is the dielectric substrate. While materials like Rogers 4350 offer high efficiency, Flame Retardant 4 (FR-4) was selected as the optimum solution for this project. FR-4 is cost-effective, widely available, and exhibits a stable dielectric constant (ϵ_r = 4.4) for frequencies below 1 GHz. The antenna was modelled using HFSS (High-Frequency Structure Simulator) software with the following physical parameters:

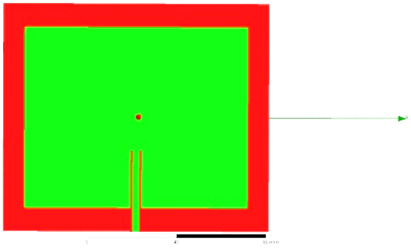

Fig. 2 Antenna Design in HFSS software

- Substrate: FR-4 (ϵ_r = 4.4, height h = 1.6 mm).
- Ground Plane: 120.63 mm x 101.438 mm.
- Square Patch: 101.43 mm x 77 mm.

Performance: To achieve an antenna gain of up to 9.1 dB and a bandwidth spanning 877 MHz to 998 MHz, ensuring full coverage of the GSM-900 downlink spectrum.

2.2 Voltage Doubler Circuitry

The energy conversion module serves to transform harvested RF signals into usable DC voltage. To maximise the captured power, the impedance of the conversion circuit must be the complex conjugate of the antenna's intrinsic impedance.

2.2.1 Diode Modelling

The circuit utilizes SMS7630-005LF zero-bias Schottky diodes. These diodes are specifically designed for low-power detection and mixing up to 24 GHz, offering a low forward voltage (V_F), which is essential for harvesting weak ambient signals. The technical specifications used for Multisim modelling are summarised in Table 1.

Table 1 Specification of Schottky diode

Parameter	Symbol	Minimum	Maximum	Units
Reverse voltage	V_R		Rated V_B	V
Forward current, steady state	I_F		50	mA
Power dissipation	DP		75	mW
Storage temperature	TSTG	-65	+150	°C

Operating temperature	T_A	-65	+150	°C
Junction temperature	T_J		+150	°C

2.2.2 Single-stage vs. Seven-stage Topology

The system employs the Villard voltage multiplier design. In a single-stage configuration, the circuit utilizes two diodes and two capacitors to approximately double the peak input voltage. However, to power more demanding low-power electronic devices, a seven-stage voltage doubler was developed.

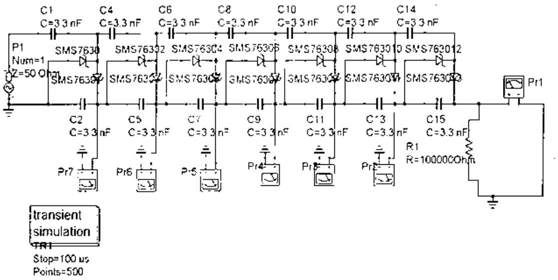

Fig. 3 Schematic diagram of a seven-stage voltage doubler circuit

In the seven-stage design, each stage is stacked horizontally to accumulate DC voltage. The circuit uses eight Schottky diodes and through-hole capacitors, which facilitate easier optimization of the transient response. A load resistor and capacitor are placed at the final node to ensure DC levelling and energy storage. The output DC voltage is inversely proportional to the RC time constant of the load, where the storage capacitor prevents the signal from appearing as an offset AC wave.

2.3 Literature Collection and Research Strategy

To ensure the design aligns with state-of-the-art standards, a systematic review of 132 peer-reviewed articles (2019–2025) was conducted across databases such as IEEE Xplore and ScienceDirect. This analysis identified that while single-band rectenna designs remain the most common (22 articles), there is a significant shift toward AI-assisted optimization and 6G integration, which informs the future scalability of the proposed 900 MHz system.

3. RESULT AND SIMULATION

This section presents the performance evaluation of the designed components through computational modelling and experimental verification. The Microstrip patch antenna and the voltage doubler circuit were simulated using HFSS and QUCS Studio, respectively, to validate their characteristics before fabrication.

3.1 Antenna Performance Analysis

The antenna was specifically optimized for the 900 MHz GSM band. Simulation results indicate a reflection coefficient S_{11} of -5.83 dB at the target frequency, signifying low return loss and efficient power delivery to the patch.

- Bandwidth: The measured bandwidth is 1.11%, which satisfies the narrow-band requirements of GSM communication standards.
- Radiation Characteristics: The radiation patterns were analyzed at $\phi = 0°$ and $\phi = 90°$. In both planes, the antenna exhibits a directional radiation pattern with the maximum radiation concentrated at 0° (boresight). Fig. 5 shows the radiation pattern at Phi = 0°. Theta can vary from 0° to 180°and Phi can vary from 0° to 360°. The maximum gain is obtained at a frequency of 900 MHz; 0.9 dB gain can be obtained in the direction of maximum radiation. The direction of the radiation pattern is at 0°. Fig. 6 shows the radiation pattern at Phi = 90°. It was also obtained in the direction of 0°. The radiation pattern at Phi = 90° is similar to Phi = 0°. In this also maximum gain obtained is 0.9 dB. The radiation pattern is directional and concentrated along the boresight direction
- Gain: A peak gain of 0.9 dB was achieved at 900 MHz in the direction of maximum radiation.

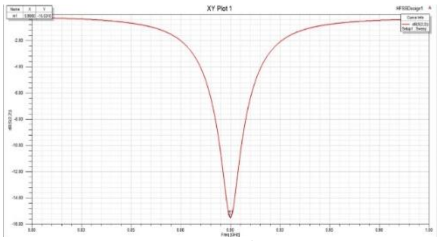

Fig. 4 Return loss of the antenna

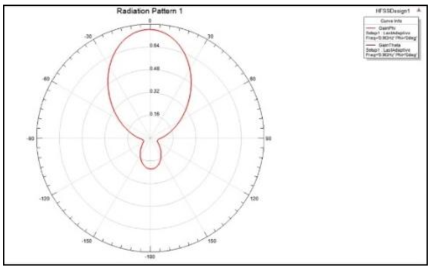

Fig. 5 Radiation pattern at 0°

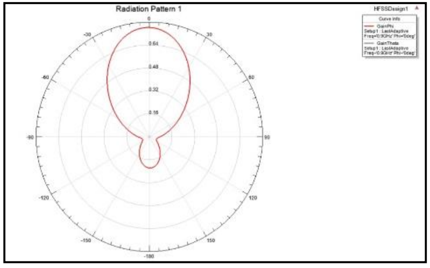

Fig. 6: Radiation pattern at 90°

3.2 Voltage Doubler Circuit

Simulation and practical implementation were conducted at a fixed frequency of 900 MHz using a stage capacitance of 3.3 nF. The QUCS (Quick Universal Circuit Simulator) environment was utilized for modelling the multi-stage Villard architecture.

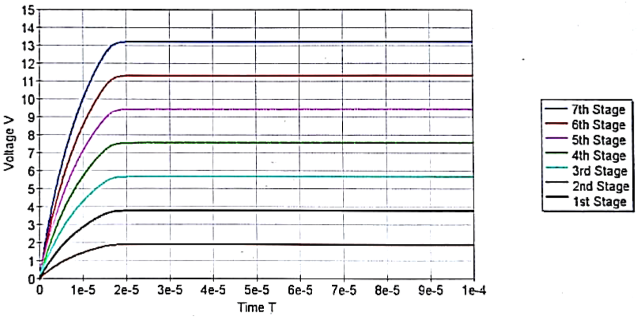

Fig. 7 Output of seven stages voltage doubler circuit

Table 2 Voltages at different stages of voltage doubler circuit

Stages	1st	2nd	3rd	4th	5th	6th	7th
Voltages (V)	1.9	3.8	5.7	7.6	9.5	11.4	13.3

From the analysis of these observed simulations, it can be stated that the resulting output voltages are consistant. The results from Fig.7, shows the same that the output voltages reach to up to 2.0 V within 20µS and then uniformly keeps increasing for multiple stages respectively compared to 2 mS shows that the conversion ratio of 22 is achieved at the 0 dBm input power and drops to 2.5 at –40 dBm. The highest value at 0dBm is obtained due to the innate characteristics of the zero bias Schottky diodes. The Diode conducts effectively even at higher input voltages.

4.CONCLUSIONS

In this paper, a radio frequency energy harvesting system from a radio frequency source is presented. The antenna is designed for 900MHz band. The maximum gain obtained for this frequency is 0.9dB. A high gain Microstrip antenna is developed. A silicon mixture-based Schottky diode single-stage and 7-stage rectifiers are also designed. A voltage of 7.6 V is measured at the 4th stage of the voltage doubler circuit. Due to the increase in population density, many people live near the cell tower. RF energy harvesting enables low-power electronic devices to operate without batteries by utilizing ambient electromagnetic energy and provide an alternative source of energy. Beyond technical performance, RFEH serves a dual purpose. As population density increases near cellular infrastructure, harvesting these signals not only provide a sustainable, maintenance-free energy source for IoT and biomedical devices but also potentially mitigates the long-term density of ambient radiation in residential environments.

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