

HIGH GAIN ANTENNA DESIGN OF A RECTENNA SYSTEM FOR RF ENERGY HARVESTING IN SMART CITY APPLICATIONS

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Abstract—The rapid expansion of smart city infrastructure and wireless communication technologies has created a growing demand for sustainable, maintenance-free energy sources. In this context, Radio Frequency (RF) energy harvesting has emerged as a promising solution for powering low-power electronic devices by utilizing ambient electromagnetic signals available in the environment. This paper presents the design and analysis of a high-gain antenna integrated rectenna system for efficient RF energy harvesting in smart city applications. The proposed system consists of a microstrip antenna designed for multi-band operation, an impedance matching network to ensure maximum power transfer, and a rectifier circuit for converting RF signals into usable DC power. The antenna is optimized to achieve high gain and improved radiation characteristics, enabling effective capture of low-intensity RF signals from sources such as cellular networks, Wi-Fi, and broadcasting systems. To enhance system performance, key parameters such as antenna geometry, substrate material, operating frequency, and rectifier efficiency are carefully analyzed and optimized. Simulation results demonstrate improved gain, bandwidth, and power conversion efficiency, making the system capable of harvesting energy even under low ambient RF conditions.

Keywords— RF Energy Harvesting, Rectenna System, High-Gain Antenna, Microstrip Antenna,

Smart City Applications, Wireless Power Transmission, Impedance Matching Network, RF-to-DC Conversion, Power Conversion Efficiency (PCE), Ambient RF Signals, Internet of Things (IoT), Sustainable Energy Systems.

I. INTRODUCTION

The rapid growth of urbanization and the emergence of smart city technologies have significantly increased the demand for energy-efficient and sustainable power solutions. Modern smart cities rely heavily on wireless sensor networks, Internet of Things (IoT) devices, and distributed monitoring systems, all of which require continuous and reliable power sources. Traditional battery-based systems present limitations such as finite lifespan, maintenance challenges, and environmental concerns due to frequent replacement and disposal. Therefore, there is a critical need for alternative energy solutions that are both sustainable and maintenance-free.

In recent years, Radio Frequency (RF) energy harvesting has gained considerable attention as a promising technique for generating electrical power from ambient electromagnetic signals. These RF signals are abundantly available in urban environments due to the widespread deployment of communication systems such as cellular networks, Wi-Fi routers, television broadcasting, and radio

transmitters. Unlike other renewable energy sources such as solar or wind, RF energy is continuously available both indoors and outdoors, making it a reliable source for low-power applications.

A rectifying antenna, commonly known as a rectenna, plays a crucial role in RF energy harvesting systems. It combines an antenna for capturing RF signals and a rectifier circuit for converting these signals into usable direct current (DC) power. A typical rectenna system consists of three main components: a receiving antenna, an impedance matching network, and an RF-to-DC conversion circuit. The efficiency of the overall system largely depends on the design and optimization of these components.

Among these components, the antenna design is particularly important, as it determines the amount of RF energy that can be captured from the environment. High-gain antennas are preferred in RF energy harvesting systems because they can collect more energy from distant and weak RF sources. Additionally, designing antennas capable of operating over multiple frequency bands enhances the ability to harvest energy from diverse sources such as GSM, Wi-Fi, and other communication systems. However, achieving high gain, wide bandwidth, and compact size simultaneously remains a significant design challenge.

Another critical aspect of rectenna design is impedance matching, which ensures maximum power transfer between the antenna and the rectifier circuit. Poor impedance matching can lead to significant power losses, reducing the overall efficiency of the system. Furthermore, the rectifier circuit must be designed to operate efficiently at low input power levels, as ambient RF signals typically have very low power densities.

This paper focuses on the design and development of a high-gain antenna-based rectenna system for RF energy harvesting in smart city applications. The proposed system aims to improve energy capture efficiency by optimizing antenna parameters, enhancing impedance matching, and designing an efficient rectifier circuit. Simulation and analysis are performed to evaluate key

performance metrics such as gain, return loss, bandwidth, and power conversion efficiency.

II. REVIEW LITERATURE SURVEY

Radio Frequency (RF) energy harvesting has emerged as a promising research area due to the growing demand for sustainable and maintenance-free power sources for low-power electronic devices, particularly in smart city environments. With the rapid proliferation of wireless communication technologies such as cellular networks, Wi-Fi, radio broadcasting, and satellite systems, a significant amount of electromagnetic energy is continuously available in the ambient environment. This ambient RF energy can be captured and converted into usable electrical power using rectenna systems, which combine an antenna for signal reception and a rectifier for RF-to-DC conversion. The concept of wireless power transmission dates back to the early work of Nikola Tesla, and over time, advancements in microwave engineering, antenna design, and semiconductor devices have enabled the practical realization of RF energy harvesting systems.

Several studies have explored different techniques for RF energy harvesting, focusing primarily on improving power conversion efficiency and system sensitivity under low input power conditions. Unlike conventional energy sources such as solar and wind, RF energy is available continuously, both indoors and outdoors, making it highly suitable for powering low-power devices such as wireless sensors and IoT nodes. However, one of the major challenges in RF energy harvesting is the extremely low power density of ambient RF signals, which significantly limits the amount of energy that can be harvested. To address this issue, researchers have proposed various circuit-level and system-level optimizations, including the use of voltage multipliers, multi-stage rectifiers, and energy

storage elements such as capacitors to stabilize the output power.

A key component of any RF energy harvesting system is the antenna, which is responsible for capturing electromagnetic signals from the environment. Extensive research has been conducted on different antenna structures, including dipole, monopole, microstrip (patch), slot, and fractal antennas. Among these, microstrip antennas are widely preferred due to their compact size, lightweight structure, low fabrication cost, and ease of integration with rectifier circuits. Recent developments have focused on designing high-gain, multiband, and wideband antennas to enhance the ability to capture energy from multiple RF sources such as GSM, Wi-Fi, and LTE bands. High-gain antennas are particularly important in improving the received power from distant or weak RF sources, thereby increasing the overall efficiency of the rectenna system.

Another critical aspect of rectenna design is the impedance matching network, which ensures maximum power transfer between the antenna and the rectifier circuit. Since the impedance of the antenna and rectifier are often different and vary with frequency and input power, improper matching can lead to significant reflection losses and reduced system efficiency. Various matching techniques such as L-section matching, π -networks, and stub matching have been widely studied and implemented to optimize performance. In addition, adaptive and tunable matching networks have been proposed to improve efficiency under varying environmental conditions.

The rectifier circuit plays a vital role in converting the captured RF signals into DC power. Most rectifier designs utilize Schottky diodes due to their low forward voltage drop, fast switching speed, and suitability for high-frequency applications. Researchers have developed different rectifier topologies, including single-diode rectifiers, voltage doublers, and multi-stage rectifiers, to improve RF-to-DC conversion efficiency. Multi-stage rectifiers, in

particular, are effective in boosting output voltage under low input power conditions, although they may introduce additional losses and complexity. Recent advancements have also explored the use of CMOS-based rectifiers and novel semiconductor materials to enhance efficiency and sensitivity.

Furthermore, various rectenna configurations such as single-band, dual-band, multiband, and broadband systems have been investigated to maximize energy harvesting capability. Single-band rectennas are simpler and more efficient at a specific frequency but are limited in capturing energy from multiple sources. In contrast, multiband and broadband rectennas can harvest energy from a wider frequency spectrum, increasing the total harvested power, although often at the cost of reduced efficiency at individual frequencies. Researchers have also explored rectenna arrays and metasurface-based designs to further enhance gain and power capture capability.

Despite significant progress in this field, several challenges remain in achieving efficient RF energy harvesting under practical conditions. The low and unpredictable nature of ambient RF signals, impedance mismatch due to non-linear rectifier behavior, and efficiency degradation at low input power levels are key issues that need to be addressed. Additionally, there is a trade-off between antenna size, gain, bandwidth, and system efficiency, which makes the design process complex. Therefore, ongoing research is focused on developing high-gain, compact, and multi-band rectenna systems with improved power conversion efficiency and sensitivity.

III. RESEARCH METHODOLOGY

The proposed research focuses on the design and development of a high-gain rectenna system for efficient RF energy harvesting in smart city applications. The methodology follows a systematic approach that integrates antenna design, impedance matching, and rectifier circuit development to achieve optimal performance

under low ambient RF power conditions. The first step involves identifying suitable RF energy sources available in the environment, such as GSM, Wi-Fi, and other wireless communication bands typically ranging from 800 MHz to 2.5 GHz. These frequency bands are selected due to their continuous availability and widespread presence in urban areas, making them ideal for energy harvesting applications.

The next stage focuses on the design of a high-gain microstrip antenna capable of operating over multiple frequency bands. The antenna is designed using appropriate substrate materials and optimized dimensions to achieve desirable parameters such as high gain, low return loss, wide bandwidth, and acceptable Voltage Standing Wave Ratio (VSWR). Special attention is given to antenna geometry and feeding techniques to enhance radiation efficiency and ensure effective capture of weak ambient RF signals. Simulation tools such as HFSS or CST are employed to model and analyze the antenna performance, allowing iterative optimization of design parameters.

Following the antenna design, an impedance matching network is developed to ensure maximum power transfer between the antenna and the rectifier circuit. Since the impedance of the antenna and rectifier may differ significantly and vary with frequency, matching techniques such as L-section or stub matching are used to minimize reflection losses. Proper impedance matching is critical in improving the overall efficiency of the rectenna system, especially under low input power conditions.

The rectifier circuit is then designed to convert the captured RF signals into usable DC power. A Schottky diode-based rectifier is selected due to its low threshold voltage and high switching speed, which are essential for efficient operation at low power levels. To enhance output voltage and conversion efficiency, multi-stage rectifier configurations or voltage doubler circuits may be implemented. The rectifier design is simulated and optimized to achieve maximum RF-to-DC

conversion efficiency across the selected frequency bands.

Finally, the complete rectenna system is integrated and evaluated through simulation and performance analysis. Key parameters such as antenna gain, return loss, bandwidth, output voltage, and power conversion efficiency are analyzed to assess system effectiveness. The results are compared and optimized to ensure reliable operation in real-world smart city environments where RF power levels are typically low and variable.

This structured methodology ensures a comprehensive design approach that addresses the key challenges of RF energy harvesting and enables the development of an efficient, compact, and sustainable rectenna system for modern wireless applications.

IV. EXISTING SYSTEM

Existing RF energy harvesting systems are primarily based on conventional rectenna architectures that consist of a basic antenna, an impedance matching network, and a rectifier circuit designed to convert RF signals into DC power. These systems typically utilize single-band or narrowband antennas that operate at specific frequencies such as GSM, Wi-Fi, or ISM bands. While such designs are relatively simple and cost-effective, they are limited in their ability to capture energy from multiple RF sources simultaneously, resulting in low overall harvested power.

Most of the existing systems employ low-gain antennas, which restrict their capability to receive weak ambient RF signals, especially in environments where the power density is extremely low. Additionally, the impedance matching networks used in traditional rectenna designs are often optimized for fixed conditions and specific input power levels. This leads to inefficient power transfer when operating under varying environmental conditions, causing significant

energy losses. Furthermore, conventional rectifier circuits, although widely implemented using Schottky diodes, exhibit reduced efficiency at low input power levels due to threshold voltage limitations and non-linear characteristics.

Another limitation of existing systems is their poor performance in real-world ambient environments. Many designs are optimized under controlled laboratory conditions with relatively higher input power levels, which are not representative of actual urban scenarios where RF signals are weak and unpredictable. As a result, the overall power conversion efficiency of these systems drops significantly in practical applications. In addition, single-stage rectifiers and basic circuit configurations often fail to generate sufficient output voltage required to power even low-energy devices.

Moreover, existing rectenna systems face challenges such as impedance mismatch, narrow bandwidth, limited sensitivity, and inefficient energy conversion. These issues hinder their ability to provide a reliable and continuous power supply for smart city applications, where multiple low-power devices operate simultaneously. Therefore, there is a need for improved rectenna designs that incorporate high-gain, multi-band antennas, efficient matching networks, and optimized rectifier circuits to enhance overall system performance.

V. PROPOSED METHODOLOGY

The proposed methodology aims to design and develop a high-gain, multi-band rectenna system capable of efficiently harvesting ambient RF energy for smart city applications. Unlike conventional systems, the proposed approach focuses on improving energy capture, power transfer efficiency, and RF-to-DC conversion under low input power conditions typically found in real environments. The system integrates three major components: a high-gain microstrip antenna, an

optimized impedance matching network, and a high-efficiency rectifier circuit.

Initially, a multi-band microstrip antenna is designed to operate across commonly available RF frequency bands such as GSM, Wi-Fi, and LTE, which typically lie between 800 MHz and 2.5 GHz. The antenna geometry is carefully optimized to achieve high gain, improved radiation efficiency, and wider bandwidth, enabling it to capture RF energy from multiple sources simultaneously. Techniques such as slotting, defected ground structures, or antenna array configurations may be incorporated to enhance gain and directivity without significantly increasing the antenna size.

To ensure maximum power transfer from the antenna to the rectifier, an efficient impedance matching network is designed. Since the rectifier input impedance varies with frequency and input power levels, matching techniques such as L-section matching or stub-based networks are employed to minimize reflection losses and improve overall system efficiency. The matching network is optimized through simulation to maintain consistent performance across multiple frequency bands.

The rectifier circuit is designed using a Schottky diode due to its low forward voltage drop and high switching speed, which are essential for low-power operation. A multi-stage voltage doubler or charge pump configuration is implemented to boost the output DC voltage, making it suitable for powering low-power electronic devices. The rectifier is optimized to achieve high RF-to-DC conversion efficiency even at very low input power levels, which is a critical requirement for ambient energy harvesting systems.

The entire rectenna system is modeled and simulated using electromagnetic and circuit simulation tools such as HFSS and ADS to evaluate key performance parameters, including return loss, VSWR, gain, output voltage, and power conversion efficiency. Iterative optimization is carried out to achieve the best possible performance under

practical conditions. The final design aims to provide a compact, cost-effective, and efficient solution for powering IoT devices, wireless sensors, and other low-power electronics in smart city environments.

VI. BLOCK DIAGRAM

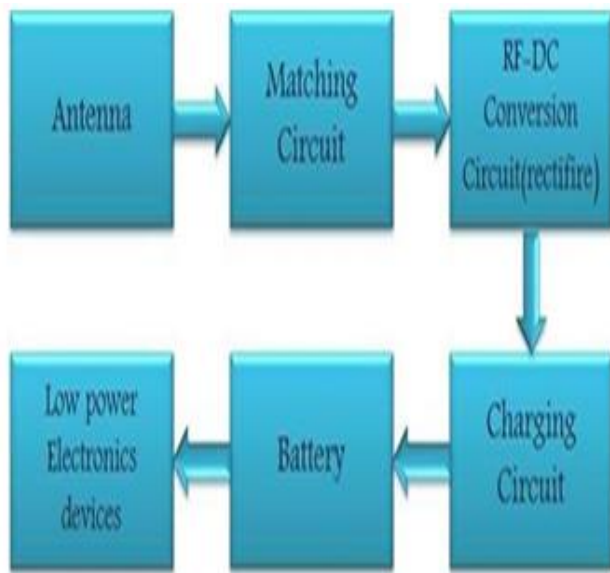


Fig. 6.2. Block Diagram

VII. RESULTS AND OUTCOMES

The performance of the proposed high-gain rectenna system was evaluated through simulation and analytical methods to determine its effectiveness in harvesting ambient RF energy for smart city applications. The designed microstrip antenna demonstrated improved characteristics in terms of gain, bandwidth, and radiation efficiency. The antenna exhibited a significant reduction in return loss (S11), indicating better impedance matching and efficient signal reception across the targeted frequency bands. Additionally, the Voltage Standing Wave Ratio (VSWR) remained within acceptable limits, confirming minimal signal reflection and improved transmission efficiency.

The integration of the optimized impedance matching network further enhanced the overall system performance by ensuring maximum power transfer between the antenna and the rectifier circuit. As a result, the losses due to impedance mismatch were minimized, leading to improved energy harvesting capability. The rectifier circuit, designed using a Schottky diode and multi-stage configuration, successfully converted the captured RF signals into usable DC power. The output voltage showed a noticeable increase compared to conventional single-stage rectifiers, demonstrating the effectiveness of the voltage boosting technique.

Simulation results indicated that the proposed system is capable of harvesting low-level ambient RF signals and converting them into a stable DC output suitable for powering low-power electronic devices. The overall power conversion efficiency (PCE) of the system was improved due to the combined effect of high antenna gain, efficient matching, and optimized rectifier design. The system also showed reliable performance across multiple frequency bands, confirming its suitability for real-world environments where RF signals are distributed over a wide spectrum.

Furthermore, the results highlight that the proposed rectenna system can operate effectively under varying environmental conditions, making it a practical solution for smart city applications such as wireless sensor networks, IoT devices, and remote monitoring systems. The ability to harvest energy from freely available RF sources reduces dependency on conventional batteries, thereby contributing to eco-friendly and sustainable energy solutions.

Overall, the outcomes of this work demonstrate that the proposed high-gain rectenna system offers enhanced efficiency, improved sensitivity, and reliable performance, making it a promising approach for next-generation RF energy harvesting applications.

VIII. CONCLUSION

In this work, a high-gain antenna-based rectenna system for RF energy harvesting in smart city applications has been successfully designed and analyzed. The study addressed the growing need for sustainable, maintenance-free power solutions for low-power electronic devices such as wireless sensors and IoT nodes. By utilizing ambient RF signals available from sources like cellular networks, Wi-Fi, and broadcasting systems, the proposed system demonstrates a practical approach toward energy-efficient and eco-friendly power generation.

The proposed rectenna system integrates a multi-band high-gain microstrip antenna, an optimized impedance matching network, and an efficient rectifier circuit. The antenna design plays a crucial role in enhancing the ability to capture weak RF signals by providing improved gain and wider bandwidth. The impedance matching network ensures maximum power transfer between the antenna and the rectifier, thereby minimizing losses and improving overall system efficiency. Furthermore, the use of a Schottky diode-based multi-stage rectifier enhances the RF-to-DC conversion efficiency, especially under low input power conditions typically found in real-world environments.

Simulation and analysis results confirm that the proposed system achieves better performance in terms of return loss, VSWR, gain, and output voltage compared to conventional rectenna designs. The system is capable of harvesting low-level ambient RF energy and converting it into usable DC power, which can be effectively used to power small electronic devices. The multi-band operation further improves the energy harvesting capability by enabling the system to capture signals from multiple RF sources simultaneously.

One of the key contributions of this work is the improvement in power conversion efficiency

through the combined optimization of antenna design, matching network, and rectifier circuit. The proposed system overcomes several limitations of existing designs, such as low gain, narrow bandwidth, and poor efficiency at low power levels. Additionally, the compact structure and low-cost implementation make it suitable for large-scale deployment in smart city environments.

In conclusion, the developed high-gain rectenna system presents a promising solution for future energy harvesting applications by reducing dependency on conventional batteries and supporting the development of self-powered electronic systems. This work contributes to the advancement of green energy technologies and aligns with the vision of sustainable and intelligent urban infrastructure.

Future work can focus on further enhancing system performance by implementing rectenna arrays, adaptive impedance matching techniques, and advanced materials such as metamaterials. Experimental validation, real-time deployment, and integration with energy storage systems can also be explored to improve practical applicability and scalability of the proposed system.

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