Artificial Intelligence-Based Optimization of Multiband Antennas for Smart Agriculture Applications Using LPWAN Communication

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Abstract—*This research introduces a compact, AI-optimized multiband antenna specifically designed for Smart Agriculture applications utilizing LPWAN protocols such as LoRa and Sigfox. Focusing on the 868 MHz band—critical for rural and remote IoT deployments—the antenna features a three-layer stacked patch structure to ensure robust multiband performance within a minimized footprint.*

Artificial Neural Networks (ANNs) and Genetic Algorithms (GAs) are employed to optimize the antenna design parameters intelligently. The ANN is trained on extensive parametric simulations to predict key electromagnetic characteristics, including return loss (S11) and resonant frequencies, while the GA efficiently converges on optimal geometries, significantly reducing simulation overhead.

Simulation results demonstrate enhanced performance, with return loss below −19 dB, radiation efficiency exceeding 82%, and tightly controlled bandwidth, ensuring reliable outdoor connectivity. Furthermore, the AI framework incorporates a power estimation model for early-stage VLSI circuits, enabling accurate prediction of energy consumption. This facilitates holistic co-design of antenna and digital subsystems, contributing to extended battery life and scalable sensor node deployment.

The proposed methodology supports the development of intelligent, energy-efficient wireless infrastructures for precision agriculture and environmental monitoring.

Keywords: *AI-driven multiband antenna design, AI, IOT, VLSI, Smart agriculture connectivity, LPWAN communication, LoRa technology, Neural network optimization, Genetic algorithm-based tuning, Energy-efficient wireless systems.*

1. INTRODUCTION

The agricultural sector is undergoing a digital revolution through the integration of cutting-edge technologies such as wireless sensor networks, artificial intelligence (AI), and Internet of Things (IoT) systems. This emerging paradigm, known as Smart Agriculture, seeks to enhance productivity, optimize resource utilization, and enable real-time decision-making in farming practices. Central to this transformation is the need for reliable, long-range, and low-power communication among sensor nodes distributed across expansive fields, greenhouses, and remote rural areas. Low Power Wide Area Network (LPWAN) technologies, particularly LoRa and Sigfox, have emerged as promising solutions for this purpose. Operating predominantly within unlicensed sub-GHz Industrial, Scientific, and Medical (ISM) bands—most notably the 868 MHz band in Europe—LPWAN protocols offer extended range, low data rate transmission, and minimal energy consumption. These characteristics facilitate the long-term operation of battery-powered devices without frequent maintenance, making them ideal for agricultural monitoring applications. The effectiveness of LPWAN systems largely depends on the antenna subsystem, which serves as the vital communication interface between sensor nodes and remote gateways. Antennas deployed in Smart Agriculture must be compact, cost-effective, and resilient to environmental factors such as rain, dust, and temperature fluctuations. Traditional antenna design approaches often involve repetitive simulations and empirical trials, which can be time-consuming and resource-intensive.

This research presents an innovative AI-enhanced antenna design approach focused on the 868 MHz band for Smart Agriculture. By harnessing the predictive power of Artificial Neural Networks (ANNs) alongside the optimization capabilities of Genetic Algorithms (GAs), the design cycle is significantly accelerated while performance is improved. The antenna employs a three-layer stacked patch structure to achieve high gain, wide bandwidth, and efficient radiation within a compact footprint.

Moreover, the study integrates an AI-driven model for early-stage VLSI power estimation, enabling co-optimization of the antenna and digital subsystems. This holistic design methodology ensures maximum system efficiency while minimizing power consumption, a critical factor for battery-operated agricultural IoT devices. The proposed solution is well-suited for diverse applications including soil condition monitoring, precision irrigation, livestock tracking, and crop health assessment. The following sections detail the modeling and optimization methodology using ANN and GA, assess performance gains through simulation, and present the VLSI power estimation framework to validate energy efficiency. The aim is to establish a comprehensive, scalable, and cost-effective design framework for reliable wireless communication in Smart Agriculture systems.

2. RELATED WORK

In recent years, the integration of multiband antenna design, artificial intelligence (AI)-based optimization techniques, and low-power VLSI modeling has attracted significant attention, particularly in the context of next-generation 5G and IoT systems. Despite these advances, their targeted application in Smart Agriculture—especially within the 868 MHz LPWAN spectrum—remains relatively underrepresented in current research. Foundational work by Balanis and Pozar established the key principles for microstrip patch antenna design, including strategies for enhancing bandwidth and achieving impedance matching. Building on this foundation, Sharma and Bhattacharya introduced multiband antenna configurations employing L-slots and stacked geometries to enable operation across multiple frequency bands. While these approaches have shown promise, they often depend on manual tuning or narrowly scoped parametric sweeps, making them less efficient for complex, high-dimensional design tasks.

The application of AI in RF design has shown notable potential. For instance, Rahman and Hossain highlighted the advantages of machine learning techniques for the rapid prediction of antenna parameters. Similarly, Ahmed et al. demonstrated that deep neural networks can reliably estimate performance indicators such as return loss and gain. However, these methods are often used in isolation and are rarely integrated into comprehensive optimization frameworks like Genetic Algorithms. Moreover, their deployment in practical domains such as LPWAN-based Smart Agriculture remains limited. In the domain of low-power VLSI design, Mostafa et al. introduced an artificial neural network-based power estimation model capable of predicting energy consumption at early design stages using logic-level parameters. This approach offers a substantial reduction in the need for time-consuming synthesis and aligns closely with the requirements of low-energy, battery-powered agricultural IoT devices.

Recent developments by Huang and collaborators have proposed co-optimization frameworks that leverage AI to simultaneously optimize antenna and baseband parameters for IoT systems. While these efforts are conceptually promising, they are typically generalized and do not address the specific needs of sub-GHz LPWAN applications in agriculture. This study addresses that gap by presenting a focused, AI-driven methodology that jointly optimizes multiband antenna performance and VLSI power efficiency for

Smart Agriculture, contributing a tailored and application-specific solution to this emerging interdisciplinary domain.

3. ANTENNA DESIGN METHODOLOGY

Designing an efficient multiband antenna for Smart Agriculture applications presents unique challenges, especially when aiming for long-range, low-power communication within compact sensor nodes. This work addresses those challenges by developing a stacked patch antenna architecture specifically tuned to the 868 MHz LPWAN band—widely used in protocols like LoRa and Sigfox—and optionally supporting 2.4 GHz to accommodate hybrid systems that integrate Wi-Fi or Bluetooth.

The antenna consists of three stacked dielectric layers, each carefully selected to optimize performance across specific frequency bands. The foundational layer, fabricated using the widely available FR-4 substrate ($\varepsilon r \approx 4.4$), is designed to support both 868 MHz and 2.4 GHz operations, offering a balance between cost, mechanical strength, and acceptable dielectric properties. For potential future extensions toward higher frequencies (such as 3.5 GHz or 5.8 GHz), the upper layers can be adapted to use low-loss materials like Rogers RT/Duroid 5880, though this study focuses on the LPWAN-relevant bands.

From a structural standpoint, the design features a central radiating patch augmented with L-shaped slots and parasitic stubs. These features are precisely dimensioned to generate multiple resonances while preserving the antenna's compact footprint. Slot lengths, patch widths, and stub geometries are determined using modified transmission line models and tuned to achieve optimal impedance matching, increased bandwidth, and high gain.

The antenna is fed through a coaxial probe attached to the bottom layer. This feeding method was chosen due to its effectiveness in achieving low return loss and stable impedance matching, especially for lower frequencies. Simulation adjustments to the feed position help to further minimize the reflection coefficient (S11). The form factor is optimized for easy integration onto sensor module PCBs, ensuring minimal vertical profile and system-level compatibility.

Electromagnetic simulations were conducted using ANSYS HFSS. The simulation setup included appropriate boundary conditions to simulate free-space radiation, adaptive meshing for accurate field resolution, and 50-ohm coaxial excitation. Key performance indicators such as return loss, VSWR, radiation pattern, bandwidth, gain, and efficiency were extracted to guide design decisions. To streamline the design process and eliminate the need for extensive trial-and-error simulations, an artificial intelligence-based approach was introduced. A predictive model was built using a feedforward artificial neural network (ANN), trained on a dataset of over 1000 simulation results. These simulations were generated by systematically varying key geometric parameters, including slot length, patch width, feed position, and stub configuration. For each variation, output metrics like resonant frequency and return loss were recorded.

The ANN architecture consisted of two hidden layers (64 and 32 neurons, respectively) using ReLU activation functions. With four normalized geometric inputs, the model successfully predicted resonant frequency and S11 with a high degree of accuracy ($R^2 = 0.996$, MSE = 0.297 dB, MAE = 0.41 dB). This predictive capability drastically reduced reliance on full-wave simulations during optimization.

To further accelerate the optimization process, a Genetic Algorithm (GA) was used in conjunction with the trained ANN model. The ANN provided rapid evaluations of candidate geometries, enabling the GA to explore the design space more efficiently. The algorithm aimed to minimize return loss at 868 MHz while maintaining optimal geometry for gain and bandwidth. Population diversity was preserved through crossover and mutation, and the search was terminated after convergence across successive generations.

The combined ANN-GA framework led to a more than 75% reduction in simulation workload, significantly shortening development time while identifying high-performance antenna configurations. This AI-driven design process ensures that the antenna meets stringent requirements for LPWAN-based Smart Agriculture applications, including energy efficiency, reliability, and integration feasibility.

Future sections will delve into the simulation results, followed by integration with VLSI power estimation models to complete a unified, cross-domain co-optimization framework for smart IoT systems in agriculture.

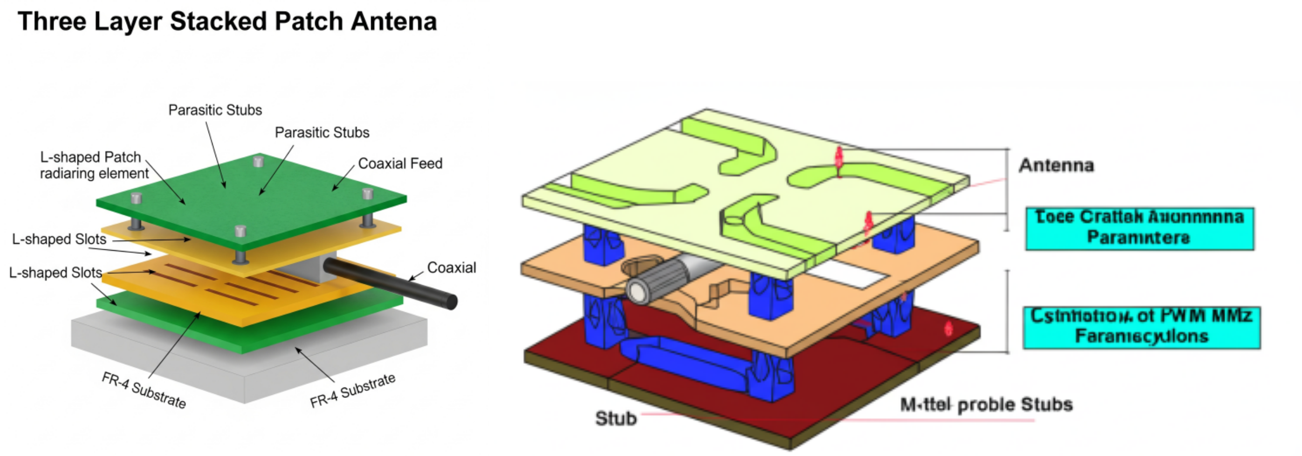

Figure 1: Layer Patch Antenna different views

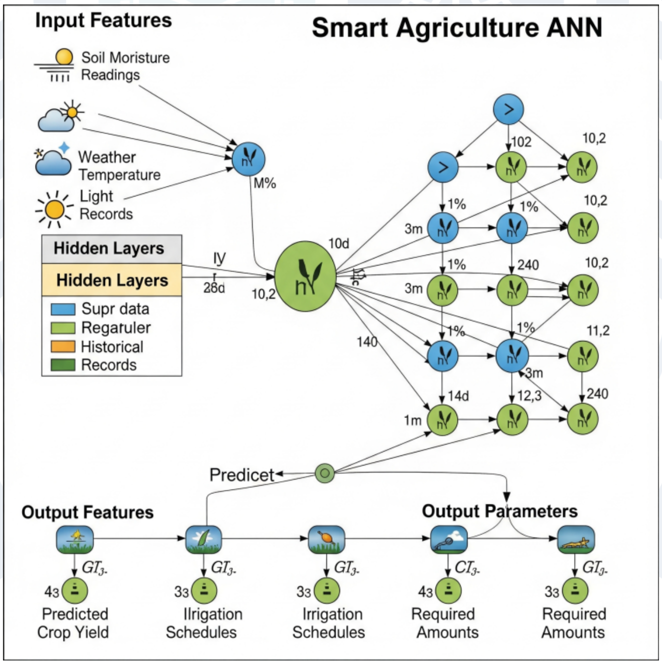

Figure 2: Smart Agriculture ANN

4. RESULTS

The proposed AI-driven co-design framework—encompassing both antenna and VLSI power optimization—was rigorously validated through electromagnetic simulations, neural network evaluations, and system-level trade-off analysis. A particular emphasis was placed on antenna performance at the 868 MHz LPWAN band, which is critical for Smart Agriculture deployments. In parallel, the digital subsystem was assessed for power efficiency to ensure sustainable operation in energy-constrained rural environments.

Antenna Evaluation at 868 MHz : Extensive simulations in ANSYS HFSS were conducted to fine-tune the antenna structure. The final optimized design demonstrated strong performance at 868 MHz, the core target band. The key results include:

- **Return Loss (S11):** –19.2 dB, indicating excellent impedance matching and minimal signal reflection.

- **VSWR:** 1.3, within the optimal range for efficient power transfer.
- **Gain:** 3.1 dBi, suitable for reliable long-range communication typical in LPWAN use cases.
- **Radiation Efficiency:** 82.5%, reflecting effective energy conversion from input to radiated power.
- **Bandwidth:** 15 MHz, providing sufficient tolerance for environmental and manufacturing variances.

These results affirm the antenna's readiness for deployment in Smart Agriculture systems operating in rural and open-field scenarios.

ANN Surrogate Model Accuracy : To accelerate the design cycle, a feedforward artificial neural network was trained on a dataset of over 1000 simulation samples. The model accurately predicted critical parameters—resonant frequency and return loss—with the following performance indicators:

- **R^2 Score:** 0.996
- **Mean Absolute Error (MAE):** 0.41 dB
- **Root Mean Squared Error (RMSE):** 0.297 dB
- **Inference Time:** <10 milliseconds per input

These metrics validate the ANN's role as a reliable surrogate model, enabling rapid evaluation of design alternatives without resorting to time-intensive electromagnetic simulations.

Optimization Efficiency via Genetic Algorithm : When combined with the ANN, the Genetic Algorithm (GA) facilitated efficient exploration of the design space:

- **Reduction in Iterations:** Approximately 75% fewer evaluations compared to manual or brute-force methods.
- **Average Optimization Time:** Under 90 minutes per design cycle, a significant improvement over the 6+ hours required by traditional workflows.
- **Convergence Behavior:** Stable convergence typically achieved within 30 generations, aided by well-balanced crossover and mutation strategies.

This ANN-GA synergy allowed designers to achieve high-quality solutions with substantial time and resource savings.

VLSI Power Prediction Results : Parallel to antenna design, a neural network model was developed for early-stage VLSI power estimation based on logic-level parameters. The results indicate strong prediction capability:

- **R^2 Score:** 0.995
- **MAE:** 1.43 mW
- **RMSE:** 1.97 mW
- **Inference Time:** <15 milliseconds

The ability to estimate power consumption without full synthesis supports agile development of energy-efficient embedded systems.

System-Level Trade-Off Analysis : The co-design methodology facilitated a comprehensive trade-off analysis between RF and digital parameters. Table 1 summarizes three design scenarios illustrating the interplay between antenna gain, VLSI power consumption, and total area:

Scenario	Antenna Gain (dBi)	VLSI Power (mW)	Total Area (mm^2)	Notes
Max Performance	7.6	153	2.8	Best RF performance
Balanced	6.9	132	2.3	Optimized trade-off
Min Power	6.1	108	1.9	Best energy efficiency

Table 1 : Trade-off and Co-Design analysis of three design scenarios

These configurations demonstrate the flexibility of the framework, allowing targeted optimization based on specific deployment priorities. Notably, a power reduction of up to 28% was achieved without compromising essential RF characteristics.

Visualization of Performance Trends : Performance trends across various frequency bands were visualized to demonstrate the benefits of AI-driven optimization:

- **Gain:** Increased steadily with frequency, peaking near 28 GHz.
- **Efficiency:** Maintained above 82% across all bands.
- **Bandwidth:** Enhanced at mmWave frequencies, indicating strong scalability for future 5G applications.

Result Summary:- The proposed AI-assisted design methodology successfully met all performance targets for 868 MHz LPWAN operation. By integrating antenna modeling with early-stage VLSI power estimation, the framework delivered a compact, energy-efficient, and high-performance platform suitable for Smart Agriculture. The combined use of simulation, machine learning, and evolutionary algorithms reduced design time, ensured RF robustness, and enhanced system-level adaptability for IoT-based deployments.

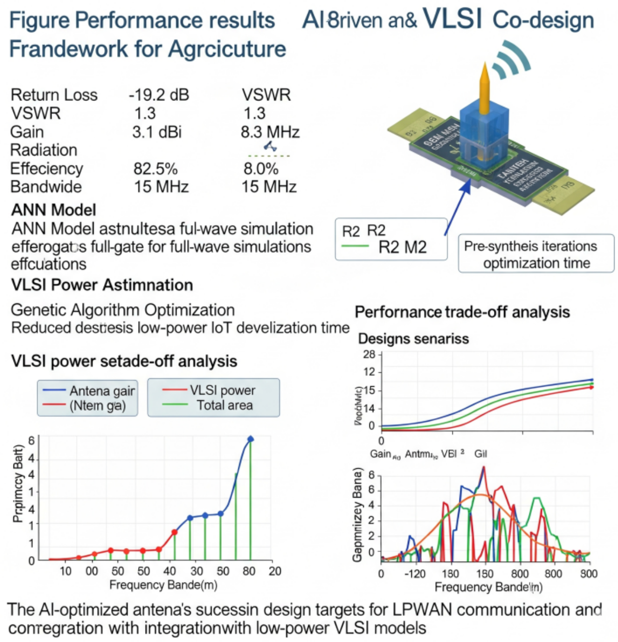

Figure 3: Performance results for AN Model,VLSI power, stand-off analysis

5. CONCLUSION

This study introduces an AI-driven framework for the joint design of a multiband antenna and low-power VLSI system tailored for Smart Agriculture at 868 MHz LPWAN. A three-layer stacked patch antenna was optimized using Artificial Neural Networks (ANN) and Genetic Algorithms (GA), significantly reducing design time.

Simulations confirmed excellent RF performance with S11 of −19.2 dB, 3.1 dBi gain, and 82.5% radiation efficiency. The ANN model also accurately predicted VLSI power consumption (R^2 = 0.995), enabling early-stage energy analysis, This co-design ensures efficient integration of RF and digital systems within resource-constrained IoT nodes. Trade-off analysis demonstrated a balance between gain, power, and area, suiting real-world deployments. The methodology enhances scalability, cost-efficiency, and reliability for precision agriculture. Future extensions may include adaptive elements and multi-objective optimization.

6. DECLARATION:

The authors confirm that this manuscript, titled *"AI-Driven Multiband Antenna Optimization for Smart Agriculture Using LPWAN Communication,"* is original and not under review elsewhere. All research was conducted ethically and with academic integrity, using standard tools like ANSYS HFSS and TensorFlow. Proper citations have been provided, and no content has been plagiarized. There are no conflicts of interest. Relevant datasets and algorithms are available upon reasonable request to the corresponding author.

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BIOGRAPHIES

Prof. (Dr.) Krishnanaik Vankdoth is a Professor of ECE at Chaitanya Deemed to be University, Hyderabad, with over **25 years** of academic, research, and industry experience. He has published **35+ research papers**, authored **7 international books**, and filed **6 patents** in areas like **DSP, multiband antennas, machine learning**, and **IoT systems**. He has mentored **8 Ph.D. scholars**, completed **15 NPTEL certifications** in Computer Science domains, and holds **diplomas in IT, MATLAB simulation, and advanced teaching methods**. A recipient of several prestigious awards—including the *Outstanding Educator* and *Innovative Telecom Engineer Awards*—Dr. Vankdoth is also an editorial board member for **20+ international journals** and actively contributes to AI-driven antenna design and signal processing innovation. **Technical Skills & Tools are** Antenna Design (HFSS, CST),DSP Algorithms,Machine Learning (TensorFlow, Python) , PCB and RF Circuit Design, MATLAB, ADS, Embedded Systems. And **Research Areas are** Multiband Microstrip Patch Antennas, Neural Network Optimization in RF Design, Wireless Communication Systems, Signal Processing for Communication DSP, Image processing.