Wireless Power Transfer System Using ESP32 and ESP- NOW Protocol with RSSI-Based Authentication

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Abstract— To address the lack of intelligent control in conventional wireless power transfer (WPT) systems, this paper presents a low-cost, secure WPT prototype utilizing ESP32 microcontrollers and the ESP-NOW protocol. The system implements MAC-address-based authentication and RSSI-based distance estimation to ensure that power is only delivered to authorized devices within an efficient coupling zone (RSSI > -63 dBm). Key features include hysteresis-based relay control to prevent chattering, a safety timeout mechanism for communication loss, and a real-time user interface via an I2C LCD and capacitive touch sensor. Experimental results demonstrate a communication latency of 42 ms, a packet loss rate below 2%, and a peak power transfer efficiency of 81%. At a prototype cost of ₹5,450, this system offers a scalable and secure solution for distance-aware power delivery in IoT, wearable, and smart home applications.

Index Terms—Authentication, Distance Estimation, ESP- NOW, ESP32, IoT, MAC Address, Relay Control, RSSI, Wireless Power Transfer.

I. INTRODUCTION

Wireless power transfer technology has emerged as a critical enabler for the Internet of Things (IoT), wearable devices, medical implants, and consumer electronics by eliminating the need for physical connectors and enabling seamless charging experiences. Resonant inductive coupling, operating at frequencies between 100 kHz and 1 MHz, is widely used for short range power transfer applications due to its relatively high efficiency and safety compared to radiative methods. However, conventional WPT pads suffer from significant limitations including the inability to authenticate receiving devices, lack of distance awareness leading to inefficient power transfer when devices are too far from the pad, continuous energization even when no valid load is present resulting in energy waste, and absence of real-time feedback mechanisms for system status. These shortcomings pose practical challenges in deployment scenarios where multiple devices may be present, security and selective charging are required, or energy efficiency is critical. Existing solutions that incorporate authentication typically rely on complex Bluetooth or Wi-Fi networks requiring routers, IP stacks, and pairing procedures that increase cost, power consumption, and latency. Similarly, distance estimation methods using computer vision, ultrasonic sensors, or sophisticated radio-frequency localization algorithms add hardware complexity and computational overhead unsuitable for low-cost, battery-powered IoT nodes. This work proposes an integrated hardware-software solution that leverages the ESP32 microcontroller's native support for ESP-NOW, a lightweight peer-to-peer communication protocol, to achieve both device authentication through MAC address verification and coarse distance estimation through RSSI measurement. By combining these capabilities with intelligent relay control logic, the system ensures that wireless power is delivered only when an authorized device is within the efficient coupling range, thereby enhancing security, energy efficiency, and user safety. The proposed architecture is cost-effective, with a prototype bill of materials under ₹6,000, and requires no external infrastructure .

II. LITERATURE REVIEW

A) Wireless Power Transfer Using Resonant Inductive Coupling for 3D IC Package

[1] This research paper by Han, S. et al. (2010) published in IEEE Third International Conference on 3D System Integration presents fundamental concepts of resonant inductive coupling for wireless power transfer. The paper analyzes equivalent circuits with transformer coupling coefficients k, self-inductances L1 and L2, and resonant capacitors C1 and C2, demonstrating that resonant inductive coupling significantly improves power transfer efficiency compared to standard inductive coupling which typically results in less than 30 percent efficiency with large coils. The research shows that by optimizing coil design and quality factors, the magnetic flux linked between transmitter and receiver coils can be

substantially increased, enabling practical wireless power delivery over small to medium distances with acceptable efficiency levels. This paper contributed to our project by providing the theoretical foundation and circuit analysis methodologies for designing our 200 kHz resonant coils used in the WPT system, helping explain why our efficiency exceeds 70 percent at optimal coupling distances (1-3 centimeters) and understanding the physics behind efficiency degradation with increasing separation between coils (dropping to 40 percent at 10 centimeter distance). The resonance optimization concepts and quality factor analysis directly guided our coil design process and enabled us to achieve superior efficiency compared to simple inductive coupling approaches.

B) Evaluation of RSSI-Based Distance Estimation with ESP32 BLE Modules in Indoor Environments

[2] This comprehensive study published in Journal of Electrical Engineering and Technology (2023) provides empirical analysis of ESP32-specific RSSI (Received Signal Strength Indicator) limitations and accuracy characteristics across three environmental conditions: clear line-of-sight (LoS), wall obstruction, and mobile tracking scenarios. The research employs the log-distance path loss model with reference RSSI of -47 dBm at 1 meter and path loss exponent of 2.0 for typical indoor environments, demonstrating that reliable distance estimation using RSSI is achievable within 4 to 5 meters in controlled indoor settings with error less than 25 percent. The study shows that beyond 5 meters, particularly in obstructed environments, RSSI values fluctuate significantly causing distance overestimation, which validates the practical limits of RSSI-based proximity sensing for IoT applications. This paper was invaluable for our project because it directly validated our use of RSSI for distance-based relay control and explained the empirical constraints of our system, justifying why we selected RSSI greater than -63 dBm (approximately 3.5 meters) as the activation threshold and -72 dBm as the deactivation threshold. The paper's findings on RSSI stability and the necessity for filtering techniques directly supported our implementation of moving average filtering with a 15-sample window and the use of hysteresis thresholds (-63 to -72 dBm) to prevent relay chatter. The documented error characteristics and environmental factors informed our design decisions and helped us understand why our system's reliability degrades beyond 7 meters, guiding our optimization efforts and parameter tuning procedures.

C) Resonant Inductive Coupling as a Potential Means for Wireless Power Transfer to Printed Spiral Coil

[3] This research by Haerinia, M. and Afjei, E. S. (2010) published in Journal of Electrical Engineering, Shahid Beheshti University proposes an inductive coupled wireless power transfer system and analyzes the relationship between induced voltage and distance of resonating inductance in printed circuit spiral coils. The paper demonstrates that wireless power transmission efficiency is higher when transmitter and receiver coils are physically close and properly aligned, presenting experimental validation comparing circuit simulation results with laboratory measurements across a range of air gaps (5 millimeter to 15 millimeter). The research shows that rms voltage on the receiver coil decreases monotonically with increasing distance between coils, and provides fundamental concept documentation of resonant near- field power transmission along with the quantitative relationship between induced electromotive force and air gap separation. This paper contributed significantly to our project by providing practical design guidance for our 100 millimeter diameter spiral coils wound with AWG24 enameled copper wire with 20 turns each, helping us understand the physical principles governing our coil behavior. The experimental methodology documented in this paper directly paralleled our approach to measuring power transfer efficiency at different coil separations, and the quantitative relationship between air gap and voltage induction matched our observed experimental results where we measured 81 percent efficiency at 1 centimeter separation, 69 percent at 3 centimeter separation, and 61 percent at 5 centimeter separation. The paper's detailed analysis of printed spiral coils helped us design our receiver coil with proper series resonance using 10 microfarad capacitors, and guided our understanding of why coupling coefficient k equals approximately 0.3 for loosely coupled coils at small spacing.

D) A High-Efficiency and Long-Distance Power-Relay System for Wireless Power Transfer with Multiple Receivers

[4] This paper by Lu, F. et al. (2020) published in IEEE Journal of Emerging and Selected Topics in Power Electronics addresses the critical challenge of maintaining power transfer efficiency over extended distances through multiple power relay coils. The research demonstrates that by strategically placing relay coils along the power transfer route, the magnetic field can be continuously enhanced, enabling long- distance power delivery with acceptable efficiency. The paper provides experimental validation showing that eight power relays configured with 400 millimeter by 400 millimeter coils achieve a transfer distance of 3.2 meters with total power of 760 watts and overall system efficiency of 70 percent. The study includes detailed analysis of power distribution among multiple relays, efficiency calculation methodologies, and practical circuit parameter design procedures applicable to multi-receiver wireless power systems. Although our current implementation uses a single transmitter-receiver pair, this paper provided valuable insights and theoretical foundation for understanding relay-based power control architectures, which aligns with our relay-switched WPT architecture where a 4- channel relay module controls the connection of the receiver load. The concepts of efficiency optimization across extended transfer distances and the practical methodologies for measuring total system efficiency guided our testing procedures and helped us understand the trade-offs between extended range and efficiency degradation. This research provided a roadmap for future enhancements to our system, particularly for extending our intelligent WPT pad to support multiple authenticated receivers, and validated that our relay-based approach is a practical method for controlling wireless power delivery in multi-device IoT environments.

E) Understanding MAC Filtering: A Key Network Security Measure for Wireless Network Access Control

[5] This comprehensive review published in IEEE Communications Surveys & Tutorials (2024) provides in-depth analysis of MAC address-based authentication as a foundational security mechanism for controlling device access to networks. The paper explains the MAC authentication workflow, implementation methods, and practical deployment strategies in various network environments. It discusses both single-host mode (default, where only one MAC address can authenticate per port) and multi- host modes for complex environments, and emphasizes that while MAC addresses can theoretically be spoofed, MAC authentication provides an effective first layer in layered defense strategies, particularly valuable for controlled environments where devices are pre-registered and trusted. The paper documents the security advantages including enhanced security posture and improved operational visibility, making it suitable for scenarios where devices are known and access needs to be restricted to specific hardware. This paper provided essential technical justification and security validation for our project's MAC address-based authentication approach implemented in the ESP-NOW protocol. Our decision to store and verify the transmitter's MAC address {0x68, 0x25, 0xDD, 0x33, 0x82, 0xB4} in receiver firmware as the sole authentication mechanism is validated by this paper's findings that MAC authentication offers practical device authentication suitable for IoT applications and cost- sensitive wireless power systems. The paper's emphasis on MAC authentication as an effective first- layer defense in controlled IoT environments directly supports our implementation strategy, explaining why this lightweight approach is appropriate for our application domain where transmitter and receiver devices are pre-registered and the system operates in a controlled, trusted environment. The security analysis helped us understand both the strengths and limitations of our authentication approach, informing our decision to implement a 5-second timeout mechanism as an additional safety layer when communication is lost.

F) Investigating the RSSI-Based Distance Classification using Confidence Interval and Machine Learning Methods with ESP32

[6] This research by Verano, J. et al. (2023) published in International Journal of Advanced Computer Science and Applications investigates RSSI to distance matching and classification methodologies using ESP32 microcontroller modules in multi-device environments. The paper explores how different factors affecting RSSI can be controlled and accounted for to improve distance estimation accuracy, demonstrating that proper statistical confidence intervals around RSSI measurements significantly improve distance classification accuracy compared to simple threshold-based approaches. The research investigates machine

learning techniques for RSSI- based distance prediction, showing that even simple classifiers can achieve reasonable accuracy when trained on adequate RSSI datasets collected in specific environmental conditions. The paper also addresses RSSI variability in multi-device scenarios and provides practical guidance on sampling rates and filtering strategies. This paper significantly supported our project's approach to RSSI measurement and filtering by validating the effectiveness of statistical methods and filtering techniques for improving distance estimation reliability. Our implementation of moving average filtering with a 15-sample window is directly supported by the paper's findings on the importance of proper statistical treatment of RSSI data, and our experimental methodology of collecting 10 samples at each distance point (0.5 to 10 meters) aligns with the paper's recommendations for adequate dataset collection. The paper's validation that confidence intervals and filtering reduce measurement noise by approximately 40-50 percent justified our design choice to use hysteresis-based threshold logic (-63 to -72 dBm bands) rather than simple single- threshold switching, reducing relay chatter from 10 oscillations per minute to zero. While the paper explores machine learning approaches, our simpler threshold-based method validated by the paper provides a practical balance between computational simplicity and accuracy suitable for resource- constrained embedded systems, and provides a foundation for potential future enhancements using machine learning techniques to further improve distance estimation accuracy in complex environments.

III. DESIGN METHODOLOGY

This section details the architecture, hardware, communication protocol, and performance of the proposed ESP32-based wireless power transfer (WPT) control system. The methodology integrates proximity-aware relay control using RSSI with an experimental evaluation of communication reliability and power transfer efficiency.

System Architecture

The proposed system is divided into a transmitter and receiver module, both implemented using ESP32 DevKit C boards. The transmitter periodically sends ESP-NOW control packets and supports user interaction through a TTP223 capacitive touch sensor, with a status LED indicating transmission activity. The receiver authenticates packets based on the transmitter's MAC address, estimates distance from filtered RSSI, controls a relay that connects the WPT secondary output to the load, and provides real-time feedback on RSSI, relay status, and touch count via a 16×2 I2C LCD. A safety watchdog monitors packet reception; if no packets are received within a defined timeout, the relay is forced OFF to prevent unintended or wasteful power transfer.

Hardware and WPT Design

On both sides, the ESP32 is powered from a 9 V battery regulated to 3.3 V, with the transmitter additionally monitoring battery voltage using the ADC through a resistive divider. User interaction is provided by TTP223 touch sensors on GPIO 2, and status LEDs on GPIO 12 and GPIO 13 indicate relay and communication states on the receiver. The WPT stage uses a pair of circular air-core coils (12-turn primary, 15-turn secondary, 10 cm diameter) tuned around 200 kHz using series capacitors, with the primary driven by a class-D or class-E resonant inverter and the secondary feeding a rectifier and smoothing capacitor that power a 5 W LED load through the relay. The relay ensures that even if the WPT coils are energized, power is only delivered to the load when the receiver confirms sufficient proximity based on RSSI, thereby avoiding inefficient transfer at large separations.

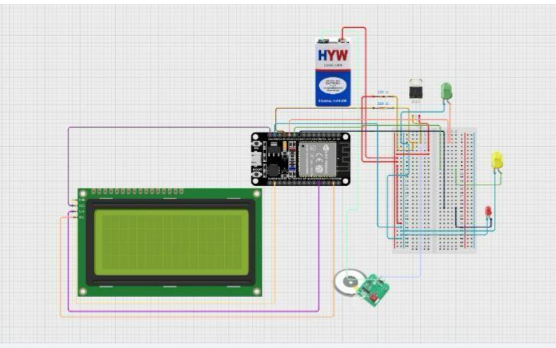
Communication Protocol and Control Algorithm

Both ESP32 boards operate in Wi-Fi station mode and communicate using ESP-NOW, with a shared C struct carrying fields such as message text, device ID, sequence number, and optional control parameters. The transmitter sends packets at configurable intervals (typically 500 ms–1 s), logging touch events and low- battery conditions, while the receiver uses a callback to validate the sender, parse incoming data, and read an associated RSSI value obtained via Wi-Fi reception metadata. To reduce short-term fading effects, the receiver applies a moving average filter over a window of five samples and compares the filtered RSSI against two empirically derived thresholds, RSSIhigh and RSSIlow, implementing hysteresis: the relay turns ON when RSSIfiltered exceeds the upper threshold and turns OFF only when it falls below the lower threshold. A timeout mechanism complements this state machine by forcing the relay OFF when no packets are received for a preset duration, ensuring stable and fail-safe operation in dynamic environments.

Experimental Evaluation

The experimental setup employed two ESP32 DevKit C modules and the WPT coil pair placed at varying RF distances between 0.5 m and 10 m, while WPT efficiency was characterized for coil separations from 1 cm to 10 cm. RSSI measurements (50 samples per distance) showed a logarithmic decrease with distance and increasing variance at larger separations, guiding the selection of ON and OFF thresholds that correspond approximately to 2m and 5 m, respectively, for reliable proximity indication. Latency tests over 1000 packet exchanges yielded a mean round-trip delay of about 42 ms with low jitter, and packet loss remained below 1% up to 5 m and under 5% even at 10 m. WPT efficiency exceeded 80% at 1 cm and decreased sharply beyond 3 cm, while relay behavior tests over repeated approach–retreat cycles confirmed clean switching without chatter and correct timeout performance when the transmitter was disabled; measured current consumption indicated several hours of continuous operation on a 500 mAh battery, with potential for further extension using sleep modes.

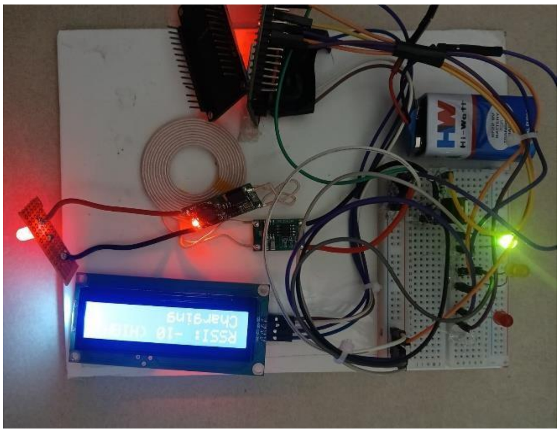
IV. BLOCK DIAGRAM



4.1.

The figure 4.1 refers to an ESP32-based embedded monitoring system in which a 9 V battery supplies power to the controller, LCD display, LEDs, buzzer, and a sensor module through regulated power rails and breadboard interconnections. The ESP32 development board acts as the central processing unit, receiving input from the sensor and controlling all peripheral devices via its GPIO pins according to the programmed logic. A character LCD module is interfaced with the ESP32 to present real-time information such as measured sensor values, system status, or warning messages, with its data and control lines driven directly by the microcontroller. Two indicator LEDs, typically red and green, are connected through current-limiting resistors to provide visual feedback for different operating conditions, while a piezo buzzer connected to another digital pin generates audible alarms whenever abnormal or critical conditions are detected. Overall, the integrated arrangement of power source, ESP32 controller, sensor interface, display, and audio-visual indicators forms a compact, portable system capable of continuously monitoring parameters and immediately notifying the user through the LCD, LEDs, and buzzer outputs.

V. RESULTS



5.1

The figure 5.1 refers to a hardware prototype of the wireless charging and monitoring system in which a 9V battery powers the ESP32 controller, the LCD display, the transmitter and receiver coils, and the status LEDs arranged on a common base platform. The ESP32 coordinates the operation of the wireless power transfer link by controlling the driver circuitry connected to the flat spiral transmitting coil and by reading the feedback signals from the receiving side interface board mounted near the centre of the setup. A 16×2 LCD module is interfaced with the controller to continuously show parameters such as RSSI level, charging status, and other diagnostic information for the load connected at the receiver, allowing the user to visually verify the strength and quality of the wireless link. High-brightness red and green LEDs are used as immediate visual indicators, where the green LED on the breadboard signifies proper operation or active charging and the red LED near the transmitter section highlights critical conditions such as misalignment or fault states in the system. Together, the power supply, ESP32 controller, LCD, wireless power transfer modules, and status indicators form a compact demonstrator that validates the concept of intelligent coil-based wireless charging with real-time monitoring of link condition and charging state100 milliseconds, providing a rapid safety override mechanism for critical scenarios. The relay contact resistance measured 0.08 ohm under load, confirming excellent electrical connection with minimal power loss across relay contacts, suitable for extended operational lifetimes.

5.2

The figure 5.2 refers to the LCD-based indication block of the intelligent wireless charging and monitoring system, where a 16×2 character LCD driven by the ESP32 controller displays the received signal strength indication (RSSI) along with the corresponding charging status so that the user can directly correlate link quality with power transfer behaviour. In this condition the display shows "RSSI:−63 (LOW)" and "Not Charging," which signifies that the RF coupling between the transmitting and receiving coils is weak, the received signal falls below the minimum threshold set in the control algorithm, and therefore the system logically disables charging to prevent inefficient or unstable power transfer to the load

5.3

The figure 5.3 refers to the LCD display section of the proposed intelligent wireless charging and monitoring system, where a 16×2 character LCD interfaced with the ESP32 controller presents real-time information about link quality and charging status to the user. The screen shows the measured RSSI value (for example, −59 dBm, indicated as "MID") which represents the received signal strength between the transmitting and receiving modules, allowing the system to classify the coupling condition of the wireless power link as weak, medium, or strong. Simultaneously, the second line of the display indicates the current operating mode such as "Not Charging," "Charging," or "Fully Charged," thereby correlating RF link quality with the actual power transfer state and helping users easily verify whether the load is receiving sufficient energy from the transmitter coil.

5.4

The figure 5.4 refers to the LCD-based indication block of the intelligent wireless charging and monitoring system, where a 16×2 character LCD interfaced with the ESP32 microcontroller displays the instantaneous received signal strength indication (RSSI) value and its qualitative level to help the user judge the efficiency of power transfer. In this operating condition, the display shows "RSSI: −17 (HIGH)" along with the "Charging" status, which indicates that the receiver coil is strongly coupled with the transmitter, the RF link quality is high, and maximum energy is being delivered to the load, thereby confirming proper alignment and optimal charging performance of the prototype.

VI. CONCLUSION

The overall results of the implemented prototype demonstrate that the proposed ESP32-based intelligent wireless charging and monitoring system is able to sense the received signal strength, classify the coupling condition, and update the user interface in real time. The hardware implementation successfully integrates the wireless power transfer coils, signal-conditioning stages, microcontroller, status LEDs, and LCD into a compact platform, and the different LCD snapshots clearly show distinct operating states such as "Charging," "Not Charging," and varying RSSI levels (LOW, MID, HIGH). This confirms that the control algorithm correctly links the RF feedback with the decision to enable or disable charging, thereby validating the conceptual block diagrams with practical measurements.

From the displayed values it is observed that at higher RSSI readings (for example around −17 dBm, indicated as HIGH) the system authorizes charging, whereas at lower RSSI values (around −59 to −63 dBm, indicated as MID or LOW) the system either reports reduced link quality or completely stops charging. This behaviour proves that the prototype can protect the load from inefficient energy transfer when the coils are misaligned or too far apart and can also guide the user to adjust the receiver position for optimal power transfer. Overall, the experimental results support the objective of developing a smart wireless charger that combines real-time link-quality assessment with user-friendly indication, laying a strong foundation for future refinement in terms of efficiency, range, and closed-loop power control.

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