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An Intelligent Wireless Socket System for Safe and Efficient Power Control Using RF Communication Architecture

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ABSTRACT: Modern power control systems require low-latency, reliable, and secure operation, which conventional and IoT-based smart sockets fail to ensure due to network dependency. A wireless embedded system using RF communication is implemented to enable direct device control without internet involvement. The system integrates an Arduino Nano with an nRF24L01 transceiver to establish real-time transmitter-receiver communication. User inputs are encoded and transmitted as RF signals, and the receiver performs switching using relay control. This architecture ensures fast response, reduced latency, and improved reliability. Additionally, integrated energy monitoring and protection mechanisms enhance efficiency and operational safety in power management systems.

KEYWORDS: Smart Socket, RF Communication, Wireless Control, Arduino Nano, nRF24L01, Overload Protection, Power Management, Energy Efficiency, Wireless Trans receiver.

I. INTRODUCTION

Power control systems require low-latency and reliable operation, which conventional and IoT-based smart sockets fail to provide due to network dependency and delays. A wireless embedded system using RF communication enables direct device-to-device control without internet involvement, integrating an Arduino Nano with an nRF24L01 transceiver for fast transmitter-receiver communication. User inputs are encoded as RF signals and decoded in real time to control electrical loads through relay switching, achieving millisecond-level response. The system also incorporates real-time energy monitoring and protection features such as overload detection and automatic shutdown, ensuring high reliability, improved security, and efficient power management.

II. RELATED WORK

Early smart sockets operated on fixed timer mechanisms, offering limited flexibility and no real-time adaptability. With the advancement of embedded systems, Wi-Fi-based smart plugs enabled remote control and energy monitoring but introduced latency, network dependency, and security risks due to cloud reliance. Alternative communication technologies such as Bluetooth, Zigbee, and Z-Wave provide low power consumption but suffer from limited range or require additional gateway hardware. To overcome these limitations, an RF-based system using the nRF24L01+ transceiver operates at 2.4 GHz, delivering low-power, low-latency communication with a range of up to 100 m (outdoor) and 40 m (indoor), without requiring internet or external infrastructure. The system achieves fast response and cost efficiency while maintaining reliable performance. Additionally, integrated current monitoring and intelligent

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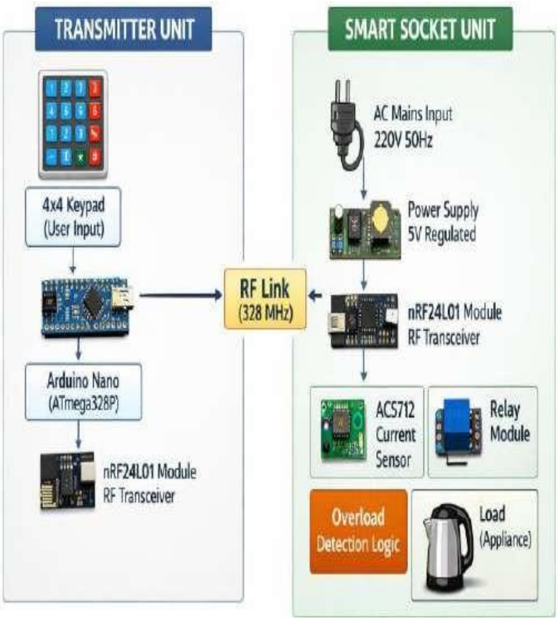
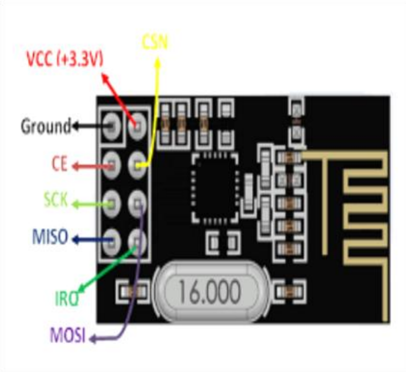
protection mechanisms detect overload conditions in real time and provide immediate feedback through alert signals, ensuring both operational safety and user awareness.

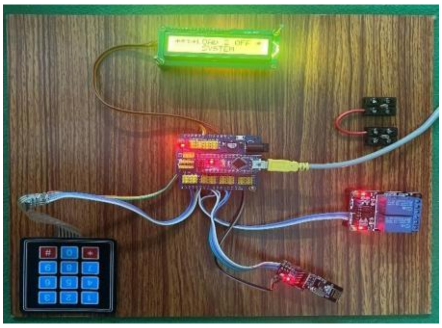
III. SYSTEM ARCHITECTURE AND DESIGN

The system consists of two main units: a portable transmitter acting as a handheld controller and a receiver embedded within a standard wall socket. The transmitter communicates wirelessly with the socket, enabling direct control of connected devices.





Transmitter Unit (Tx)



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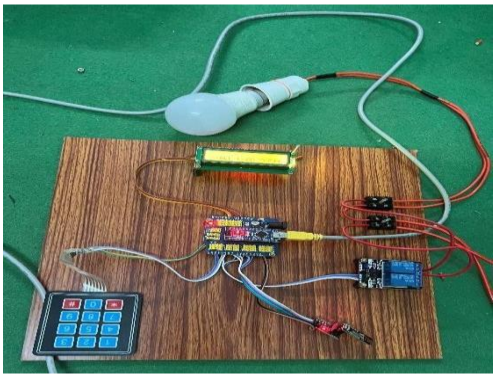
The system is designed for simple, reliable operation using an embedded architecture. The transmitter unit is built around an Arduino Nano (ATmega328P) operating at 5V and 16 MHz, with a typical current consumption of ~19 mA. A 4×4 membrane keypad provides user input, and software debouncing with a 50 ms delay ensures stable and accurate signal detection. Wireless communication is achieved using an nRF24L01+ RF transceiver operating at 2.4 GHz with a data rate of 2 Mbps for fast transmission. Since the RF module requires 3.3V, a voltage regulator is used to ensure safe and stable operation.

Receiver Unit (Rx)



The system uses a transformer less power supply to convert 230V AC to regulated 5V DC using a capacitor, bridge rectifier, and voltage regulator. A relay controlled through a transistor switches high-power loads, with a flyback diode for protection. Current is measured using a Hall effect sensor, providing isolated and real-time monitoring. The microcontroller processes readings using averaging to filter noise and triggers overload protection when current exceeds a set threshold continuously, ensuring safe and stable operation.

IV. ALGORITHM ONE DETECTS OVERLOAD

Start with threshold set to 10 A, count at zero.
Among the wireless protocols considered for smart sockets, Wi-Fi stands out with high power consumption but offers an extensive range of over 30 meters and a high data rate, making it best suited for real-time control directly over a home network. Bluetooth, by contrast, consumes low power and provides a moderate data rate, yet its range is limited to about 10 meters, which restricts its use to close-proximity applications and makes it less ideal for whole-home deployments. Zigbee operates on very low power and delivers a low data rate over a per-hop range of roughly 20 meters; however, its mesh networking capability allows mains-powered sockets to act as repeaters, making it highly suitable for large, resilient smart socket networks. MQTT itself is not a physical-layer protocol but an application-layer messaging protocol that typically runs over Wi-Fi or Ethernet; it incurs low overhead and supports high data rates, with range determined by the underlying network, and is considered best for cloud-based control due to its lightweight publish-subscribe model. Finally, dedicated RF transmitters and receivers consume very low power, achieve an impressive range of over 100 meters in open areas, and offer a moderate data rate, making them ideal for simple remote switching where long range and low power are prioritized over bidirectional data throughput.
Loop:
Last half minute's readings - taken every millisecond
are added up then split into fifty parts. That number
becomes the present typical value
Whenever the present average goes above the limit,
proceed accordingly
count = count + 1
If the total goes above five, proceed to the next step
deactivate relay
Trigger an "OVERLOAD" signal toward the distant
unit
end if
else
One less each time, but never dropping below zero

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end if
end loop

Comparison of Communication Protocols

A structured packet format ensures reliable communication. It includes sync bytes (0xAA), device address, command code, optional data, and a checksum for error detection. The receiver validates the checksum before execution and sends an acknowledgment (0xFF). If no response is received within 50 ms, the sender retries up to two times, ensuring robust and error-free data transmission.

Performance Evaluation

Testing was conducted in both laboratory and real home environments. An oscilloscope was used for timing analysis, while a multimeter ensured accurate calibration. Variable resistive loads (0-15 A) simulated real conditions, and a spectrum analyzer monitored signal interference, ensuring reliable system performance.

Communication Range

The RF communication achieved reliable performance up to 120 m outdoors with near 100% success, slightly decreasing to 95% at 150 m and 82% at 200 m. Indoors, full reliability was maintained up to 30 m through obstacles, with performance around 88% at 50 m. For stable operation, an effective range of 100 m (outdoor) and 40 m (indoor) is recommended.

Response Time

The system achieved an average response time of 15.8 ms, typically ranging between 13-18 ms, with occasional delays up to 24 ms due to retransmissions. In comparison, standard Wi-Fi smart plugs showed much higher latency (~287 ms), sometimes reaching 500 ms. The RF system provides near-instant response, similar to a physical switch.

Power Monitoring Accuracy

The ACS712 sensor was tested against a reference multimeter from 0.5 A to 10 A, showing a deviation of less than ±2%. For example, a 1000 W reading ranged between 980–1020 W, indicating reliable accuracy for household energy monitoring. This level of accuracy makes the sensor suitable for real-time power measurement in smart socket applications. Additionally, its consistent performance ensures stable and dependable readings under varying load conditions.

Overload Protection Performance

Overload protection was highly responsive, detecting 11 A in ~48 ms and disconnecting by 56 ms, while 15 A was handled within 40 ms. Under short-circuit conditions, detection occurred in 4 ms with shut down by 12 ms, significantly faster than conventional breakers, ensuring effective protection.

Energy Savings

In a one-month home test, TV energy usage reduced from 28.4 kWh to 18.2 kWh (~36%), while AC consumption dropped from 186.5 kWh to 142.8 kWh (~23%), due to automatic control and elimination of unnecessary usage.

Reliability and Comparative Analysis

The system was tested continuously for 1000 hours (~16,000 operations), achieving a success rate of ~99.25%. All 23 overload events were correctly detected, with only one false trigger due to transient surge, later improved through filtering. Compared to other technologies, the RF system provides 16 ms response time, 40 m indoor range, and operates without internet, ensuring better reliability and security. Despite a cost of around ₹6000, it outperforms Wi-Fi and Zigbee solutions in latency, independence, and overall efficiency.

Comparative Feature Analysis

The RF-based smart socket operates without internet dependency, unlike Wi-Fi systems, and does not require a hub like Zigbee. It achieves a fast response time of 16 ms, compared to 200-500 ms (Wi-Fi) and 80-150 ms (Zigbee). The system provides up to 40 m indoor range, exceeding Wi-Fi and Zigbee coverage. It also offers improved security by avoiding cloud connectivity. With a cost of around ₹6000, it delivers better performance, reliability, and safety compared to existing solutions.

Existing Smart Socket Systems

Existing smart socket solutions mainly use cloud-based IoT, mobile apps, and Wi-Fi to control devices, monitor energy usage, and support voice assistants like Alexa and Google Assistant. However, they often face problems such as delay, dependence on internet connection, and security risks. Some systems use Bluetooth or Zigbee, but they still depend on cloud platforms, which can reduce speed and reliability. Overall, while these solutions improve automation and efficiency, they do not provide fast, direct, and secure communication like transmitter–receiver-based systems.

Research On IoT-Based Energy Monitoring Systems

Studies on IoT-based energy management suggest that integrating machine learning (ML) and real-time monitoring can reduce power wastage by up to 30%. MQTT-based communication has been found to be the most efficient protocol for data transmission in low-latency and resource-constrained environments. The research indicates that a localized, non-internet-dependent system can provide better security and faster response times, which are critical for industrial applications.

Comparison of Communication Protocols

Protocol	Power Consumption	Range	Data Rate	Suitability for Smart Socket
Wi-Fi	High	30m+	High	Best for real-time control with internet
Bluetooth	Low	10m	Moderate	Limited range and speed
Zigbee	Very Low	20m	Low	Suitable for mesh networks
MQTT	Low	N/A	High	Best for cloud-based control
RF Transmitter & Receiver	Very Low	100m+	Moderate	Better range, lower power, ideal for remote switching

V. CONCLUSION AND FUTURE WORK

The system provides 100 m outdoor range, 15.8 ms response time, and ~99.2% reliability using direct RF communication without internet. It achieves ±2% power accuracy, overload cutoff within <60 ms, and ~26% energy savings in real use. The design ensures high security and uninterrupted operation. Future improvements include mesh networking, RF encryption, and optional mobile integration.

VI. RESULT

The system achieved a 16 ms response time with RF range up to 100 m (outdoor) and 40 m (indoor). Power accuracy was ±2%, and overload protection disconnected loads within 50-60ms. Testing showed ~25% energy savings with reliable, low-latency operation without internet dependency.

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