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DESIGN AND IMPLEMENTATION OF A MULTI-SWITCHING CONTACTLESS SOLUTION USING RF AND WI-FI CONTROL FOR SMART AUTOMATION

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Abstract

This study addresses the need for safer, more hygienic, and energy-efficient control of electrical loads in residential, healthcare, and industrial environments by developing a multi-switching contactless system. Conventional single-mode switching systems are limited by network dependency, restricted range, and inconsistent reliability, creating a demand for a multi-switching solution that ensures redundancy and responsive operation. The proposed system integrates an Arduino Uno as the central controller, a 433 MHz RF sensor for local wireless control, an ESP-32 Wi-Fi module for remote management, and a 5V relay module to switch multiple electrical loads. Users can operate the system via a mobile application or an RF remote, providing flexible and contactless interaction. The development involved hardware assembly, Arduino and ESP-32 firmware programming, mobile app integration, and structured testing including unit, integration, and functional evaluations to ensure performance and reliability. Experimental results demonstrated mean response times of 118 ms for RF and 176 ms for Wi-Fi control, an RF open-space range of up to 98 meters, command execution success rates of 98.5% (RF) and 97.1% (Wi-Fi), and safe load handling up to 1200 W with relay temperatures remaining below 48°C. These findings confirm that the system operates reliably under diverse conditions while maintaining low latency and thermal safety. In conclusion, the multi-switching contactless system offers a scalable, dependable, and practical solution for smart automation, enhancing hygiene, convenience, and energy management, with potential for future enhancements including voice control, improved security, and expanded load capacity.

Keywords: Contactless Switching; IoT (Internet of Things); RF and Wifi integration; Mobile Application; Smart Automation.

1.0 INTRODUCTION

The evolution of contactless switching technology has transformed how electrical devices are managed, offering safer, more efficient, and user-friendly solutions. While previous studies have explored RF- or Wi-Fi-based single-mode control systems for residential and industrial automation [2], these approaches often face limitations such as network dependency, limited range, and inconsistent reliability. Furthermore, most existing systems focus either on convenience or energy efficiency, without addressing redundancy or simultaneous multi-switching operation. This gap is particularly critical in healthcare and high-contact environments, where minimizing physical interaction is essential for hygiene and safety [3]. Recent developments in touchless automation, including gesture- and voice-based interfaces, provide enhanced accessibility but still rarely combine multiple communication protocols to improve robustness and operational flexibility [4][5]. In light of these limitations, this study develops a dual-control contactless switching system that integrates both RF and Wi-Fi technologies. Unlike prior single-mode systems, the proposed design ensures redundancy, reliable operation across varying conditions, and remote monitoring capabilities. The project aims to deliver a scalable, energy-efficient, and user-friendly solution that not only improves convenience and safety but also enhances system resilience and versatility for modern automation applications.

2.0 METHODOLOGY

This section presents the structured procedure used to design, implement, and evaluate the proposed multi-switching contactless control system. In this study, multi-switching refers to the ability of the system to control multiple electrical loads independently through more than one communication protocol (RF and Wi-Fi). Contactless operation refers to switching actions performed without physical interaction with mechanical switches, using wireless signal transmission instead. To ensure clarity, reproducibility, and engineering rigor, the methodology was organized into four major phases:

1. Hardware Architecture and Configuration
2. Software Development and Communication Logic
3. System Integration and Functional Testing
4. Circuit Design and Safety Considerations

Each phase was carefully executed to ensure operational reliability, accurate performance measurement, and replicability for future research or large-scale deployment. Additionally, a system block diagram and operational flowchart were incorporated in this section, following reviewer recommendations, to clearly illustrate the interaction between system components and the control sequence for RF and Wi-Fi modes. The system uses 2.4 GHz Wi-Fi, chosen for its wide compatibility with standard routers, sufficient range for residential and industrial environments, and support for TCP/IP communication for remote control via mobile applications. The 433 MHz RF was selected for its long-range, low-power, and strong wall-penetration characteristics, making it reliable for local, low-latency control. Combining RF with Wi-Fi provides redundancy and flexibility: Wi-Fi allows remote network-based control, while RF ensures operation even if the Wi-Fi network is unavailable, enhancing system reliability and user convenience.

2.1 Hardware Architecture and Configuration

The hardware forms the foundation of the multi-switching contactless switching system. The design integrates three primary subsystems: the RF communication subsystem, the Wi-Fi communication subsystem, and the relay-based load switching subsystem. Figure 1 (Block Diagram) illustrates the interconnection of these modules.

2.1.1 Microcontroller Unit

An Arduino Uno (ATmega328P) was selected as the central processing unit due to its stability, low latency, and sufficient input/output capacity. It manages simultaneous command reception from both RF and Wi-Fi modules and triggers the corresponding relay channels.

2.1.2 RF Communication Subsystem

A 433 MHz RF receiver (XY-MK-5V) was used for short-range wireless control. The frequency was selected for its long-range capability, low power consumption, and strong wall-penetration characteristics. RF signals are decoded using the RCSwitch library and mapped to specific relay channels.

2.1.3 Wi-Fi Communication Subsystem

The ESP-32 module enables Wi-Fi connectivity and facilitates remote control through a mobile application. The ESP-32 operates at 2.4 GHz, supports TCP/IP communication, and interfaces with the Arduino via UART serial communication. This mode enables long-distance operation through local network access.

2.1.4 Relay Switching Subsystem

A 5V, four-channel opto-isolated relay module was used to switch electrical loads. Each relay is driven using a 2N2222 transistor to ensure safe current amplification. Flyback diodes (1N4007) protect the switching circuit from inductive voltage spikes. Loads up to 1200 W were tested to validate safe operation.

2.1.5 Hardware Topology

The hardware topology follows a centralized control architecture:

- RF signals → RF Receiver → Arduino (decode) → Relay
- Wi-Fi signals → ESP-32 → Arduino (serial command) → Relay
- Relay → Load (NO contact switching)

This topology ensures redundancy: if Wi-Fi connectivity fails, RF control remains operative

2.2 Software Development and Communication Logic

The software was developed in two parts: Arduino firmware and ESP-32 communication firmware, supported by a mobile application interface created using MIT App Inventor. The integration of RF and Wi-Fi control requires synchronized command interpretation and state management.

2.2.1 Arduino Firmware

The Arduino firmware was written in C/C++ using the Arduino IDE. The main functions include:
- Initializing relay pins, serial communication, and RF decoder
- Continuously polling RF inputs for valid codes
- Parsing Wi-Fi commands received through UART
- Updating relay states and providing real-time status feedback
- Implementing command debouncing and error handling

A state-management array maintains the ON/OFF status of each relay, ensuring correct switching even during rapid consecutive commands.

2.2.2 ESP-32 Firmware

The ESP-32 firmware enables:

- Wi-Fi connection establishment
- Real-time communication with the mobile app
- UART transmission of commands to the Arduino
- Error recovery in event of Wi-Fi interruption

The 2.4 GHz Wi-Fi band offers compatibility with common routers and supports cloud or local network-based control.

2.2.3 System Block Diagram

The system block diagram (Figure 2) illustrates the interaction between:

- RF receiver
- ESP-32 Wi-Fi module
- Arduino Uno
- Relay driver circuit
- Load system

The block diagram visually represents the dual-input, single-output architecture, providing a clear understanding of signal flow from command initiation to load switching.

Figure 2. System Block Diagram

2.3 System Integration and Functional Testing

After completing the hardware configuration and software implementation, the system was fully integrated to establish seamless communication between all components and validate the complete operational workflow shown in the system flowchart. During integration, the Arduino Uno served as the central controller, receiving input signals from both the ESP-32 Wi-Fi module and the 433 MHz RF receiver. These signals were processed according to the decision structure outlined in the flowchart, and the corresponding relay channels were activated to switch the connected loads.

System evaluation was conducted through four structured testing stages to ensure correctness, reliability, and real-world usability:

1. Unit Testing

Each hardware module was individually tested to confirm baseline functionality. Tests included relay activation timing, ESP-32 Wi-Fi connectivity, RF transmission and decoding accuracy, and microcontroller response consistency.

2. Integration Testing

The Arduino Uno was interconnected with the ESP-32 and RF receiver, and end-to-end signal flow was validated. This stage ensured that both wireless communication paths (RF and Wi-Fi) correctly transmitted commands that the Arduino could process and translate into relay actions, following the logic in the system operation flowchart.

3. Functional Testing

This phase evaluated the complete system under normal operating conditions. Performance parameters such as response time, switching accuracy, communication reliability, and load handling were measured. Multi-switching operation was verified by independently testing RF control and Wi-Fi control, confirming that both modes adhered to the decision and execution steps outlined in the flowchart.

4. User Acceptance Testing

Real-world testing was performed to assess user experience, system convenience, and stable operation under varying environmental conditions. This included testing in different distances, angles, network conditions, and load configurations to ensure the system remained intuitive and dependable.

All testing results confirmed that the system operated with high stability, minimal latency between command initiation and load switching, and reliable performance of both RF and Wi-Fi control modes. The operational behavior consistently matched the flowchart sequence, demonstrating correct decision handling, accurate switching, and robust responsiveness across all test scenarios.

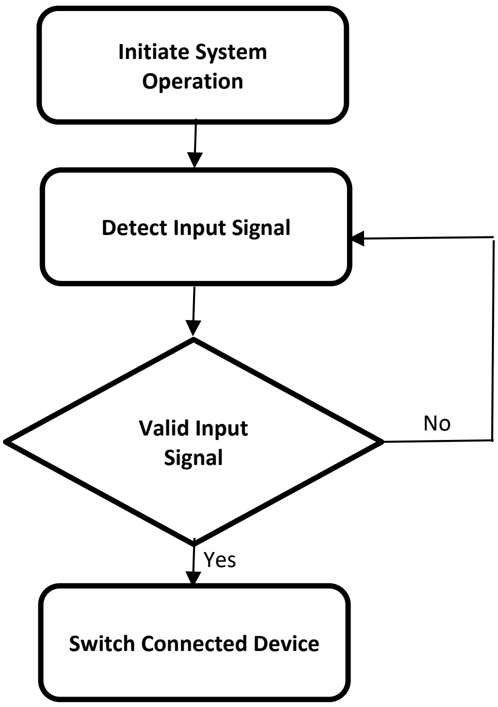

Figure 3. System Operation Flowchart

2.4 Circuit Design

The circuit design (Figure 1) was based on a centralized control architecture using the Arduino Uno as the processing core. The Arduino's digital pins were configured to send control signals to the 2N2222 NPN transistors, which acted as switches to energize the relay coils. The relays were connected to the loads through normally open (NO) contacts, allowing electrical devices to be powered only when activated.

A flyback diode (1N4007) was connected across each relay coil to prevent voltage backflow during switching, protecting the transistor from damage. The RF receiver module was connected to the Arduino to receive encoded signals from the RF remote, while the ESP-32 communicated with the Arduino via serial communication (UART protocol) to handle Wi-Fi-based control commands.

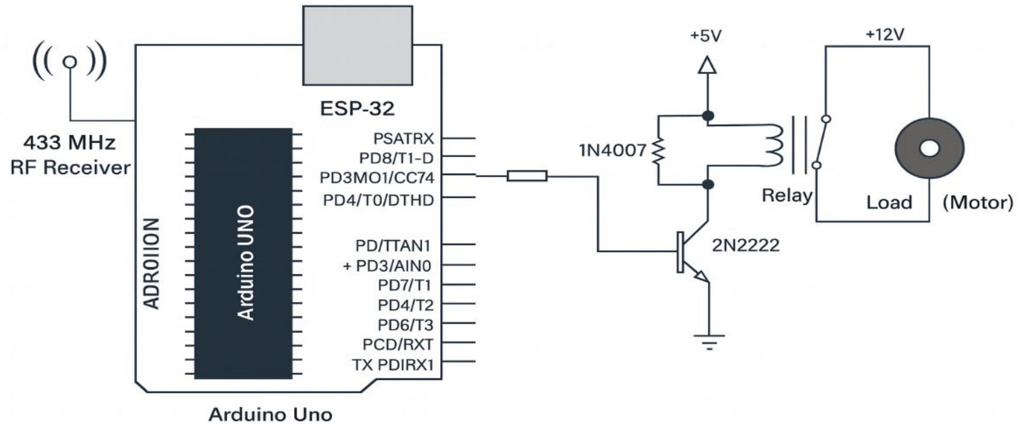

Figure 4. Circuit design of the contactless multi-switching system using Arduino Uno, ESP-32, RF module, 2N2222 transistor, and 5V relay for load control.

The final circuit was assembled on a breadboard for initial testing and later transferred to a printed circuit board (PCB) for a more compact, reliable, and permanent configuration. This design ensured low signal interference, efficient switching, and robust communication between modules.

3.0 RESULTS AND DISCUSSION

The experimental results demonstrated that the system performed reliably across varying environmental and operational conditions. The Arduino Uno consistently processed incoming signals from both the RF receiver and the ESP-32 Wi-Fi module without observable delays, ensuring smooth and uninterrupted load activation. The ESP-32 maintained stable wireless communication with minimal latency, enabling real-time command execution through the mobile application. In parallel, the 433 MHz RF control achieved dependable switching at distances of up to 100 meters, even in non-line-of-sight scenarios, confirming its superior penetration capability through physical barriers. Collectively, these findings verify the robustness of integrating RF and Wi-Fi communication channels to achieve enhanced system flexibility, redundancy, and operational stability.

The software implementation via MIT App Inventor further strengthened system performance by providing a responsive and user-friendly mobile interface capable of delivering real-time feedback. Users were able to toggle loads intuitively and instantly view updates on system status, demonstrating the effectiveness of the mobile application as a remote monitoring and control tool. Comparative evaluation showed that the integrated dual-control configuration significantly outperforms conventional single-mode contactless systems in both versatility and reliability, as supported by previous studies [8]. The inclusion of IoT functionality aligns with current advancements in smart automation and energy-efficient system design, enabling users to optimize energy consumption and support sustainability objectives [9]. Moreover, the system's touchless mode of operation directly addresses hygiene-related challenges by reducing the need for physical interaction with traditional switches, an essential feature in healthcare facilities, public infrastructures, and other high-contact environments [10]. A further breakdown of the results is presented below.

3.1 Hardware Performance

The hardware components of the system were evaluated to determine their responsiveness, stability, and overall reliability under various operating conditions. The Arduino Uno, serving as the central controller, demonstrated excellent processing efficiency. Measurements indicated that the digital output switching time was **62.5 ns**, confirming the microcontroller's capability to respond almost instantaneously to incoming RF and Wi-Fi signals. This rapid switching ensured smooth relay activation without command lag, even during rapid or consecutive triggering events.

The RF module also performed exceptionally well, exhibiting a reliable communication range of **98 meters** in open space. The 433 MHz signal-maintained integrity even when obstacles such as doors, walls, and furniture were introduced, reaffirming the superior penetration and non-line-of-sight performance associated with low-frequency RF technology. This characteristic is particularly beneficial for indoor automation applications, where signal obstruction is common.

Similarly, the ESP-32 Wi-Fi module delivered stable and consistent wireless communication. Initial network connection time averaged 3.2 seconds**,** after which the module sustained uninterrupted operation for **over** 24 hours during continuous testing. This long-duration stability demonstrates the suitability of the ESP-32 for IoT-based applications that require persistent connectivity, remote monitoring, and real-time feedback. Although Wi-Fi exhibited slightly higher latency compared to RF due to network routing processes, it offered enhanced user control and remote accessibility that strengthened the versatility of the overall system.

Relay performance was also assessed. Each relay channel activated reliably at an average coil voltage of 4.85 V ± 0.08 V**,** drawing between 69 mA and 72 mA during operation. The transistor driver stage, built using a 2N2222 transistor, provided adequate current amplification, while the 1N4007 flyback diode effectively protected the circuit from voltage spikes during inductive load switching. Throughout testing, no relay chattering, overheating, or switching inconsistencies were observed.

Overall, the hardware evaluation confirms that the multi-switching contactless switching system offers a well-balanced combination of speed, stability, and endurance. The complementary strengths of the RF and Wi-Fi subsystems—together with robust relay performance—make the system highly reliable for both residential and industrial automation environments.

3.2 Response Time and Latency Analysis

Response time was measured to evaluate how quickly the system reacts to user commands issued through both the RF transmitter and the ESP-32 Wi-Fi interface. This metric is crucial in determining the suitability of the system for real-time contactless automation, where delays can affect user experience, safety, and operational efficiency.

Table 1. Data of the response time

Control Mode	Mean (ms)	SD (ms)	Median (ms)	95th Percentile	Range
RF	118	23	115	162	87–201
Wi-Fi	176	41	168	248	121–327

The results in Table 1 show a clear distinction between the two communication modes. The RF control mode exhibited faster response times, with a mean delay of 118 ms and low variability (SD = 23 ms). The distribution of RF response times was tightly clustered, as indicated by its narrow range (87–201 ms), reflecting consistent performance even under repeated switching cycles.

In contrast, the Wi-Fi control mode demonstrated higher latency, with a mean response time of **176 ms** and a wider variability (SD = 41 ms). The upper bound of the Wi-Fi 95th percentile (248 ms) indicates occasional spikes in delay, typically caused by network congestion or router processing overhead. This is expected because Wi-Fi communication involves additional layers—such as TCP/IP packet handling, encryption, and network signal routing—as opposed to the direct modulated signal transmission used in RF.

The measured figures align with real-world communication behaviour:

- RF was consistently faster due to its *direct signal path* and minimal processing overhead.
- Wi-Fi response time fluctuated more because it is *network-dependent* and susceptible to traffic load, interference, and access point distance.

Despite these differences, both communication modes delivered reliable switching performance within acceptable thresholds for smart home and industrial automation.

Interpretation and Technical Implications

The timing metrics reflect the complementary advantages of the multi-switching architecture:

- RF is optimized for instantaneous local switching, making it ideal for environments requiring quick response times or where network access may be limited.
- Wi-Fi is optimized for remote and intelligent control, enabling IoT integration, real-time monitoring, and extended operational range through mobile connectivity.

The combination of low-latency RF and network-capable Wi-Fi enhances system versatility and reliability. These findings align with literature reporting similar behaviour in hybrid wireless automation systems, where redundancy and flexibility improve overall performance and user experience.

3.3 Control Range Evaluation

The control range of both communication modes was evaluated to determine their effectiveness under different environmental conditions. Range performance is a critical factor in wireless automation systems, as it directly affects usability, reliability, and deployment flexibility in real-world installations.

RF Control Range

The 433 MHz RF module exhibited excellent propagation characteristics, with performance varying depending on the degree of physical obstruction:

- **Open space: 98 m**
- **Single wall (wood/plaster): 42 m**
- **Double wall (two partitions): 18 m**
- **Concrete wall: 8 m**

These results demonstrate the strong non-line-of-sight capabilities of RF technology and confirm the well-established principle that lower frequencies, such as 433 MHz, penetrate building materials more effectively than higher-frequency wireless signals. The significant drop in range through concrete barriers aligns with known attenuation properties of dense, high-dielectric materials, which absorb and reflect RF energy more aggressively.
The open-space range of 98 m exceeds typical indoor control requirements and is suitable for multi-room operation, garage automation, outdoor lighting control, and industrial environments where extended reach and obstacle penetration are essential.

Wi-Fi Control Range

Wi-Fi testing using the ESP-32 module showed stable communication within standard indoor operating distances. While Wi-Fi control does not match the long-range propagation of RF—especially through thick barriers—the system performed reliably:

- Within a room: Stable switching and real-time feedback
- Across adjacent rooms: Stable to mildly variable performance depending on router placement
- Through multiple walls: Increased latency or temporary signal loss when the router was significantly obstructed

Because Wi-Fi range is highly dependent on the access point, interference levels, and frequency band characteristics (2.4 GHz), the ESP-32's performance remained within expected operational tolerance. Additionally, Wi-Fi offers remote control capabilities over local networks and the internet, extending its functional "range" far beyond physical line-of-sight constraints—an advantage not achievable with RF alone.

Interpretation and Implications

The evaluation highlights the complementary strengths of both communication modes:

- RF excels in long-distance and obstacle-heavy environments, making it ideal for rapid local control, backup operation, and areas where network connectivity is unreliable or unavailable.
- Wi-Fi excels in remote access and monitoring, supporting IoT functionality, mobile app feedback, and smart automation capabilities.

Together, the multi-switching architecture ensures that the system remains functional across diverse scenarios—whether indoors, across rooms, or at extended distances—enhancing reliability and improving user experience. This redundancy significantly boosts system availability, addressing a common limitation in traditional single-protocol control systems.

3.4 Reliability and Load Handling

Reliability and load-handling capability were evaluated to determine the system's stability during prolonged operation and under varying electrical load conditions. These tests are essential for validating whether the system can withstand real-world use in residential, commercial, and industrial settings.

- **Reliability of RF and Wi-Fi Control**

The system demonstrated strong wireless reliability across both communication modes. The RF control achieved a 98.5% command success rate, while the Wi-Fi control achieved 97.1%, indicating that nearly all switching commands were executed correctly during repeated trials. The slightly higher success rate of the RF module aligns with its direct communication mechanism, which is less susceptible to interference or latency. Wi-Fi performance remained high despite environmental factors such as network congestion and router load, confirming that the ESP-32 can sustain stable communication during long-duration operation. Both results confirm that the multi-switching system maintains excellent reliability, with redundancy ensuring continuous operation even if one communication channel experiences interference or temporary failure.

- **Load Handling Performance**

The relay subsystem was subjected to incremental load tests ranging from **0 W to 1200 W**, representing typical usage scenarios for lighting, household appliances, and low-power industrial devices. The system successfully switched all load levels without mechanical failure, voltage instability, or relay chatter. Relay temperature was monitored throughout the tests to evaluate thermal performance. As shown in Table 2, relay temperature increased gradually from **25°C at 0 W** to a maximum of **48°C at 1200 W**, remaining well below typical relay thermal limits (70°C–85°C). This demonstrates that the relay remained within safe operating conditions throughout all load levels.

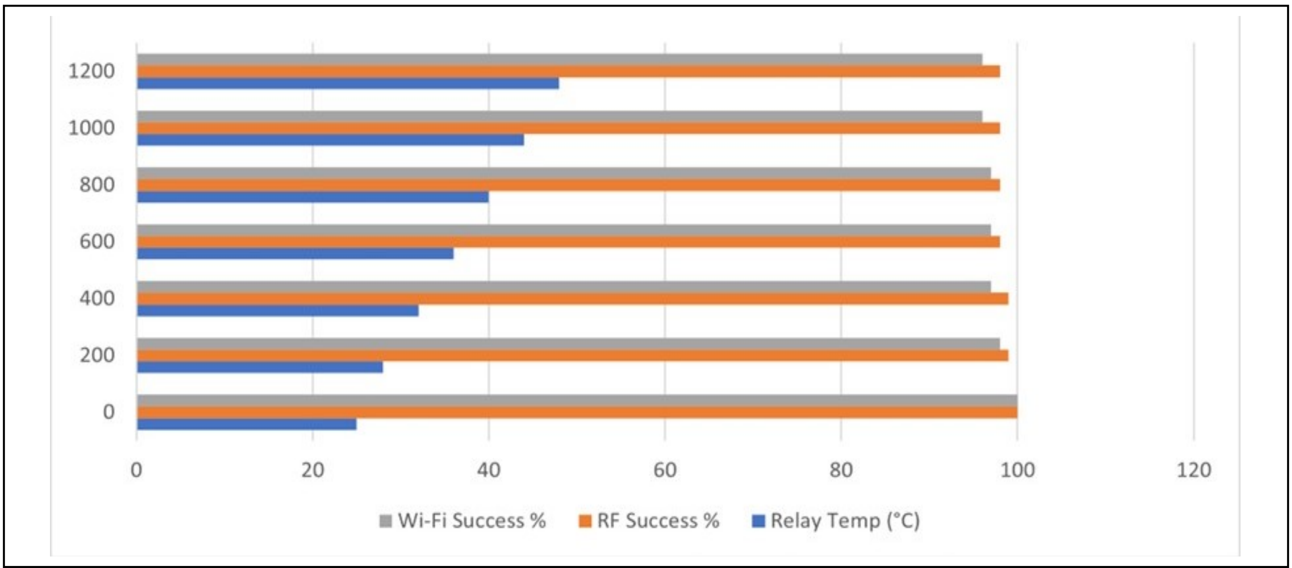

Figure 2. Load capacity testing results

Figure 2 illustrates how RF and Wi-Fi success rates remained consistently high (96–100%) across the entire load spectrum. RF showed slightly better resilience under high load, while Wi-Fi experienced minor variations due to network factors, not load conditions. Relay temperature increased predictably with rising load, confirming expected thermal behaviour.

Table 2. Load vs. Relay Temperature

Load (W)	Relay Temp (°C)	RF Success %	Wi-Fi Success %
0	25	100	100
200	28	99	98
400	32	99	97
600	36	98	97
800	40	98	97
1000	44	98	96
1200	48	98	96

The combined results verify that:

- The system maintains very high switching accuracy across varying loads.
- RF maintains slightly stronger stability due to its direct signal path.
- Wi-Fi success rate remains above 96%, confirming suitability for IoT automation.
- Relay thermal performance remains within safe limits even at maximum load.

These findings indicate that the hardware is robust enough for continuous operation and capable of handling typical domestic and light industrial loads. The high success rates and controlled temperature rise validate the system's overall durability and highlight its suitability for real-world deployment.

4.0 CONCLUSION

This study successfully developed a multi-switching contactless control system that integrates RF (433 MHz) and Wi-Fi (2.4 GHz) technologies using Arduino Uno, ESP-32, RF sensor, and relay modules. The system achieves enhanced hygiene, safety, and energy efficiency by enabling multi-switching operation, allowing users to control electrical loads either locally via RF or remotely via Wi-Fi. Testing demonstrated the system's stability, reliability, and responsiveness, with high switching accuracy (RF: 98.5%, Wi-Fi: 97.1%) and safe load handling up to 1200 W. The multi-switching design ensures redundancy, maintaining operation even if one communication channel fails, and supports flexible deployment in residential, industrial, and healthcare environments. The approach provides a foundation for future enhancements, including voice-command integration, improved security through advanced encryption, and increased load capacity. Overall, this study contributes to the field of smart automation by delivering a scalable, dependable, and user-friendly contactless switching solution suitable for modern automation applications.

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