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An Offline-First Low-Cost Smart Home Automation System Using Bluetooth and Android-Based Voice Control for Resource-Constrained Environments

Muhammad I Abdulganiyu[1], Isaac H Daniel[1], Alhassan Shuaibu[1], and Nicodemus Kure[1]

[1] Department of Physics, Kaduna State University, Kaduna, Kaduna State, Nigeria

Corresponding E-mail: almahzubs@gmail.com

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Abstract

The widespread adoption of Internet of Things (IoT)-based smart home systems has led to increasing reliance on cloud-dependent architectures that require stable internet connectivity. However, such dependence restricts deployment in environments with limited or unreliable network infrastructure. This study presents the design, implementation, and performance evaluation of an offline-first smart home automation system based on Bluetooth communication and Android-based voice control. The system integrates a NodeMCU ESP8266 microcontroller, an HC-05 Bluetooth module, and a multi-channel relay interface to enable localized appliance control without internet dependency. A dual-mode interaction framework is implemented, supporting both manual control through a graphical user interface and voice-command input using speech recognition. System performance is evaluated in terms of response time, communication range, packet delivery success rate, power consumption, and operational stability. Experimental results indicate average response times of 0.3 s and 0.8 s for manual and voice-control modes, respectively, with stable communication achieved over a 10 m line-of-sight range. Packet delivery success rates of 98.0% and 94.5% were obtained under line-of-sight and obstructed indoor conditions, respectively, demonstrating reliable command execution in practical operating environments. The results demonstrate that the proposed offline-first architecture provides a robust, cost-effective, and infrastructure-independent solution for localized smart home automation, particularly in resource-constrained environments.

Keywords: Smart home automation; Bluetooth communication; Android voice control; Internet of Things (IoT); offline-first architecture; embedded systems; resource-constrained environments.

I. Introduction

Smart home automation has become an important application of the Internet of Things (IoT), enabling the monitoring and control of household devices through interconnected systems [1–3]. Various IoT architectures have been proposed for smart environments, incorporating wireless communication, embedded control, and cloud-based technologies [2], [4–5]. Many smart home solutions employ internet-enabled communication technologies, including Wi-Fi and cloud-based platforms, to provide remote accessibility and support system scalability [4], [6–8]. However, reliance on internet connectivity can limit their effectiveness in environments where network access is unavailable, unstable, or unreliable. Internet-connected smart home architectures may also introduce security and privacy concerns associated with remote connectivity and data exchange [9].

In many developing and resource-constrained environments, limitations in network availability and supporting infrastructure can restrict the practical deployment of internet-dependent automation systems [10–11]. This has motivated interest in low-cost smart home solutions that can operate locally using affordable embedded platforms and require minimal external communication infrastructure [12]. Such architectures can provide localized appliance control without continuous dependence on external networks, making them potentially suitable for environments with limited connectivity.

Existing studies have explored various approaches to home automation, including GSM-based systems, Wi-Fi-enabled IoT platforms, Bluetooth-based automation systems, and voice-controlled interfaces [8], [13–16]. These approaches differ in their communication requirements, deployment complexity, operating range, and dependence on external network infrastructure. Bluetooth-based systems are particularly suitable for short-range localized control because they enable direct communication between mobile devices and embedded controllers without requiring continuous internet connectivity [15], [17]. Bluetooth Low Energy (BLE)-based implementations have also demonstrated the feasibility of energy-efficient localized appliance control in smart home environments [17]. By enabling direct communication between the mobile device and the control unit, Bluetooth-based architectures can reduce dependence on external communication infrastructure and support autonomous local operation.

This study presents an offline-first smart home automation system that integrates Bluetooth communication with Android-based manual and voice control for localized appliance management. Unlike internet-dependent smart home platforms, the proposed architecture emphasizes low-cost deployment, responsive local control, operational reliability, and independence of the core appliance-control functions from internet infrastructure. The system is experimentally evaluated in terms of response time, communication range, packet delivery success rate, power consumption, and operational stability under practical indoor conditions. In addition to dual-mode manual and voice-based interaction, the study provides a quantitative evaluation of communication reliability and system performance under line-of-sight and obstructed operating conditions. The proposed architecture, therefore, provides a practical and cost-effective approach to localized smart home automation, particularly for deployment in resource-constrained environments.

II. Materials and Methods

A. System Design and Architecture

The developed smart home automation system adopts a modular architecture comprising a user interface, communication interface, control unit, and switching unit. The overall system architecture is illustrated in Fig. 1. An Android smartphone serves as the user command interface and communicates wirelessly with the HC-05 Bluetooth module. The HC-05 module provides the communication interface between the smartphone and the NodeMCU ESP8266 controller. The NodeMCU processes the received commands and generates the corresponding control signals for the four-channel relay module, which performs independent switching of the assigned loads.

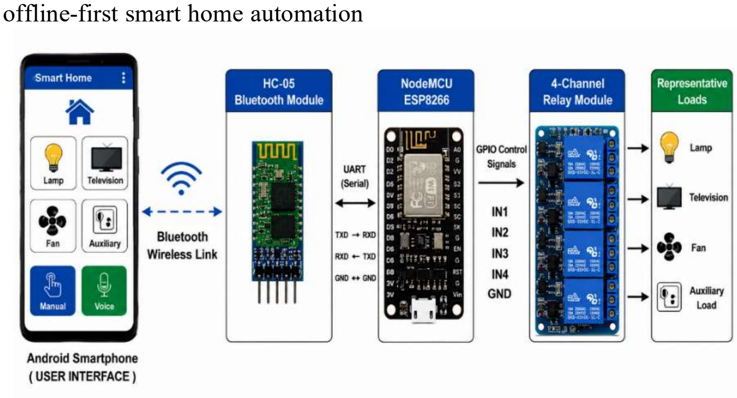

Fig. 1. System architecture of the proposed smart home automation system.

The hardware implementation of the control unit is presented in Fig. 2 from different viewing angles. The implementation comprises the NodeMCU ESP8266 controller, HC-05 Bluetooth module, four-channel relay module, and associated interconnections. The HC-05 module was configured in slave mode and interfaced with the NodeMCU through serial communication at a baud rate of 9600 bps. The four-channel relay module provides the switching interface between the low-voltage control circuitry and the connected load circuits, enabling the NodeMCU to control the assigned loads independently.

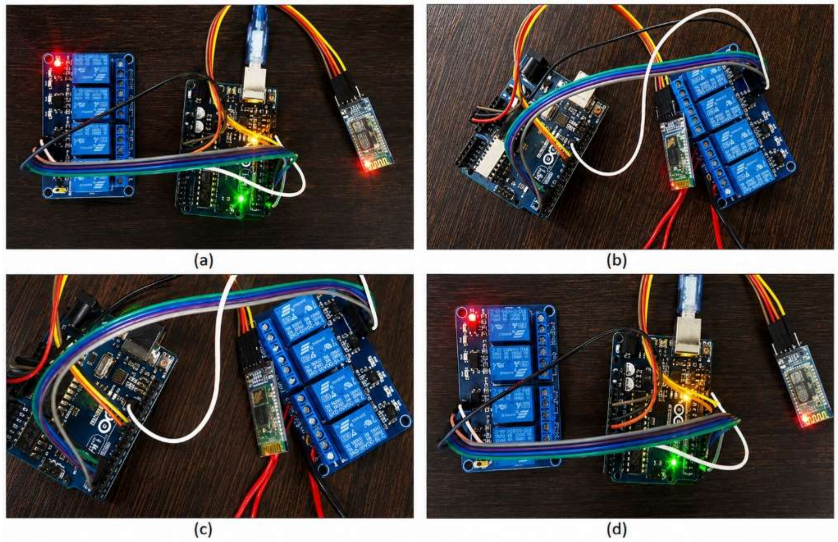

Fig. 2. Hardware implementation of the developed smart home automation control unit showing the NodeMCU ESP8266, HC-05 Bluetooth module, four-channel relay module, and associated interconnections from different viewing angles: (a)–(d).

B. Experimental Prototype and Representative Loads

The experimental prototype developed for system validation is shown in Fig. 3. The prototype comprises an enclosed control unit and four coloured bulbs connected to the individual relay channels. The bulbs were used as representative loads to demonstrate multi-channel switching, with the burgundy, orange, yellow, and green bulbs assigned to represent a lamp, fan, television, and auxiliary load, respectively. This configuration enabled the independent switching functionality of the four relay channels to be evaluated under controlled experimental conditions.

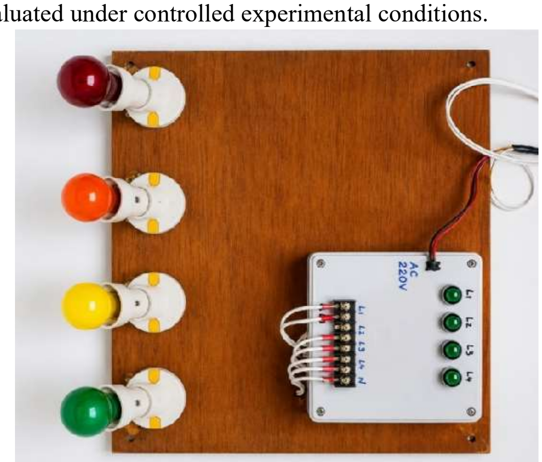

Fig. 3. Experimental prototype of the developed smart home automation system showing the enclosed control unit and four coloured bulbs used as representative loads.

Fig. 4 shows the hardware control unit before and after the enclosure. Fig. 4(a) presents the internal arrangement of the electronic components and associated wiring, while Fig. 4(b) shows the completed control unit housed within the enclosure.

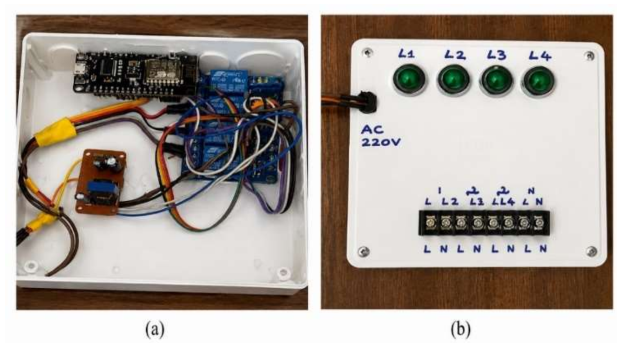

Fig. 4. Hardware control unit of the developed smart home automation system: (a) internal component arrangement before enclosure and (b) completed unit after enclosure.

C. Android Application and System Operation

An Android smartphone running Android 11 was used as the user interface device for both manual and voice-based control operations. Bluetooth pairing between the smartphone and the HC-05 module established a direct communication link between the mobile application and the control unit. Consequently, the core appliance-control communication pathway operated locally without requiring internet connectivity or cloud-based services.

The Android application user interface is shown in Fig. 5. The home dashboard in Fig. 5(a) provides access to the available control functions, while Fig. 5(b) presents the ON/OFF control interface for individual loads. Fig. 5(c) shows the voice-control interface, which enables voice-command input and displays the Bluetooth connection status.

During operation, user commands are processed by the Android application and transmitted as encoded signals through the Bluetooth communication link. The NodeMCU decodes the received signals and activates the corresponding relay channels to control the assigned representative loads.

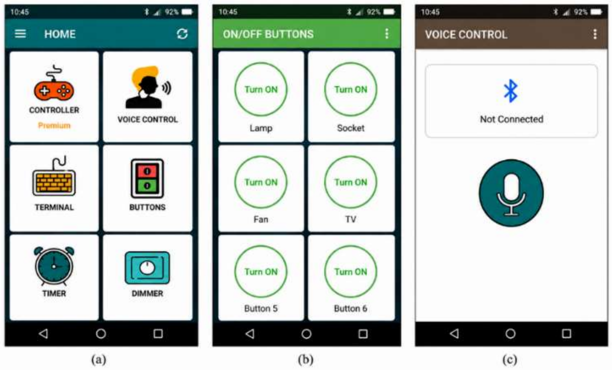

Fig. 5. Android application user interface: (a) home dashboard, (b) ON/OFF load-control interface, and (c) voice-control interface.

D. Response-Time Model

Following the general end-to-end latency decomposition approach used in IoT systems, in which overall response time is represented by the cumulative delays associated with individual processing and communication stages, the total response time of the proposed system was modelled as given by (1) [18].

$$T_{total} = T_{user} + T_{proc.} + T_{comm.} + T_{relay} \quad (1)$$

where T_{user}, $T_{proc.}$, $T_{comm.}$, and T_{relay} represent the delays associated with user interaction, application processing, Bluetooth communication, and relay switching, respectively. Equation (1) adapts the general end-to-end latency decomposition principle to the functional stages of the proposed smart home automation system.

E. Experimental Setup and Performance Evaluation

The experimental evaluation of the proposed smart home automation system was conducted in a controlled indoor environment to assess functional performance, response time, communication range, communication reliability, power consumption, and operational stability. The primary test environment consisted of a furnished room with approximate dimensions of 5 m × 4 m × 3 m, representing a typical indoor residential setting. Both line-of-sight (LOS) and obstructed communication scenarios were considered to evaluate system performance under different indoor propagation conditions.

1) Functional Performance Test

The functional performance of the system was evaluated by independently switching the four representative loads using both manual and voice-control modes. Commands were transmitted from the Android application to the NodeMCU controller through the HC-05 Bluetooth link, and the corresponding relay-channel activation was observed. Successful operation was defined as the correct activation of the intended relay channel in response to the transmitted command without unintended switching of another channel.

2) Response-Time Measurement

Response-time measurements were performed through repeated switching operations in both manual and voice-control modes. Each measurement was repeated ten times under identical operating conditions to assess the consistency of system response. Response time was measured from the instant a user command was initiated through the smartphone application to the activation of the corresponding relay channel. The mean response time and standard deviation were determined separately for the manual and voice-control modes.

3) Communication-Range Evaluation

Communication-range measurements were performed incrementally using a measuring tape under both LOS and obstructed conditions. The LOS test was conducted in an open corridor without physical obstructions between the smartphone and the control unit. The obstructed test was conducted with an interior wall and indoor furniture positioned between the smartphone and the HC-05 Bluetooth module to represent a practical indoor communication environment. At each test distance, communication was considered successful when transmitted commands were correctly received and executed without interruption.

4) Packet Delivery Success and Error-Rate Evaluation

Communication reliability was evaluated through repeated command-transmission tests under both LOS and obstructed conditions. A total of 200 control commands were transmitted from the Android application to the NodeMCU controller under each test condition. A command was classified as successfully delivered when the corresponding relay channel was correctly activated on the first transmission without retransmission.

The packet delivery success rate was calculated as the ratio of successfully executed commands to the total number of transmitted commands, expressed as a percentage. The corresponding error rate was determined as the percentage of commands that were not correctly executed on the first transmission. The system was also monitored for unintended relay activation and false switching events during the tests.

5) Power Consumption Measurement

The power consumption of the control system was measured using a digital power meter under standby and active operating conditions. During standby measurement, the NodeMCU ESP8266 and HC-05 Bluetooth module remained powered while the relay channels were inactive. During active measurement, the system was operated with relay switching enabled. The power consumed by the representative loads was excluded from the measurements to isolate the power requirement of the control circuitry.

6) Operational Stability Test

To evaluate operational stability over an extended period, the developed prototype was subjected to a continuous 4-hour operation test under periodic switching conditions. Repeated switching commands were executed using both manual and voice-control modes with the representative loads.

Throughout the test, the system was monitored for communication interruptions, missed commands, unintended relay activation, relay malfunction, and software or controller failure. Bluetooth communication behaviour following temporary loss of connectivity due to increased separation distance or physical obstruction was also observed after the smartphone was returned within the effective communication range.

III. Results and Discussion

The developed system was experimentally evaluated to assess its functional performance, response time, communication range, communication reliability, power consumption, and operational stability.

A. Functional Performance

The functional performance of the system was evaluated using the four representative loads connected to the relay channels. Each relay channel was assigned to represent a specific household appliance, and switching operations were performed using both manual and voice-control modes. As summarized in Table I, all four relay channels responded successfully to the corresponding control commands during functional testing.

Table I. Functional Performance of the Representative Load Channels.

Channel	Appliance	Mode	Status
IN1	Lamp	Voice/Manual	Successful
IN2	TV	Voice/Manual	Successful
IN3	Fan	Voice/Manual	Successful
IN4	Auxiliary appliance	Voice/Manual	Successful

The successful operation of all four channels demonstrates the ability of the developed system to independently control multiple representative loads using either manual or voice-based commands.

B. Response Time Analysis

The response-time performance of the system was evaluated for both manual and voice-control modes. The average response times obtained from ten repeated measurements are summarized in Table II and illustrated in Fig. 6.

Table II. Response Time Analysis

Method	Average Response Time (s)	Standard Deviation (s)
Manual	0.30	0.04
Voice	0.80	0.09

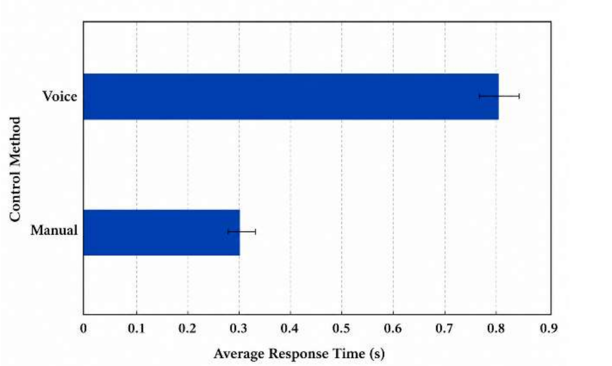

Fig. 6. Comparison of average response times for manual and voice-control modes.

The results show that manual control achieved a shorter average response time of 0.3 s compared with 0.8 s for voice control. The additional delay observed in voice-control mode is primarily attributed to speech-recognition processing within the Android application before command transmission through the Bluetooth link. Nevertheless, both control modes provided responsive operation for the localized switching functions evaluated in this study.

C. Communication Range Evaluation

The Bluetooth communication range was evaluated under both line-of-sight (LOS) and obstructed indoor conditions. The LOS measurements were conducted in an open corridor without physical obstructions, while the obstructed communication test involved an interior wall and indoor furniture positioned between the smartphone and the HC-05 Bluetooth module to represent a practical indoor communication environment. The measured communication ranges are summarized in Table III and illustrated in Fig. 7.

Table III. Bluetooth Communication Range Evaluation.

Condition	Maximum Reliable Range (m)
LOS	10
Obstructed	6

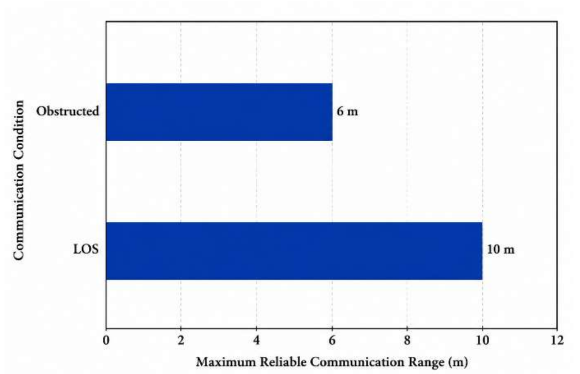

Fig. 7. Maximum reliable Bluetooth communication range under LOS and obstructed indoor conditions.

A maximum reliable communication range of 10 m was achieved under LOS conditions, while the range decreased to 6 m under obstructed conditions. The reduced range in the obstructed environment can be attributed to signal attenuation and multipath propagation effects introduced by the interior wall and indoor furniture. Despite this reduction, the system maintained reliable command execution within the measured 6 m obstructed range, indicating its suitability for short-range localized control in typical indoor environments.

D. Packet Delivery Success and Error Rate Analysis

To evaluate communication reliability, the packet delivery success rate and corresponding error rate of the Bluetooth communication link were experimentally assessed under repeated transmission conditions. A total of 200 control commands were transmitted from the Android application to the NodeMCU controller under each of the line-of-sight (LOS) and obstructed indoor conditions. A command was considered successfully delivered when the corresponding relay channel was correctly activated on the first transmission without retransmission.

Under LOS conditions, 196 of the 200 transmitted commands were successfully executed, corresponding to a packet delivery success rate of 98.0% and an error rate of 2.0%. Under obstructed conditions, 189 commands were successfully executed, corresponding to a packet delivery success rate of 94.5% and an error rate of 5.5%. No unintended relay activations or false switching events were observed during the tests. The lower packet delivery success rate under obstructed conditions can be attributed to signal attenuation and multipath propagation effects introduced by the interior wall and indoor furniture. Nevertheless, the results demonstrate reliable command execution within the evaluated indoor communication range.

E. Power Consumption Measurements

The power consumption characteristics of the developed system were evaluated under standby and active operating conditions using a digital power meter. During standby operation, when the NodeMCU and HC-05 Bluetooth module remained powered without relay activation, the control system consumed approximately 1.8 W. Under active switching conditions involving relay operation, the measured power consumption increased to approximately 3.5 W, excluding the connected representative loads. These measurements indicate the relatively modest power requirement of the control circuitry under the evaluated operating conditions. However, because no direct power-consumption comparison with alternative communication architectures was performed, the results are presented as a characterization of the developed system rather than as evidence of superior energy efficiency.

F. Operational Stability

To evaluate the operational stability of the developed system, the prototype was operated continuously for 4 hours under periodic switching conditions. During this period, repeated control operations were performed using both manual and voice-control modes with the representative loads. The NodeMCU ESP8266 maintained stable operation throughout the test, with no observed software crashes, unexpected system resets, unintended relay activation, or relay malfunction. Consistent command processing and relay switching were also maintained during repeated operation.

Temporary Bluetooth disconnections occurred when the smartphone was moved beyond the effective communication range or when communication was sufficiently obstructed. Normal control operation was restored following reconnection after the smartphone returned within the effective Bluetooth communication range. No persistent communication failure or controller malfunction was observed during the test period. These observations demonstrate the stable operation of the proposed system during the 4-hour continuous test under the evaluated indoor conditions.

G. *Comparison with Existing Smart Home Automation Systems*

Previous studies have demonstrated the feasibility of Bluetooth- and Bluetooth Low Energy (BLE)-based architectures for localized smart home appliance control using mobile devices and embedded controllers [14], [19], [17]. Such architectures enable direct short-range communication between the user device and the control unit and can therefore support local appliance control without continuous dependence on internet connectivity. In contrast, internet-enabled home automation architectures may incorporate Wi-Fi connectivity and cloud-based services to provide remote access and additional IoT functionality [7], [8], [16].

The proposed system achieved average response times of 0.3 s for manual control and 0.8 s for voice-control operation. The longer response time observed during voice control was attributed primarily to the additional speech-recognition processing required before command transmission. Because response-time measurements reported in existing smart home studies are often obtained using different architectures, experimental conditions, and definitions of latency, a direct quantitative comparison was not undertaken. Nevertheless, the measured response times demonstrate responsive local switching performance under the operating conditions evaluated in this study.

The proposed offline-first architecture enables the core appliance-control communication pathway to operate locally between the Android smartphone and the NodeMCU controller through Bluetooth communication. This reduces dependence on external network infrastructure for basic appliance switching while supporting both manual and voice-based interaction. The experimental results, therefore, demonstrate the feasibility of the proposed architecture as a low-cost and infrastructure-independent approach to localized smart home automation, particularly in resource-constrained environments.

Although the present study focuses on a Bluetooth-based implementation, existing literature on internet-enabled and Wi-Fi-based smart home systems provides useful context for considering the relative characteristics of different communication architectures [7–8], [16]. Wi-Fi-enabled systems can support network-based remote accessibility and integration with internet and cloud services, making them suitable for applications requiring remote monitoring and broader IoT connectivity. However, these capabilities depend on the availability of supporting network infrastructure [7], [8].

In contrast, Bluetooth-based systems enable direct short-range communication between mobile devices and embedded controllers, reducing the infrastructure required for localized appliance control [15], [17]. In the proposed system, commands are exchanged locally through the Bluetooth communication link, allowing the core switching functions to operate independently of external network connectivity. However, Bluetooth communication has a limited operating range, as demonstrated by the measured maximum reliable ranges of 10 m under LOS conditions and 6 m under obstructed indoor conditions. Consequently, Bluetooth-based architectures are particularly suited to short-range localized automation where simplicity and independence from continuous internet connectivity are priorities, whereas Wi-Fi-based architectures may be more appropriate for applications requiring remote accessibility, broader network integration, and cloud-based functionality.

Overall, the experimental findings demonstrate reliable, localized operation of the proposed system, with packet delivery success rates of 98.0% and 94.5% under LOS and obstructed conditions, respectively, and stable functionality throughout the 4-hour continuous operation test. Together with the measured response times, communication ranges, and power consumption characteristics, these results indicate that the proposed offline-first architecture provides a practical approach to short-range indoor automation under the operating conditions evaluated in this study.

IV. CONCLUSION

This study presented the design, implementation, and experimental evaluation of an offline-first smart home automation system based on Bluetooth communication and Android-based manual and voice control. The developed system integrates a NodeMCU ESP8266, an HC-05 Bluetooth module, and a four-channel relay module to provide localized control of representative household loads while allowing the core appliance-control functions to operate independently of continuous internet connectivity.

Experimental evaluation demonstrated successful control of all four representative load channels using both manual and voice-control modes. Average response times of 0.3 s and 0.8 s were obtained for manual and voice control, respectively. The system achieved maximum reliable communication ranges of 10 m under line-of-sight conditions and 6 m under obstructed indoor conditions. Packet delivery success rates of 98.0% and 94.5% were recorded under the respective conditions, demonstrating reliable short-range communication within the evaluated indoor environment. The control circuitry consumed approximately 1.8 W during standby operation and 3.5 W under active switching conditions, excluding the representative loads. Furthermore, the system maintained stable functionality throughout the 4-hour continuous operation test without observed software crashes, unintended relay activation, or relay malfunction.

These findings demonstrate the feasibility of the proposed architecture as a practical and infrastructure-independent approach to localized smart home automation. Although Bluetooth communication is inherently suited to short-range applications and does not provide the remote accessibility associated with internet-enabled architectures, its ability to support direct local communication makes the proposed system suitable for small-scale indoor automation, particularly in resource-constrained environments with limited or unreliable network connectivity. Future work will investigate hybrid Bluetooth/Wi-Fi communication architectures, enhanced security mechanisms, integrated energy monitoring, and intelligent control algorithms to improve the scalability, functionality, and adaptability of the system.

DATA AND CODE AVAILABILITY

The data supporting the findings of this study are contained within the article. The source code developed for the embedded control and Android-based user interface may be made available by the corresponding author upon reasonable request.

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