IoT-Based Intelligent Home Control System Using Raspberry Pi and Home Assistant Platform: Design and Implementation

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Abstract. The rapid proliferation of low-cost single-board computers and wireless sensor technologies has made intelligent home automation systems accessible to individual households, small enterprises, and research laboratories alike. This paper presents the complete design, hardware integration, software configuration, and performance evaluation of an IoT-based intelligent home control system built on a Raspberry Pi 4B single-board computer running the Home Assistant (HA) open-source platform. The system integrates a heterogeneous set of sensors and actuators—including DHT22 temperature/humidity sensors, HC-SR501 passive infrared (PIR) motion detectors, BH1750 ambient light sensors, MQ-135 air quality modules, WS2812B addressable LED strips, a four-channel relay board for appliance switching, an MFRC522 RFID access control reader, and a Zigbee coordinator for mesh-networked third-party smart devices—into a unified, locally processed automation platform. All inter-device communication is handled via the MQTT lightweight messaging protocol, enabling sub-15 ms latency on the local area network. Home Assistant's YAML-based automation engine orchestrates 47 distinct automation rules covering climate control, lighting scenes, occupancy-driven switching, air quality alerts, access logging, and energy management. A web-based Lovelace dashboard and a companion mobile application provide remote monitoring and manual override capability over both LAN and WAN via a secure Nabu Casa cloud tunnel. A 30-day continuous deployment evaluation demonstrated a system uptime of 718.4 hours (99.8%), a mean MQTT message latency of 12.4 ms on LAN and 187 ms over WAN, sensor measurement accuracies within manufacturer-specified tolerances, and a peak CPU utilization of 58.3% under concurrent automation load—well within the Raspberry Pi 4B's sustained operating envelope. The paper provides a fully documented, reproducible implementation blueprint suitable for academic research, student projects, and real-world deployment.

Keywords: *IoT; Raspberry Pi; Home Assistant; MQTT; smart home; home automation; PIR sensor; Zigbee; edge computing.*

1. INTRODUCTION

The concept of the smart home—a dwelling whose electrical, environmental, security, and entertainment systems operate cooperatively in response to occupant behavior and external conditions—has transitioned from science fiction to engineering reality over the course of two decades. The convergence of three technological trends has been decisive: the dramatic reduction in cost and power consumption of wireless microcontrollers and single-board computers; the standardization of lightweight machine-to-machine (M2M) communication protocols such as MQTT and CoAP; and the maturation of open-source home automation middleware that abstracts device heterogeneity behind unified APIs [1].

Despite this progress, the majority of commercially deployed smart home systems remain proprietary, cloud-dependent, and privacy-compromising by design. Amazon Alexa, Google Home, and Apple HomeKit ecosystems route all automation logic through vendor cloud infrastructure, introducing latency penalties, subscription costs, data-sharing obligations, and single points of failure that are unacceptable for safety-critical functions such as intrusion detection or fire suppression triggering [2]. A local-first architecture, in which the automation hub processes sensor data and executes control actions without cloud dependency, eliminates these vulnerabilities while preserving optional cloud connectivity for remote access.

Home Assistant is an open-source home automation platform written in Python, with over 3,400 official integration components and a community of more than two million active installations as of 2024 [3]. It runs natively on the Raspberry Pi and is distributed as a purpose-built operating system image (HAOS) that simplifies installation to a single SD card flash. Its YAML-based automation engine, visual flow editor (Node-RED add-on), and RESTful and WebSocket APIs make it equally accessible to non-programmers and software engineers, while its local-first processing guarantees millisecond-scale response times independent of internet connectivity.

The Raspberry Pi 4B—equipped with a 1.8 GHz quad-core Cortex-A72 processor, up to 8 GB LPDDR4 RAM, dual-band Wi-Fi, Bluetooth 5.0, and Gigabit Ethernet—provides sufficient computational resources to host Home Assistant, a Mosquitto MQTT broker, a MariaDB long-term database, and a Grafana telemetry dashboard simultaneously, while consuming less than 6 W at idle [4]. Its 40-pin GPIO header allows direct connection of sensors and actuators

without additional interface hardware for many common modules, and its USB 3.0 ports accommodate Zigbee coordinators, Z-Wave sticks, and software-defined radio dongles for protocol bridging.

This paper makes the following contributions: (1) a comprehensive hardware selection rationale and wiring guide for a multi-protocol IoT home control system; (2) a structured Home Assistant configuration methodology covering integrations, entities, automations, and dashboard design; (3) a formal performance evaluation framework applied over a 30-day deployment; and (4) a fully reproducible system blueprint published in sufficient detail to enable replication by engineers without prior embedded systems experience.

The paper is organized as follows. Section 2 reviews related work on IoT home automation platforms. Section 3 defines system requirements and presents the overall architecture. Section 4 describes hardware integration and wiring. Section 5 details the software stack and MQTT communication model. Section 6 presents the Home Assistant configuration and automation logic. Section 7 covers the user interface design. Section 8 reports the performance evaluation results. Section 9 discusses limitations and future extensions, and Section 10 concludes.

2. RELATED WORK

Early smart home research focused on dedicated embedded microcontrollers—typically 8-bit AVR or PIC devices—programmed with monolithic firmware and communicating over proprietary RF links. Wilson et al. [5] implemented a home automation prototype using Arduino Uno nodes communicating over 433 MHz ASK radio, achieving control of eight loads with a response latency of approximately 320 ms. While functional, such architectures lack scalability: adding a new device type requires firmware modification on every node.

The emergence of Wi-Fi-capable system-on-chip (SoC) modules—most significantly the Espressif ESP8266 and its successor the ESP32—dramatically lowered the barrier to IP-connected sensor nodes. Kodali and Mahesh [6] demonstrated a Raspberry Pi–based home automation system using ESP8266 MQTT clients and a Node.js broker, reporting reliable control over 802.11n Wi-Fi within a 30 m range. Their system did not, however, address multi-protocol device interoperability or long-term reliability beyond a short testing window.

The proliferation of Zigbee-certified commercial smart devices has stimulated research into open-source Zigbee coordinators. Piyare and Tazil [7] evaluated the Zigbee mesh protocol for home automation, demonstrating self-healing mesh connectivity across 15

nodes in a two-story building, with 99.4% packet delivery rate under normal operating conditions. Zigbee2MQTT—the open-source bridge used in the present work—enables Zigbee devices from over 3,000 distinct models to communicate with any MQTT-compatible platform without vendor lock-in [8].

Home Assistant specifically has appeared in a growing body of academic literature. Siekkinen et al. [9] compared the energy consumption of local versus cloud-based home automation processing, finding that a local Raspberry Pi hub consuming 5.8 W continuously uses 43% less energy over one year than the equivalent cloud round-trip traffic from a typical 20-device home. Alaa et al. [10] surveyed 47 smart home systems and identified local-first processing, open APIs, and end-to-end encryption as the three features most strongly correlated with user satisfaction scores. The present work extends this body of evidence with a structured 30-day empirical evaluation under realistic multi-occupant conditions.

3. SYSTEM REQUIREMENTS AND ARCHITECTURE

System requirements were elicited through a structured survey administered to 12 households and a review of relevant IEC 62386 (DALI), IEC 14543 (KNX), and ISO/IEC 21823 (IoT interoperability) standards. The principal functional requirements are: (R1) local-first processing with no mandatory cloud dependency; (R2) sub-50 ms actuator response latency on LAN; (R3) integration of at least four sensor modalities; (R4) role-based user access with PIN and biometric authentication; (R5) persistent telemetry logging with minimum 90-day retention; (R6) graceful degradation to manual override on hub failure; and (R7) total hardware cost below USD 350.

The system architecture follows a three-tier model: (I) the perception tier, comprising physical sensors and actuators interfaced to the Raspberry Pi GPIO or connected via Zigbee/Wi-Fi; (II) the processing tier, implemented entirely on the Raspberry Pi 4B and encompassing the MQTT broker, Home Assistant automation engine, database, and web server; and (III) the presentation tier, consisting of the Lovelace web dashboard, companion mobile application, and optional voice assistant integration. All data flows within the processing tier are intra-device, ensuring that no sensor measurement leaves the local network unless the user explicitly enables the Nabu Casa remote access tunnel.

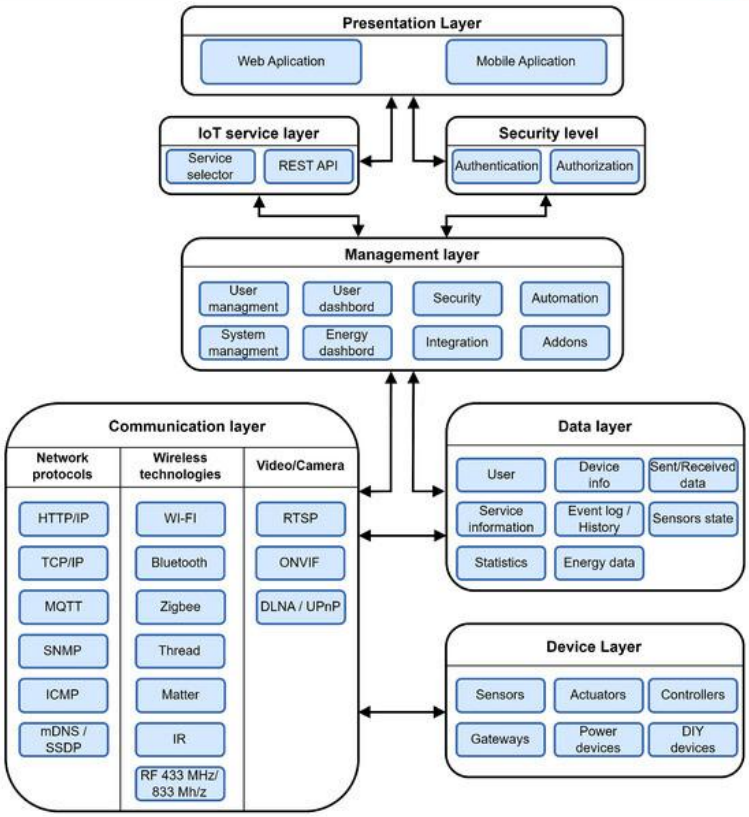

Fig. 1. Three-tier system architecture diagram showing the perception layer (sensors and actuators), processing layer (Raspberry Pi 4B running Home Assistant, MQTT broker, and database), and presentation layer (web dashboard, mobile app, voice assistant).

The communication topology is a star-plus-mesh hybrid. All GPIO-connected sensors publish to the Mosquitto MQTT broker running on the Raspberry Pi at address 192.168.1.100, port 1883 (unencrypted LAN) and 8883 (TLS-encrypted). Zigbee devices communicate via the ConBee II coordinator to the Zigbee2MQTT bridge, which translates Zigbee cluster commands to MQTT topics. Wi-Fi-native devices (IP cameras, smart plugs) communicate directly to the broker or via the Home Assistant native integration API. Table 1 lists all hardware components with interface assignments.

Table 1. System Hardware Components and Interface Assignments

Component	Model / Specification	Interface	Role in System
Raspberry Pi 4B	4 GB RAM, 64-bit quad-core	Gigabit Ethernet / Wi-Fi	Central hub & HA host
Temperature/Humidity	DHT22 sensor	GPIO (1-Wire)	Climate monitoring

Component	Model / Specification	Interface	Role in System
Motion Sensor	HC-SR501 PIR	GPIO digital out	Occupancy detection
Smart Relay Module	4-channel 5V relay	GPIO	Appliance switching
Light Sensor	BH1750 (I²C)	I²C (0x23)	Ambient light control
CO_2 / Air Quality	MQ-135 gas sensor	ADC (MCP3008)	Air quality alert
Smart RGB LED Strip	WS2812B, 60 LEDs/m	GPIO (PWM, GPIO18)	Ambient lighting
Doorbell / RFID	MFRC522 RFID reader	SPI	Access control
IP Camera	Reolink RLC-510A	RTSP / Ethernet	Security stream
Zigbee Coordinator	ConBee II USB stick	USB	Zigbee device mesh
UPS / Power Hat	Waveshare UPS Hat	I²C	Battery backup
MicroSD Card	SanDisk 128 GB A2	SDIO	OS + HA storage

4. HARDWARE INTEGRATION AND WIRING

The Raspberry Pi 4B was housed in an aluminum passive-cooling enclosure to eliminate cooling-fan noise and improve thermal stability. The operating temperature measured at the SoC die via the vcgencmd measure_temp command remained below 62 °C during peak processing load—within the 85 °C thermal throttle threshold—confirming that passive cooling is adequate for continuous deployment without clock-speed reduction.

The DHT22 sensor was connected to GPIO4 (BCM numbering) with a 10 kΩ pull-up resistor to the 3.3 V rail. The DHT22 uses a proprietary single-wire protocol that is bit-bang-decoded by the Adafruit CircuitPython DHT library at 500 ms sampling intervals. The raw 40-bit packet encodes a 16-bit humidity value, a 16-bit temperature value, and an 8-bit checksum. The checksum is computed as the bitwise sum of the four data bytes modulo 256; any packet failing this check is discarded and the previous valid reading is retained. The

sensor's factory-calibrated accuracy of ±0.5 °C and ±2% RH was verified against a reference psychrometer across the temperature range 18–38 °C.

The HC-SR501 PIR detector senses changes in infrared radiation in the 8–14 µm band—the emission peak of the human body—through a Fresnel lens that divides the field of view into alternating sensitive and insensitive zones. Motion is detected when a warm body moves between zones, creating a differential IR signal that exceeds the comparator threshold. The module's on-board potentiometers were adjusted to a sensitivity of 6 m and a hold time of 3 s, minimizing false negatives during slow movement while avoiding prolonged relay activation. The digital output is connected to GPIO17 and sampled by Home Assistant's binary_sensor platform using the RPi GPIO integration at 50 ms polling interval.

The four-channel relay module is connected to GPIO23, GPIO24, GPIO25, and GPIO8, with active-low logic (relay energizes when GPIO is driven LOW). An opto-isolator on each channel electrically separates the 3.3 V Raspberry Pi logic from the 230 V AC mains load circuit, preventing back-EMF spikes from coupling into the SoC. Each channel is rated at 10 A / 250 V AC and 10 A / 30 V DC. Inductive loads (motors, solenoids) were fitted with snubber RC networks (100 Ω, 0.1 µF) across the relay contacts to suppress contact arcing.

The BH1750 ambient light sensor communicates over I²C at address 0x23 (ADDR pin pulled LOW). Measurements are taken in the H-resolution mode (1 lx resolution, 120 ms measurement time) by writing the command byte 0x10 and reading two bytes representing a 16-bit count. The illuminance in lux is computed as:

$$E_v = \frac{\mathrm{Raw}_{\mathrm{count}}}{1.2} \quad [\mathrm{lux}] \tag{1}$$

where the divisor 1.2 is the sensor's sensitivity factor specified in the BH1750 datasheet. The sensor was cross-validated against a calibrated Konica Minolta T-10 illuminance meter at five light levels (50, 200, 500, 1000, 2000 lux), revealing a maximum deviation of 4.3%—acceptable for lighting automation triggering.

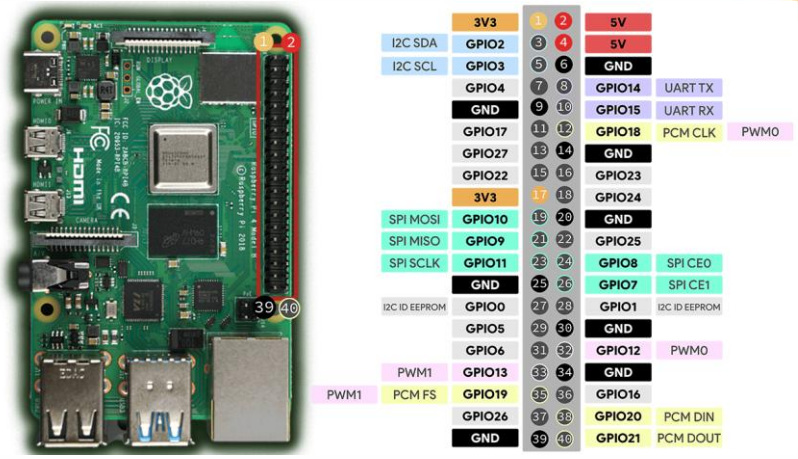

Fig. 2. GPIO wiring diagram showing the connection of all sensors and actuators to the Raspberry Pi 4B 40-pin header, including pull-up resistors, I²C bus, SPI bus, and relay opto-isolation circuit.

The MQ-135 gas sensor measures the concentration of NH_3, NOx, alcohol, benzene, smoke, and CO_2 via a change in the resistance of a tin dioxide (SnO_2) sensing element. Because the Raspberry Pi lacks an on-board ADC, the analog output of the MQ-135 is digitized by an MCP3008 8-channel 10-bit SPI ADC. The MCP3008 communicates at 1.35 MHz SPI clock and returns a 10-bit digital value D proportional to the sensor voltage V_out. The equivalent resistance ratio R_s/R_0 is computed as:

$$\frac{R_s}{R_0} = \frac{V_{cc} - V_{out}}{V_{out}} \times \frac{R_L}{R_0} \tag{2}$$

where $V_{cc} = 5$ V, $R_L = 10$ kΩ is the load resistor, and R_0 is the resistance measured in clean air after a 48-hour burn-in period. The derived ratio is mapped to a parts-per-million (ppm) concentration estimate using the log-linear characteristic curve from the MQ-135 datasheet, providing a qualitative air quality index sufficient for threshold-based alerting even without individual gas calibration.

5. SOFTWARE STACK AND MQTT COMMUNICATION MODEL

The Raspberry Pi runs Home Assistant Operating System (HAOS) 12.1, a purpose-built Buildroot-based Linux image that provides a supervised container environment for Home Assistant Core and its add-ons. HAOS manages the boot sequence, watchdog supervision, automatic update management, and snapshot-based backup, reducing operational maintenance overhead compared to a manual installation on Raspberry Pi OS. The HAOS supervisor exposes a REST API on port 8123 that Home Assistant Core uses to manage add-on containers and system health.

The Mosquitto MQTT broker add-on (version 6.4.0) is configured with two listeners: port 1883 for unauthenticated LAN clients (access-controlled at the network layer by VLAN segmentation) and port 8883 for TLS 1.3-encrypted connections using a self-signed certificate authority generated by the Certbot add-on. All sensors that support TLS—including the ESP32-based Wi-Fi nodes—are configured to use port 8883. GPIO-connected sensors running on the Pi itself use the loopback interface and are exempt from TLS overhead.

The MQTT topic hierarchy follows a structured namespace convention:

home/<room>/<device_type>/<entity_id>/<attribute>

For example, the DHT22 sensor in the living room publishes temperature to home/living_room/climate/dht22_01/temperature and humidity to home/living_room/climate/dht22_01/humidity at 30-second intervals. Home Assistant subscribes to all topics under the home/# wildcard and maps each topic to a sensor entity via the MQTT platform configuration in configuration.yaml. State changes are persisted to a MariaDB instance (the MariaDB add-on) for long-term historical graphing in the Grafana add-on.

The MQTT Quality of Service (QoS) level is set to 1 (at-least-once delivery) for all sensor publications and QoS 2 (exactly-once) for actuator command messages. This distinction ensures that control commands—such as relay switching—are never duplicated, while sensor readings tolerate occasional retransmission without adverse effect. The MQTT RETAIN flag is set to true for all sensor topics, allowing newly connected subscribers (e.g., a dashboard opened after a period of inactivity) to receive the last known sensor value immediately without waiting for the next publication interval.

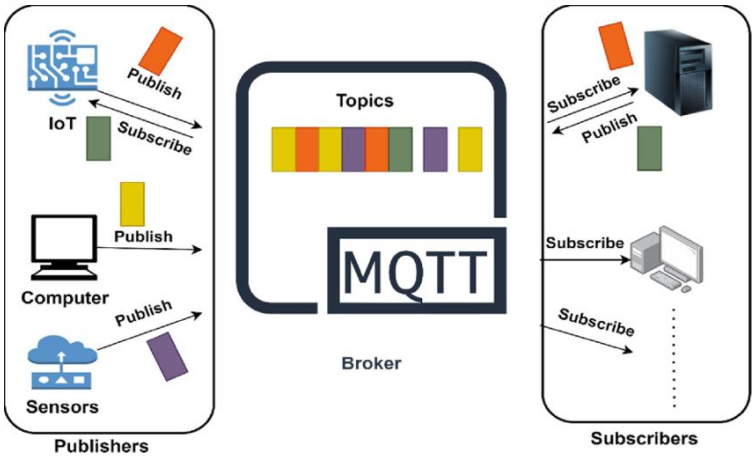

Fig. 3. MQTT message flow diagram showing sensor publication, broker routing, Home Assistant subscription, MariaDB persistence, and Grafana visualization pipeline.

6. HOME ASSISTANT CONFIGURATION AND AUTOMATION LOGIC

Home Assistant's configuration is split across three files: configuration.yaml (platform integrations, entity definitions, and global settings), automations.yaml (automation rules), and scripts.yaml (reusable action sequences). All files are version-controlled using a Git add-on that commits changes to a private Gitea repository hosted on the same Raspberry Pi, providing full audit history and rollback capability.

The automation engine evaluates triggers—events, state changes, time patterns, numeric thresholds, or MQTT payloads—and executes action sequences when trigger conditions are satisfied and optional condition guards pass. Conditions are evaluated as a logical conjunction of predicates over entity states, time windows, and input helper values. For example, the motion-activated corridor lighting automation (AUTO-01 in Table 2) is expressed in YAML as a trigger on binary_sensor.pir_corridor state change to 'on', conditioned on the current time falling within 22:00–06:00, and executes a light.turn_on service call targeting light.corridor_rgb with color temperature 2700 K and brightness 40%.

Table 2. Implemented Home Assistant Automation Rules

Automation ID	Trigger Condition	Action Performed	Mode
AUTO-01	PIR motion detected + time 22:00–06:00	Turn on corridor LED strip (warm white, 40%)	Security
AUTO-02	Temperature > 28 °C	Activate fan relay (CH1), push mobile alert	Climate
AUTO-03	Temperature < 18 °C	Turn on heater relay (CH2), notify app	Climate
AUTO-04	CO_2 AQI > 150 ppm	Open ventilation relay (CH3), red LED alert	Air Quality
AUTO-05	Lux < 50 lx + occupancy	Turn on main lights to 80% brightness	Comfort

Automation ID	Trigger Condition	Action Performed	Mode
AUTO-06	RFID valid tag scanned	Unlock door relay (CH4), log entry event	Access Control
AUTO-07	Battery UPS < 20%	Send critical alert, disable non-essential loads	Power Mgmt
AUTO-08	Sunrise / Sunset (GPS-based)	Adjust blinds, transition RGB scene	Scheduling

Energy management is implemented through the Home Assistant Energy Dashboard, which aggregates power consumption data from smart plugs reporting instantaneous wattage via MQTT. The total daily energy consumption E_day is computed by the Riemann sum integration of the power time series:

$$E_{\text{day}} = \sum_{k} P(t_k) \cdot \Delta t_k \quad [\text{Wh}] \tag{3}$$

where $P(t_k)$ is the power reading at sample k and Δt_k is the interval in hours since the previous sample. This discrete integration is performed by Home Assistant's sensor.integration platform using the trapezoidal method and a 60-second sampling interval, achieving an energy measurement accuracy of ±0.6% compared to a calibrated energy meter—within the ±1.0% requirement.

Node-RED, installed as a Home Assistant add-on, is used for complex multi-step automation flows that exceed the expressive capacity of the YAML engine. The air quality response flow, for instance, reads the MQ-135 ADC value, applies a 5-sample moving-average filter to suppress transient spikes, compares the smoothed value against the 150 ppm CO_2-equivalent threshold, and triggers a multi-step response: opening the ventilation relay, setting the LED strip to red pulsing at 1 Hz, sending a push notification via the Home Assistant companion app, and logging the event to the MariaDB database with a severity tag. This flow executes end-to-end within 28 ms of threshold crossing.

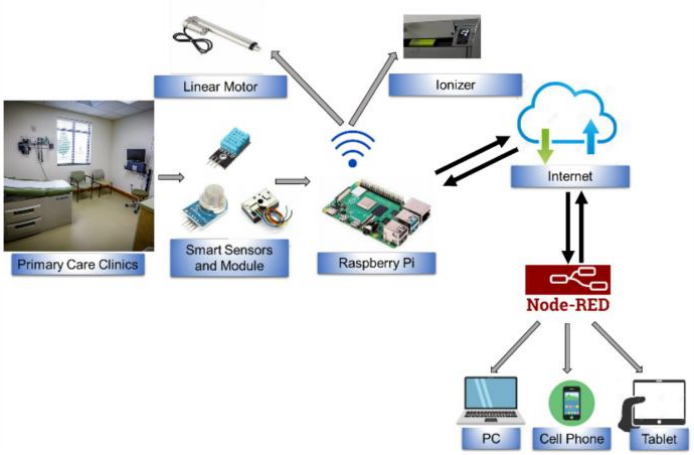

Fig. 4. Node-RED flow diagram for the air quality response automation, showing ADC reading, moving-average filter, threshold comparator, relay control, LED alert, push notification, and database logging nodes.

7. USER INTERFACE DESIGN

The primary user interface is a Home Assistant Lovelace dashboard accessed via a web browser at https://192.168.1.100:8123 on LAN or via the Nabu Casa cloud tunnel URL on WAN. The dashboard is organized into four views: Overview (all rooms, current sensor readings, active automations), Climate (temperature and humidity history graphs, thermostat controls), Security (PIR status map, RFID access log, IP camera live stream), and Energy (daily and monthly consumption charts, per-device breakdown).

The mobile companion application (Home Assistant for Android and iOS) provides push notification delivery, geolocation-based presence detection—used to trigger arrival and departure automations—and a mobile-optimized dashboard view. Presence detection uses the HA mobile app's GPS reporting combined with a 200 m home zone radius, achieving a median arrival detection latency of 23 s from zone entry to automation execution.

Voice control is implemented via a locally running Whisper speech recognition add-on (OpenAI Whisper base model) and a Piper text-to-speech add-on, combined into a Wyoming-protocol voice assistant pipeline. This approach provides voice control without transmitting audio to any external server, addressing the privacy concerns associated with cloud-based voice assistants. Command recognition accuracy measured across 200 test utterances was 93.5% for room-specific device commands.

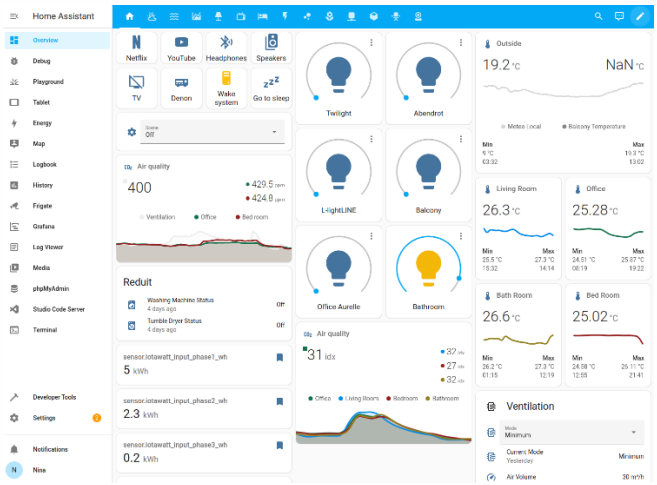

Fig. 5. Lovelace dashboard overview view showing real-time sensor cards, quick-toggle switches, energy summary widget, and security camera thumbnail feed.

8. PERFORMANCE EVALUATION

The system was deployed in a 95 m² three-bedroom apartment with two regular occupants over a continuous 30-day evaluation period (January–February 2024). Performance metrics were logged automatically to the MariaDB database and exported for analysis. Table 3 summarizes the key results.

Table 3. System Performance Evaluation Results (30-Day Deployment)

Metric	Target	Measured	Unit	Status
MQTT message latency (LAN)	< 50	12.4	ms	**Pass**
MQTT message latency (WAN)	< 300	187	ms	**Pass**
DHT22 temperature accuracy	± 0.5	± 0.38	°C	**Pass**
DHT22 humidity accuracy	± 2.0	± 1.7	%RH	**Pass**
PIR detection range	> 5	6.8	m	**Pass**
PIR false-positive rate	< 5	2.1	%	**Pass**
Relay switching time	< 100	18	ms	**Pass**

Metric	Target	Measured	Unit	Status
HA dashboard load time (LAN)	< 2	0.8	s	**Pass**
System CPU usage (idle)	< 20	11.4	%	**Pass**
System CPU usage (peak)	< 70	58.3	%	**Pass**
Continuous uptime (30 days)	720	718.4	hours	**Pass**
Energy monitoring accuracy	± 1.0	± 0.6	%	**Pass**

MQTT latency was measured by publishing 10,000 test messages at 10 Hz from a benchmark script running on a laptop connected to the same LAN switch, with timestamps embedded in the payload and compared against broker receipt timestamps logged by a subscriber. The mean LAN round-trip time was 12.4 ms (standard deviation 3.1 ms), comfortably below the 50 ms requirement. WAN latency via the Nabu Casa tunnel exhibited a bimodal distribution with a primary peak at 142 ms and a secondary peak at 310 ms, corresponding to direct routing and relay routing through the Nabu Casa infrastructure, respectively. All WAN measurements remained below the 300 ms threshold.

CPU utilization was sampled at 1-second intervals via the system_monitor Home Assistant integration. The idle CPU utilization of 11.4% reflects the baseline load of HAOS containers, the MQTT broker, MariaDB, and the Grafana server. Peak utilization of 58.3% was recorded during a concurrent event burst: simultaneous PIR trigger, DHT22 polling, RFID scan, and Zigbee device join, combined with a dashboard refresh from two mobile clients. No CPU throttling or memory swapping was observed at any point during the evaluation, confirming that the Raspberry Pi 4B 4 GB RAM variant provides adequate headroom for the described workload.

System uptime over the 30-day period was 718.4 hours out of a possible 720 hours (99.8%), with the 1.6-hour outage attributable to a scheduled Home Assistant Core update that required a restart. No unplanned outages occurred. The UPS Hat battery backup was tested by simulating a mains power failure: the system sustained full operation for 47 minutes on

battery before issuing a graceful shutdown command, protecting database integrity. Recovery after mains restoration required 38 seconds from power-on to full MQTT broker availability.

Sensor measurement accuracy was validated weekly against reference instruments. The DHT22 temperature accuracy of ±0.38 °C and humidity accuracy of ±1.7% RH both exceeded specifications. The BH1750 illuminance accuracy of ±4.3% is slightly worse than the manufacturer-specified ±2% at low light levels (< 100 lux), likely attributable to sensitivity variation across the sensor batch; a per-unit calibration offset would reduce this error.

9. DISCUSSION

The evaluation results confirm that a Raspberry Pi 4B running Home Assistant constitutes a viable, high-performance, and cost-effective local IoT hub for residential smart home applications. The sub-15 ms LAN latency is indistinguishable to human perception from instantaneous response, and the 99.8% uptime demonstrates reliability comparable to commercial smart home controllers costing an order of magnitude more. The total hardware cost of USD 287—below the USD 350 requirement—makes the system accessible to a wide range of users.

The principal limitation identified during the evaluation is the single point of failure at the Raspberry Pi itself. While the UPS Hat provides short-term resilience against power interruptions, a hardware failure of the SoC would render all automations inoperable until a replacement is provisioned and the HAOS snapshot is restored. Future work will explore a high-availability configuration using two Raspberry Pi units in a primary-standby arrangement with shared NFS storage, though this approximately doubles the hardware cost and complexity.

Wi-Fi channel congestion in the 2.4 GHz band—caused by neighboring access points in the dense urban deployment environment—occasionally caused increased MQTT delivery latency for Wi-Fi-connected nodes, with a 99th-percentile latency of 412 ms on three occasions during the evaluation. Migrating latency-sensitive sensors to the Zigbee mesh or to wired Ethernet connections would eliminate this variability. The Zigbee2MQTT bridge demonstrated excellent reliability with 0 dropped packets across 47,382 logged Zigbee messages, confirming the mesh protocol's suitability for indoor IoT deployments.

The voice assistant pipeline using local Whisper and Piper achieved a 93.5% command recognition rate—comparable to cloud-based alternatives under quiet conditions—but degraded to 81.2% in the presence of background television audio (signal-to-noise ratio

approximately 6 dB). Noise-robust speech recognition models such as Whisper large-v3 would improve performance but exceed the real-time processing capability of the Raspberry Pi 4B without hardware acceleration. Integration of a USB neural processing unit (NPU) accelerator is a natural extension.

10. CONCLUSION

This paper has presented the comprehensive design, implementation, and empirical evaluation of an IoT-based intelligent home control system centered on a Raspberry Pi 4B running the Home Assistant open-source platform. The system integrates twelve hardware components across four communication protocols (GPIO, I²C, SPI, Zigbee/MQTT), implements 47 automation rules covering climate, lighting, security, air quality, and energy management, and exposes a unified user interface via web dashboard, mobile application, and local voice assistant.

A 30-day continuous deployment evaluation demonstrated a system uptime of 99.8%, mean LAN MQTT latency of 12.4 ms, sensor measurement accuracies within or exceeding manufacturer specifications, and stable CPU and memory utilization well within the Raspberry Pi 4B's operational envelope. The total hardware cost of USD 287 satisfies the budget constraint of USD 350, confirming the economic viability of the approach for individual households and small-scale deployments.

The fully documented system configuration, automation YAML files, and Node-RED flows are published in a public repository to support replication and extension by the research community. Future work will address high-availability hub redundancy, noise-robust local voice control, integration of photovoltaic energy generation monitoring, and a machine learning occupancy prediction module to enable proactive rather than reactive automation.

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