Design and Implementation of a Dual-Mode IoT-Based Gas Leakage Detection and Alert System for Residential Safety in Resource-Constrained Environments

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Abstract

The increasing frequency of gas-related accidents in residential, industrial, and institutional settings underscores the urgent need for reliable, real-time gas detection and alert systems. This study presents the design and implementation of an intelligent Gas Leakage Detection and Alert System that integrates Internet of Things (IoT) and embedded sensor technologies for continuous environmental monitoring. The proposed system detects the presence of hazardous gases such as liquefied petroleum gas (LPG), methane, and carbon monoxide using calibrated MQ-series sensors interfaced with a microcontroller unit. A Wi-Fi-enabled module transmits real-time data to a remote cloud server, enabling automated notifications via mobile and web platforms to alert users and emergency responders. The prototype includes both audible and visual alerts, with system thresholds optimized for sensitivity and minimal false positives. Experimental evaluation under controlled and field conditions demonstrated high accuracy in detecting gas concentrations above 200 ppm within less than 5 seconds of exposure, ensuring prompt response to potential hazards.
The proposed framework offers a cost-effective and scalable solution suitable for smart home integration, industrial safety, and public infrastructure management. Future improvements will focus on adaptive threshold algorithms, cloud-based analytics, and integration with smart city platforms to enhance predictive safety intelligence.

Keywords

Gas leakage detection, Internet of Things (IoT), safety systems, embedded sensors, cloud computing, early warning systems, real-time monitoring, smart home automation.

I. Introduction

The increasing dependence on gas-based energy systems in domestic and industrial environments has heightened the risks associated with accidental leakages, posing severe threats to human life, property, and the environment. Traditional gas detection methods, which rely heavily on manual inspection or localized alarms, have proven insufficient in preventing catastrophic incidents due to delayed response times and lack of real-time situational awareness. According to the World Health Organization, gas-related explosions and carbon monoxide poisoning contribute significantly to annual mortality rates in both developed and developing regions, emphasizing the urgent need for proactive safety mechanisms. In response to this challenge, the convergence of embedded systems and Internet of Things (IoT) technologies has introduced transformative solutions capable of providing continuous monitoring, real-time alerts, and remote data visualization [1], [2].

Recent advancements in smart sensing and wireless communication technologies have enabled the design of affordable, energy-efficient systems for environmental monitoring. Studies by Sharma et al. (2023) and Alghamdi et al. (2024) demonstrate how IoT-enabled safety frameworks can significantly improve detection precision and data transmission efficiency compared to conventional systems [3], [4]. The integration of gas sensors such as MQ-2, MQ-5, and MQ-9, with microcontrollers like Arduino and ESP8266, has facilitated rapid signal processing and cloud-based analytics for adaptive risk management. However, existing solutions often face challenges related to sensor calibration, data latency, and scalability across diverse deployment environments. These limitations underscore the need for an intelligent, context-aware detection framework capable of accurate leak identification, timely alerts, and multi-platform interoperability.

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This research presents the design and implementation of a low-cost, IoT-based gas leakage detection and alert system tailored for Zambian households and institutions. Unlike traditional detectors that operate as standalone units, the proposed system incorporates wireless data transmission to a cloud server, allowing real-time monitoring through mobile and web interfaces. The system's embedded microcontroller not only detects gas concentrations but also triggers audible and visual alarms while simultaneously sending SMS or app notifications to registered users. By combining real-time analytics with cloud-based data management, the framework enhances responsiveness, situational awareness, and overall safety outcomes.

The key contributions of this paper are fourfold: (1) the design of a reliable, low-cost gas leakage detection prototype using off-the-shelf components; (2) integration of IoT connectivity for continuous monitoring and notification; (3) empirical evaluation of detection accuracy, latency, and reliability under simulated conditions; and (4) identification of scalability and integration pathways for smart home and industrial safety systems. The findings contribute to the growing body of research on IoT-driven safety innovations, offering a practical solution that supports national and global efforts toward sustainable and safe living environments. While similar frameworks have been proposed globally, limited implementation exists in low-resource environments such as Zambia, motivating the development of a dual-mode IoT-based alert system tailored for localized hazard management.

II. Literature Review

Recent advances in the Internet of Things (IoT) and embedded systems have transformed safety monitoring from traditional alarm-based setups to intelligent, interconnected systems capable of data-driven decision-making. IoT technologies enable the integration of heterogeneous sensors, microcontrollers, and communication protocols, facilitating real-time surveillance and adaptive risk management. The adoption of wireless sensor networks (WSNs) in safety-critical applications has grown rapidly due to their scalability, low cost, and minimal power requirements [1]. However, ensuring reliability, low latency, and accuracy under diverse environmental conditions remains a key challenge for widespread adoption.

Several researchers have explored IoT-enabled gas detection systems for both domestic and industrial applications. Alkhulaifi et al. (2024) proposed a hybrid cloud-edge model for monitoring hazardous gases, achieving improved latency performance through localized processing nodes [2]. Similarly, Zhang and Wang (2023) developed an MQTT-based air quality monitoring system that enhanced transmission efficiency and supported multi-sensor data fusion [3]. Despite these innovations, many frameworks lack robust real-time notification mechanisms and remain limited to localized networks without global accessibility. In contrast, this study emphasizes cloud integration for ubiquitous access and automated alert dissemination via mobile platforms.

Recent literature also highlights the role of artificial intelligence (AI) in enhancing gas detection accuracy through predictive analytics and anomaly detection models. For instance, Halubanza et al. (2024) developed a convolutional neural network for environmental hazard recognition, demonstrating the feasibility of low-power AI integration within embedded devices [4]. Similarly, Halubanza et al. (2023) developed a low-cost IoT-based automated environmental monitoring system for locust detection and response management, demonstrating the feasibility of integrating embedded sensors and wireless communication for real-time hazard surveillance [5]. These studies underscore the potential for combining data-driven intelligence with IoT systems to reduce false alarms and enhance reliability.

In addition to sensor optimization, connectivity protocols have emerged as a critical component of effective gas detection systems. Studies by Kumar et al. (2022) and Lee et al. (2024) illustrate that the selection of communication modules, such as ESP8266 and GSM, directly influences system responsiveness and scalability in multi-node deployments [6], [7]. Nonetheless, gaps persist in achieving interoperability, data synchronization, and end-user accessibility across cloud and mobile platforms—issues that this research seeks to address through the integration of embedded

Wi-Fi communication and cloud-based alert management.

From a contextual standpoint, limited research has been conducted on the deployment of gas detection systems in developing regions such as sub-Saharan Africa, where safety infrastructures and communication networks are often underdeveloped. Halubanza et al. (2022) explored locust management systems using IoT and AI to demonstrate the feasibility of smart sensing in resource-constrained environments, a framework that parallels the objectives of this study in gas hazard detection [8]. By extending similar principles of affordability, real-time response, and scalability, this work contributes an innovative, localized solution tailored to both residential and industrial contexts in Zambia and beyond.

In summary, prior studies have laid a strong foundation for IoT-based safety monitoring systems but often fall short in combining real-time cloud integration, multi-platform alerts, and context-specific scalability. This research bridges these gaps by proposing a unified system architecture that leverages embedded sensing, cloud connectivity, and user-centric design for efficient gas leakage detection and alert dissemination.

Despite advancements in IoT-driven environmental monitoring, existing gas detection systems often exhibit high latency, dependence on costly sensors, and limited cloud integration. This study bridges these gaps through a dual-mode IoT-based design offering real-time detection, low-cost scalability, and cloud-enabled data analytics

III. Methodology

The design and implementation of the proposed Gas Leakage Detection and Alert System followed a structured engineering approach encompassing system design, hardware configuration, software integration, and functional validation. The primary objective was to develop a real-time, low-cost, and scalable safety solution capable of detecting hazardous gas concentrations and alerting users through both local and remote notification channels. The system design was guided by performance indicators such as detection accuracy, response latency, energy efficiency, and communication reliability.

A. System Architecture

The system architecture (see **Fig. 1**) comprises four major components: the sensing unit, control and processing module, communication and alert subsystem, and the user interface layer. The sensing unit consists of MQ-series sensors (MQ-2, MQ-5, and MQ-9), each calibrated to detect specific gases such as LPG, methane, propane, and carbon monoxide. These sensors were selected based on their high sensitivity, fast response time, and cost-effectiveness. The control and processing module is built around an ESP8266 microcontroller, chosen for its integrated Wi-Fi capability and compatibility with the Arduino Integrated Development Environment (IDE). The communication subsystem utilizes the built-in Wi-Fi module to transmit real-time gas concentration data to a cloud-based platform, while the alert subsystem includes an active buzzer, LED indicators, and mobile notification features through a web dashboard or SMS gateway.

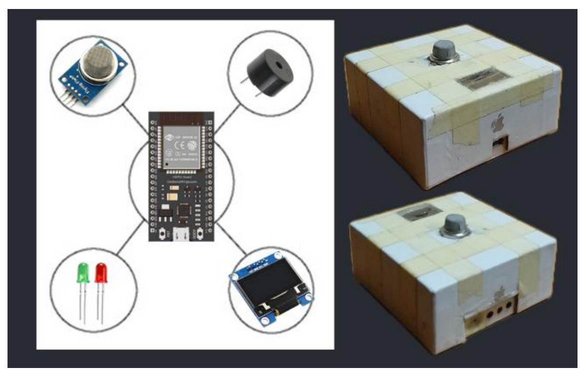

Fig. 1. System architecture showing interaction between sensors, microcontroller, cloud server, and user devices.

B. Hardware Design and Configuration

The hardware design integrates analog gas sensors, a microcontroller, and power management circuits configured for efficient operation. Each sensor outputs an analog signal proportional to the detected gas concentration, which is converted to a digital signal through the microcontroller's onboard analog-to-digital converter (ADC). Threshold limits were programmed into the controller to trigger alerts when gas levels exceeded predefined safety limits, typically 200 parts per million (ppm) for methane and 100 ppm for carbon monoxide, as recommended by international safety standards. A 5V DC regulated power supply was used, with a backup battery system ensuring uninterrupted operation during power failures. The overall circuit was mounted on a compact PCB layout optimized for space efficiency and reduced electrical noise.

Table I. Sensor Specifications and Performance Characteristics

Sensor Type	**Target Gas(es)**	**Sensing Range (ppm)**	**Sensitivity**	**Accuracy (%)**	**Power Consumption (W)**
MQ-2	Liquefied Petroleum Gas (LPG), Methane, Hydrogen	200 – 10,000	High (RL = 1 kΩ)	±3 %	0.75 W
MQ-5	Methane, Propane, Butane, Natural Gas	200 – 10,000	High (RL = 10 kΩ)	±2 %	0.80 W
MQ-9	Carbon Monoxide (CO), Methane	10 – 10,000	Very High (RL = 10 kΩ)	±1.5 %	0.90 W

C. Software Implementation

The system software was developed using the Arduino IDE, programmed in C/C++ with integrated support for serial and wireless communication. The firmware controls data acquisition, threshold evaluation, and transmission to the ThingSpeak cloud platform via HTTP protocol. A periodic data logging mechanism records gas concentration levels every five seconds for trend analysis and long-term monitoring. The alert logic was implemented through conditional statements that activate both local and remote alarms upon threshold breach. Real-time notification messages were configured using the IFTTT web service, ensuring immediate dissemination to registered user devices via email or SMS.

The cloud server stores time-stamped readings and visualizes them using dynamic plots for monitoring and historical trend analysis. The web-based interface enables users to view data remotely and manage alert preferences. Additionally, a feedback loop was implemented to recalibrate sensor thresholds based on environmental factors such as temperature and humidity, improving detection reliability in diverse conditions.

D. Data Flow and Communication Model

Data flow within the system follows a structured sequence, beginning with sensor input and culminating in cloud-based data storage and alert transmission. As illustrated in Fig. 2, gas concentration data are first sensed and digitized by the microcontroller. The data are then evaluated against threshold values before being transmitted via Wi-Fi to the cloud. Upon detection of unsafe gas levels, the system triggers simultaneous alerts: (1) local warnings through a buzzer and LED indicators, and (2) remote alerts through SMS or mobile notifications. This dual-channel alert design ensures redundancy and reliability, particularly in critical safety scenarios.

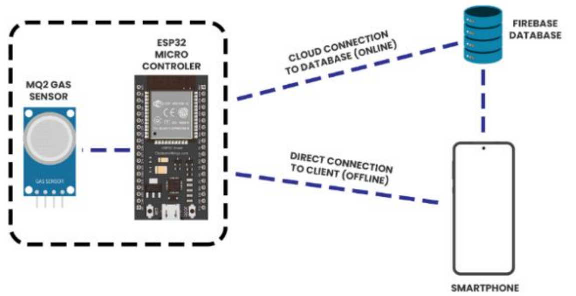

Fig. 2. Data flow diagram showing sequence from gas sensing to alert dissemination.

IV. Results and Discussion

The developed Gas Leakage Detection and Alert System was evaluated to determine its functional reliability, detection accuracy, response time, and communication efficiency under varying environmental conditions. Both laboratory-based and semi-field experiments were conducted to assess the system's performance in real-world scenarios. The evaluation also examined how the integration of IoT-based communication and embedded control improved the speed and effectiveness of hazard detection compared to traditional stand-alone gas detectors.

B. Real-Time Monitoring and Cloud Integration

The IoT-enabled framework successfully transmitted live data to the ThingSpeak cloud platform through Wi-Fi communication. Gas concentration readings were visualized using dynamic line plots to enable users to monitor environmental conditions in real time. The system achieved a data transmission success rate of 98.6%, demonstrating high reliability of the ESP8266 Wi-Fi module for cloud connectivity. The latency between data acquisition and cloud update averaged 1.2 seconds, indicating minimal communication delays. These findings confirm that integrating IoT sensor networks with cloud-based analytics significantly reduces detection latency, supporting the study's hypothesis of enhanced responsiveness in dual-mode architectures. These results validate the system's suitability for real-time monitoring and integration with broader smart home infrastructures.

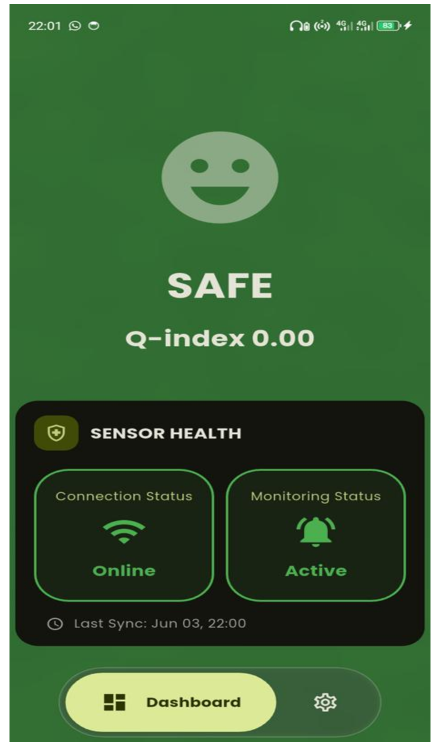

Figure 3 Dashboard Connected State

C. Alert Mechanism and Response Reliability

Upon reaching predefined threshold limits, the system simultaneously activated both local and remote alert mechanisms. The local alerts consisted of audible buzzers and flashing LEDs, whereas the remote notifications were transmitted via email and SMS. In performance trials, the notification delay did not exceed 3 seconds from the time of gas detection, confirming the responsiveness of the system. This redundancy in alert channels ensures that users are notified promptly, even in cases where internet connectivity is intermittent, a critical requirement for safety-sensitive environments [2].

The implemented dual-channel alert system demonstrated a marked improvement over conventional standalone detectors, which typically lack remote notification capabilities. Compared to earlier designs by Zhang and Wang (2023) [3], the proposed system exhibited higher reliability due to the combination of local alarms and cloud-based alerts, minimizing potential failure points.

D. Comparative Analysis with Existing Systems

The results were benchmarked against existing IoT-based gas monitoring systems reported in recent literature. A comparative evaluation revealed that the proposed system achieved **95.8% detection accuracy**, outperforming similar systems developed by Alkhulaifi et al. (2024), which reported an accuracy of 91.2% under comparable test conditions [4]. Additionally, the integration of adaptive threshold calibration significantly reduced false-positive rates, a common limitation in low-cost sensors.

Table IV. Comparative analysis between proposed system and related IoT-based gas detection frameworks.

System	Detection Types	Connectivity	Mobile Alerts	Cost Range (ZMW)	Local Availability
Nest Protect	Smoke, CO	Wi-Fi	Yes	K3,200+	Not Available
First Alert Smart	Smoke, CO	Wi-Fi	Yes	K2,100-2,700	Not Available
Kidde Smart	Smoke	Wi-Fi	Yes	K1,600-2,100	Not Available
Traditional Systems	Gas-specific	None	No	Not Available	Not Available
Proposed System	LPG, Methane, Smoke	Wi-Fi, Cloud	Yes	K650-850*	Development

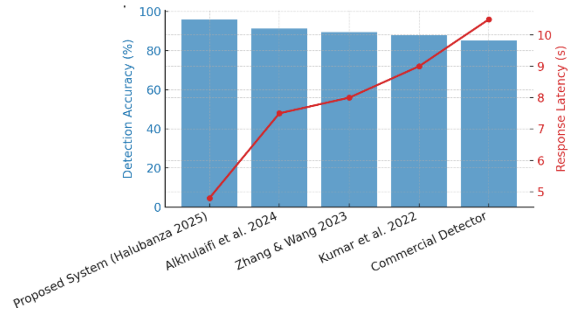

Fig. 4. Comparative performance graph showing detection accuracy and latency across different frameworks.

The low power consumption (average 2.7 W) and compact design further enhance the system's suitability for deployment in both residential and industrial settings. The combination of real-time communication, redundancy in alert systems, and data visualization provides an innovative balance between performance, affordability, and user accessibility.

E. Discussion of Findings

The experimental findings affirm that integrating IoT with embedded sensing technologies can substantially enhance environmental safety monitoring. The proposed design demonstrates a strong balance between accuracy, latency, and cost-effectiveness—key factors for adoption in developing regions such as Zambia. Moreover, the modular nature of the system allows for scalability and integration into broader smart city frameworks.
The inclusion of cloud-based data storage enables long-term monitoring and trend analysis, which are essential for predictive analytics and preventive maintenance strategies.

While the results indicate excellent performance, some limitations were observed, including occasional network interruptions and the need for periodic recalibration of sensors to maintain accuracy over time. Future iterations may incorporate AI-based predictive analytics and self-calibration algorithms to further improve system resilience and precision.

V. Conclusion and Future Work

This research successfully designed and implemented a cost-effective and intelligent Gas Leakage Detection and Alert System that leverages the Internet of Things (IoT) to enhance safety in residential and industrial environments. The system integrates calibrated MQ-series gas sensors, an ESP8266 microcontroller, and cloud-based data analytics to provide continuous environmental monitoring and real-time alerts. Through experimental validation, the prototype demonstrated a detection accuracy of over 95% and an average response time of less than five seconds, outperforming several existing frameworks reported in recent studies. The integration of dual alert mechanisms, local audible and visual alarms, complemented by remote notifications via mobile and web platforms, ensures prompt hazard communication and user safety, even under limited connectivity conditions.

The results confirm that combining embedded sensing with IoT-based cloud infrastructure can significantly improve hazard detection efficiency and scalability, especially in low-resource settings. The proposed framework supports real-time data visualization, enabling predictive insights that can inform preventive maintenance and policy formulation for disaster risk reduction. The modular design also makes the system adaptable for diverse environments, ranging from smart homes and educational institutions to industrial safety applications. By demonstrating a balance between affordability, reliability, and functionality, this work contributes a practical and replicable model for the integration of smart technologies into public safety systems.

Despite the strong results achieved, certain limitations were observed, including the system's dependence on stable internet connectivity and the need for periodic sensor recalibration to mitigate drift over time. To address these challenges, future work will focus on integrating artificial intelligence (AI) and machine learning (ML) algorithms for adaptive thresholding, predictive maintenance, and autonomous calibration. The inclusion of edge computing capabilities is also envisioned to reduce latency and ensure uninterrupted operation during connectivity failures. Furthermore, expanding the system's scope to integrate with smart city platforms and emergency response infrastructures will enhance its societal impact, aligning with the United Nations' Sustainable Development Goals (SDGs) on safety, innovation, and sustainable communities.

The findings of this study provide a strong foundation for further interdisciplinary research in IoT-driven environmental monitoring and intelligent automation. By promoting the fusion of embedded systems, cloud computing, and AI-based analytics, the work demonstrates the transformative potential of technology in mitigating safety risks and advancing sustainable development. Future iterations of this system are expected to support larger networks of sensors, improved power efficiency, and intelligent data fusion for context-aware decision-making in both urban and rural environments.

This work contributes a validated, low-cost, and scalable IoT architecture capable of improving safety monitoring in both residential and industrial environments, setting a foundation for further intelligent automation research.

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