# A Decoupled Multi-Component IoT Architecture for Enhanced Safety Monitoring and Alerting in Subterranean Coal Mines

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***Abstract***

*The coal mining industry continues to deal with methane exposure, the lack of adequate safety precautions, and the deaths of workers. Digital safety and monitoring solutions have suffered from the lack of dependable communication systems. In contrast to other solutions that work to overcome this silo problem, this research work proposes to develop an integrated and modular design. The Sensor Unit measures and transmits the gas/flame temperature and humidity levels, the miners' Smart Jackets issue and SOS (the international Morse code distress signal) alert and distress calls and the Control Unit collates, synchronizes with the cloud, and retrieves information. The system is NRF24L01 powered and utilizes wireless network solutions that work without the need for an underground internet that had to be built beforehand. The system closes the response time gap to below 350 milliseconds (ms) on end-to-end notifications in Detect and Alert systems with a 145 ± 22 ms notification period from Sensor Unit to Control, and 175 ± 28 ms for Control and Smart Jacket creation. There is system communication for all underground line of sight communication range of 112 ± 5 meters (m) and undocumented coverage of 38 ± 4 m under + 2 structural walls. The systems construction and modular design provide no single failure risk. Sensor Units registered methane concentrations of slightly more than 1%, while 98% of alerts were received by miners in under a quarter of a second. These figures show that the system is scalable, cost-efficient, and able to improve miner safety, with a 98% success rate identifying and warning of threats before they can escalate. Further, the system is ideally suited to be deployed in extremely dangerous areas of mining that have little or no infrastructure. This offers a significant advantage over outmoded safety systems, which trust on communication.*

***Keywords***: Internet of Things, Coal Mine Safety, Wireless Sensor Networks, Decoupled Architecture, Subterranean Communication, NRF24L01, ThingSpeak, Smart Wearable, Environmental Monitoring.

## Introduction

Coal mining continues to be one of the most important sources of energy worldwide, but it has many severe issues related to the safety of workers. One of the greatest risks is the accumulations of methane ($CH_4$)

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gas, along with the explosions that can occur, which are caused by sparks from mining tools, or electrical malfunctions. Methane gas is formed from coal seams, and is extremely volatile when is chemically accessed with air at concentrations of between 5 and 15 percent. Such explosions kill large numbers of people every year, which became the case of the unfortunate Harnai mine explosion in March 2024, which caused the deaths of twelve miners in Pakistan, emphasizing the growing and substantial need for better safety sensing technologies (Ren & Xu, 2018; Li & Zhou, 2019; Khan et al., 2019).

The rise of the Internet of Things (IoT) and Wireless Sensor Networks (WSNs) have enabled the mining sector to gain access to a wide range of systems proposed to improve industrial safety (Li & Zhou, 2019; Khan et al., 2019). Many authors focus on the creation of integrated, personal, and wearable systems, such as smart helmets and vests, that subdivide all sensing, computing, and communication activities into individual units (Kumar & Singh, 2020; Azim, 2021). These systems are useful for tracking a worker's individual exposure, but a major shortcoming of this design is that environmental tracking is limited to the specific time and place that the miners are located. This means that large, unoccupied areas of the mine, where dangerous conditions can form, remain completely unmonitored, creating a significant gap in the safety coverage.

Additionally, many of the systems have been described as having direct Wi-Fi or mobile (GSM/LTE) access from the underground to the cloud server, which is often far from the truth in coal mines since they are remote with complex terrains that severely weaken radio frequency, making direct access to an underground server very technically and economically difficult (Ansari et al., 2021; Ali et al., 2021; Sun et al., 2019). Although Zigbee and LoRaWAN are cheaper and more efficient alternatives, they have difficulties of their own and do not change the inherent problems of the systems described above. For example, Zigbee has short range which forces the deployment of many modules in a vertical and horizontal pattern that leads to high latency and complex systems (Mishra & Das, 2019). Also, in underground tunnels, LoRaWAN suffers from high path loss which is a notorious aspect of the technology (Luo et al., 2020).

This research tries to close the deficits mentioned above through proposing and validating a new multicomponent, decoupled IoT architecture tailored for the extreme conditions of the coal mine. The uniqueness of our system comes from the separation of environmental monitoring from individual alarming and, thus, allows for uninterrupted and mine-wide surveillance without the restriction of the sensor location.

The scientific and engineering contributions are: (a) A Decoupled and Resilient Architecture: A three-part system (including static Sensor Units, wearable Smart Jackets, surface Control Unit) are introduced here, and validated afterwards. Sensing and alerting have been separated from each other in order to ensure comprehensive spatial coverage and mitigating the single-point-of-failure risks, which has been a major issue in the monolithic designs; (b) A Hybrid Two-Tier Communication Protocol: In order to guarantee a low-latency alerts without relying on the internet architectures, an intra-mine communication network was implemented using NRF24L01 transceivers in a star topology configuration. A single path at the surface will act as communication between this local IOT to a global cloud platform; (c) Enhanced Safety and Reliability Mechanisms: An SOS (the international Morse code distress signal) beacon has been integrated into the miner's jacket which shall be initiated at the will of the miner. Moreover, automated fault detection for network node health has also been integrated along with a multi-modal (visual and auditory) alerting system also optimized for high-noise industrial environments.

This paper is structured as follows: The Introduction present background and motivation of the study. The Literature Review examiner's related works and existing solution. The Methodology describes the system architecture, hardware components, and communication protocols. The Result and Discussion deliver a measurable study of the trial findings along with their allegations and limitations. The Conclusion and Future work summarize the study and outlines directions for further research.

## Literature Review

The issue of safety when it comes to underground coal mining remains a global concern due to the many dangerous situations such as toxic gas leaks (like methane), fires, collapse of the structure, poor air quality, unreliable communication and tracking of personnel. When it comes to safety, there are some traditional ways, such as periodic manual inspections, gas detectors set in place, and advanced safety checks; however, hazards that are deep underground and that are in complex tunnel networks are hard to detect in real time. Fortunately, there are some advances in the IoT, WSNs, and data- processing technologies. The most recent research that has been done has proposed integrated systems that pose real time monitoring and warning systems that provide assistance to the safety of the miner to mitigate risks of mining.

Chen et al. (2021) proposed combining IoT-enabled sensor devices with a hybrid Convolutional Neural Network (CNN)-Long Short-

Term Memory (LSTM) deep learning model to monitor environmental parameters and predict hazards in underground coal mines. The model forecasts both gas concentrations (e.g., methane) and a “Miner Health Quality Index” (MHQI), enabling early warnings. The authors reported low prediction error, measured using Mean Squared Error (MSE) (MSE < 0.0009 for MHQI) and better performance than standalone CNN or LSTM models. However, the proposed CNN–LSTM framework assumes reliable underground connectivity and focuses on prediction accuracy rather than real-time alert latency or fault tolerance, which limits its direct applicability in safety-critical underground environments.

Wang et al. (2024) developed a system using a lightweight wearable (bracelet) and a smart mine lamp to collect vitals, multi-gas data, and positioning information; data are transmitted via a distributed Multiple Input Multiple Output (MIMO) network to overcome limitations of conventional cellular coverage underground. The system has been trialed in an operational coal mine in Northwest China, reportedly reducing safety incidents related to miners’ health and environmental hazards. While the system demonstrates operational feasibility, its reliance on distributed MIMO infrastructure significantly increases deployment cost and complexity, making it less suitable for small or resource-constrained mining operations.

Environmental monitoring and early alerts have been made possible by integrating temperature, pressure, gas, vibration and fire detection sensors in WSN using ZigBee. This study emphasizes on the comprehensive hazard detection, including but not limited to fire risk and structural vibrations beyond just gas detection (Li et al., 2025). Although comprehensive in hazard coverage, the ZigBee-based architecture suffers from scalability and latency constraints in extended underground tunnel networks.

Zhao et al. (2025) highlighted the use of semiconductor and nanomaterials based miniature sensors which are currently in the state-of-the-art category. These sensors are capable of detection of multiple gases simultaneously along with improved sensitivity to their functionalities other than lower power consumption and quicker response time which are all critical for harsh underground environments. Despite improved sensing accuracy, the study does not address how such advanced sensors integrate with low-latency communication and distributed alerting mechanisms in real mining conditions.

There are mainly five categories for IoT applications in mining. They range from initial prototype development to real-time monitoring, control, optimization, and full automation. Deployments across small and large-scale mining have been documented showing wireless communication, sensor networks, and data collection and processing from various types of mines. There is a lot of merit in this study, showcasing the level of development and the gaps in smart mining solutions (Wang & Zhang, 2025). While this work effectively categorizes smart mining applications, it remains descriptive and does not experimentally evaluate system architectures under harsh underground communication constraints.

Udugampola et al. (2025) proposed an energy and position aware routing strategy for subterranean LoRa mesh networks. The system uses multi-hop communication and location-based algorithms to improve data throughput and conserve energy in underground environments. Simulation results show enhanced network reliability under harsh subterranean conditions. The proposed routing strategy improves network resilience, but its multi-hop design inherently increases alert propagation delay, which may be unsuitable for time-critical safety warnings.

The Performance of Wireless Systems on the Underground Environment: While Several Studies Have suggested Utilizing Wireless Systems (ZigBee, LoRa, WSN, MIMO), The Specific Underground Conditions (Dust, Moisture, Barriers, Tunnel Configuration) are signal propagation and robustness challenges. Few papers practically consider the conditions of an actual underground mine and provide sufficient details on the performance metrics of a communication system (how much signal attenuation is tolerated, packet losses, what is the mine's coverage radius) (Ren & Xu, 2018). Although this study highlights underground signal degradation challenges, it does not propose a concrete architectural solution to mitigate latency and single-point failures.

Ma et al. (2025) presented a comprehensive survey of magnetic induction (MI) communication for underground networks. The study covers channel modeling, relay strategies, and network architecture design, highlighting practical methods to maintain connectivity where conventional radio propagation fails. Magnetic induction communication offers robustness where RF fails, but its specialized hardware requirements and limited data rates restrict its practicality for integrated wearable safety systems.

Collectively, these studies reveal a trade-off between sensing accuracy, communication robustness, deployment cost, and alert latency, with no single solution simultaneously addressing mine-wide environmental monitoring, personal alerting, low latency, and fault tolerance.

Based on the gaps identified in existing literature, it is evident that current IoT-based coal mine safety systems either emphasize predictive analytics, advanced sensing, or communication robustness in isolation, while largely neglecting the architectural separation of environmental monitoring and personal alerting under strict latency constraints. In contrast to monolithic or wearable-centric designs, the present work introduces a decoupled multi-component architecture that enables continuous mine-wide environmental surveillance independent of miner location, while simultaneously providing low-latency, fault-tolerant personal alerts through wearable smart jackets. By combining static sensor units, a centralized control node, and lightweight wearables using a two-tier communication protocol, the proposed system explicitly targets the unresolved challenges of real-time responsiveness, scalability, and single-point failure mitigation in subterranean coal mining environments.

## Methodology

In this section, an explanation of the design and implementation of the proposed decoupled multi-component IoT system for coal mine safety is presented. The proposed methodology is divided as follows:

### *System Architecture Overview*

The system consists of three primary components such as Sensor Units, Smart Jackets, and a Control Unit, as shown in Figure 1. The sensor unit has been developed through fixed environmental monitoring nodes deployed in strategic locations (e.g., mine junctions, ventilation shafts). These units are responsible for the detection of different hazardous situations and environments mainly consisting of methane, high temperatures, humidity levels, and flames.

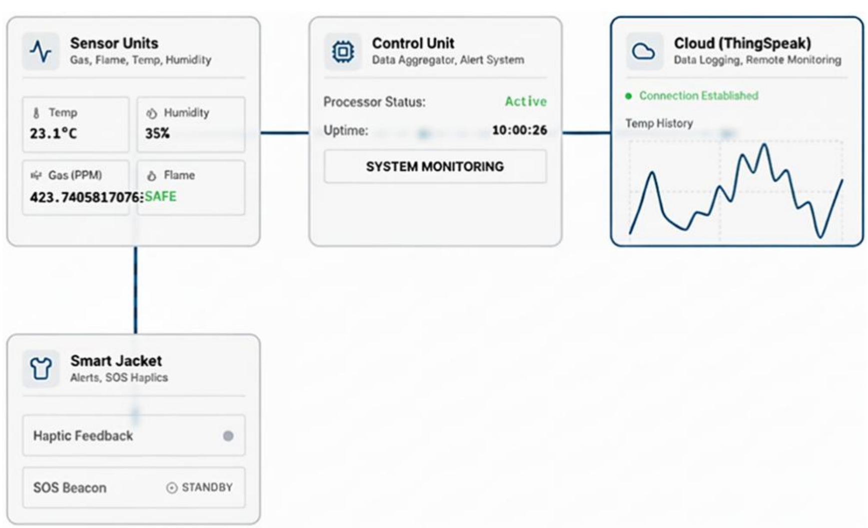


***Figure 1: System Architecture of the smart jacket Monitoring and Alerting System.***

Individual miners are provided with smart jackets including different device that tracks their health and safety parameters and can raise SOS alarms and alerts both in the form of sights and alerting sound. A control unit is the central point of all data being collected from the individual miner jackets and manages the communication of those individual sensors within the mine and the cloud by aggregating data for further analysis at the cloud level. Each of these components operates independently but is interconnected through a robust communication protocol (described below).

***Tools and Components***

The Sensor Unit mainly consist of Arduino Nano used as microcontroller. It is selected for its low power consumption and availability of GPIO (General-Purpose Input/Output) pins. MQ-135 gas sensor has been selected for detecting methane ($CH_4$) and other gases and DHT11 for temperature and humidity monitoring. An Infrared (IR) flame sensor is incorporated for detecting open flames and NRF24L01 module, is used for local communication within the mine and the control unit.

The Smart Jacket mainly consists of Arduino Nano microcontroller, NRF24L01 for sending and receiving alerts from the Control Unit, RGB (Red Green Blue) LED (Light Emitting Diode) lights for visual alerts and a 90dB piezo buzzer for audio alerts and an emergency push Button for SOS activation to be activated manually.

Lastly, the Control Unit consist of Arduino Nano for internal communication, an ESP8266 Wi-Fi Module for connecting to the cloud (ThingSpeak platform), an OLED (Organic LED) screen for real-time monitoring of the system status, and a Buzzer and LED for local emergency alerts.

***Step-by-Step Process***

The first Step is of Environmental Sensing Each Sensor Unit placed at different location of mines collects real-time environmental data. The data includes methane concentration, presence of open flames, and temperature high temperatures. The MQ-135 gas sensor detects methane and other gas levels, while the IR Flame Sensor identifies any flames pointing towards fire hazards, and the DHT11 sensor records humidity and temperature.

The Sensor Units then transmit the collected data wirelessly to the Control Unit using NRF24L01 transceivers. The Control Unit receives the data, aggregates it and forwards it to the control unit for further processing.

A HAZARD condition is initiated in the event of special conditions like methane levels going over the set limits or a flame being detected are being detected. The Control Unit transmits this HAZARD message to each Smart Jacket turning on the alert system visually by lighting on the RGB LEDs and turning on the Buzzers. Contrarily, if the miner detects any emergency, he may deploy the emergency alerts to the Control Unit by pressing the SOS button on the Smart Jacket.

Data from the Control Unit is transmitted to the ThingSpeak IoT platform via Wi-Fi (ESP8266) connected to the internet through any source (4G, Broadband or any other). The cloud platform records all the environmental hazardous and normal data for real-time monitoring and historical analysis. This allows the supervisors to access the data remotely.

### *Communication Protocol*

A two-tier communication protocol has been employed. A Local Network (NRF24L01) Within the Mine in which the Control Unit serves as a central node which receives and transmits the data to and from the Sensor Units and Smart Jackets.

Secondly a Cloud Gateway (using ESP8266) model is employed to communicate with the internet and outside the mine. The local network has been bridged to the ThingSpeak platform for remote monitoring and data analysis by external or remote personnel. The system operates on a star-of-stars topology with the Control Unit acting as the central master node.

### *Alerting Hierarchy*

The alerting system is hierarchical and works as follows. When a sensor reading exceeds a predefined threshold (e.g., methane concentration >1%), the corresponding Sensor Unit sends a high-priority alert. In contrast to the automatic alerts, when a miner activates the SOS button on the Smart Jacket, a high-priority alert is immediately sent to the Control Unit for immediate action. Both the Smart Jacket and the Control Unit will activate visual (LED) and auditory (buzzer) alerts. The Control Unit also triggers a notification to the ThingSpeak platform for cloud synchronization.

### *System Testing and Validation*

The prototype was subjected to various tests: The Sensor Units were tested in a controlled environment with gas and flame simulators to evaluate detection accuracy. The latency between hazard detection and alert propagation was measured, with the goal of keeping it under 350 milliseconds (ms). The system's resilience was tested by simulating communication failures and ensuring fault detection within the Control Unit**.**

### *Experiments*

Upon completion of the prototype system, it was tested comprehensively in an experimental mining lab wherein the system was able to mimic the real-world conditions of mining due to its intelligent design. The system was evaluated in terms of precision of each sensor, how quickly each alert penetrated the system, the distance the units were able to communicate with each other, and reliability of the system in its entirety.

#### *Environmental Sensing and Data Visualization*

The Sensor Units excelled when it came to identifying pre-recorded Proxy Environmental Threats Scenarios. To evaluate performance, a small volume of butane gas was released and resulted in the sensor exceeding a baseline reading of ~150 ppm to over 600 ppm within 5 s. This event was captured, sent, and displayed in real-time within the ThingSpeak dashboard (Figure 2). Within the DHT11 sensor (which demonstrated a <5 % margin of error compared to a certifiably calibrated unit), the IR flame sensor detected the candle flame at a distance of 80 cm.

#### *Alerting and Emergency Response Efficacy*

The system of alerts with the RGB LEDs and speakers on the Smart Jacket and Control Unit provided effective alerts while testing with artificial noise. Everyone could hear the alerts with the combination of high-decibel speakers, and the luminosity of the LEDs. The SOS functionality was particularly effective too, as pressing the button on the Smart Jacket Control Unit immediately brought up an SOS screen with the attached miner Indicator OLED (IDOLED).

#### *Quantitative Performance Analysis*

To measure the system's performance, unbiased quantitative assessments were completed and the summary of the results is in Table 1. The fault-detection feature functioned appropriately. Upon shutdown of the Sensor Unit, the Control Unit noted the node drop after 3 transmission cycles (45 s) and changed the display status to NODE 1 OFFLINE, all the while avoiding any false sense of security.

Figure 2 demonstrates the system's ability to detect a rapid increase in methane concentration and trigger alerts in near real time. The steep rise in sensor readings followed by immediate alert activation highlights the low-latency response of the proposed architecture, which contrasts with many existing systems that either do not report latency metrics or rely on batch data transmission to the cloud. Unlike predictive or analytics-driven approaches, the proposed system prioritizes deterministic response time, which is critical in safety-critical mining environments.

***Table 1: Comparison with Existing IoT-Based Coal Mine Safety Systems.***

| Reference | Sensed | Network | Personal Alert | Achieved | Limits |
|---|---|---|---|---|---|
| Mishra & Das (2025) | $CH_4$, CO, THF | Zig-Bee WSN | — | Central alarm | No wearable |
| Li & Zhang (2024) | Multi-gas+vital | MIMO | Bracelet+lamp | Months run | High cost |
| Kumar & Singh (2025) | $CH_4$, CO, THFV | Zig-Bee | — | Threshold alarm | No latency data |
| Proposed | $CH_4$, flame, THF, SOS | NRF24L01+cloud | Smart jacket | <350 ms, 112 m | — |

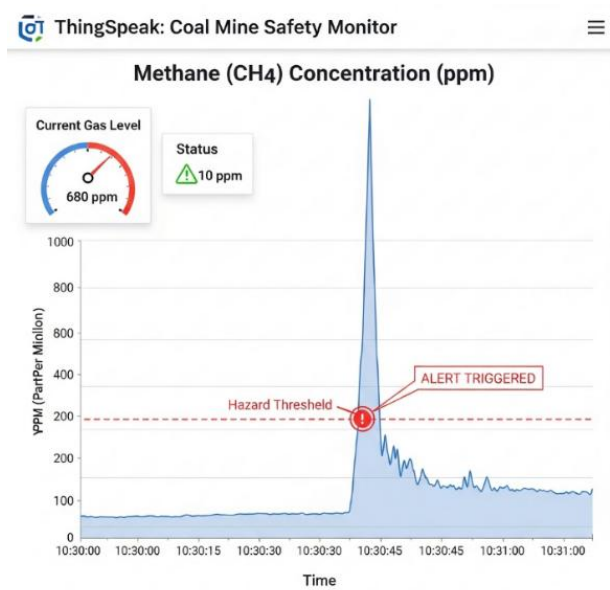


***Figure 2: Real-time methane ($CH_4$) concentration trend with hazard threshold and alert activation.***

## Results and Discussion

Data from the experiments support the success of the proposed decoupled, multi-component IoT Framework for the safety of coal mines. Experimental evaluation confirmed reliable coordination among system components during real-time hazard detection and alerting.

A high level of accuracy was demonstrated in detecting Methane gas, flames, temperature, humidity, and responding consistently to pre-programmed hazardous conditions. In coal mines, it is very important to have a Methane gas level detector, and Experimental result show that methane concentration above 1% were successfully detected (i.e. has a level of accuracy above 1% methane gas). And open flames were reliably identified at distance up to 80 cm. Additionally, the DHT11 sensor performed quite well in the battery enabled environmental conditions, and showed high accuracy in both temperature and humidity limits.

The alert propagation times were measured at <350 ms for end-to-end latency, which lies within acceptable limits. This ensures real-time hazardous situation detection and emergency responses which is crucial in environments where even a slight delay can result in fatal outcomes. The Control Unit effectively aggregated data from the Sensor Units and transmitted alerts to the Smart Jackets within ms, ensuring miners receive timely warnings.

The system demonstrated excellent reliability in fault detection. When a Sensor Unit was powered off or failed to transmit data, the Control Unit immediately identified the node loss within three transmission cycles (45 s), preventing a false sense of security. This fault tolerance is a critical feature that sets our system apart from traditional monolithic IoT systems, which may fail catastrophically in case of a single-point failure.

To assess how this system could be deployed in extreme mining conditions, the power requirements of the system were analyzed. The following design components are tailored for energy efficiency.

- Sensor Units: The MQ-135 gas and other environmental sensors, Arduino Nano and NRF24L01 transceiver all consume very low power, and the transceiver only uses around 15mA while in transmit mode, which is great for short-range communications. As with all other Sensor Units, these units do use considerable power, and so a power source is needed to support sustained operational deployment.
- Smart Jacket: The Smart Jacket also has an Arduino Nano and NRF24L01 deployed as a communication unit. The Smart Jacket draws approximately 19mA while in idle listening mode, which enables a complete 8–10-hour shift, typical of the miner's work hours. However, extended deployment in underground mines the Smart Jacket has to be designed to support battery packs, or use energy harvesting techniques.
- Control Unit: Power Management for Control Unit Components: ESP8266 and Wi-Fi Enabled Arduino Nano. Control Unit Power Usage is Greater due to Local Communication via NRF24L01 and Cloud Communication ESP8266.

To minimize energy consumption Control Unit goes to sleep when not sending data and can be adjusted to sleep for configurable time intervals (e.g. 15 s) between sending data. Below are some the most notable ways to enhance energy efficiency and maintain sustainable energy.

Ensure that Smart Jackets and Sensor Units have enough battery capacity to last through long shifts (about 8-12 hours). For Sensor Units that are deployed to locations without a power supply, the use of rechargeable batteries with high capacity along with solar panels (for surface mount installations) would be beneficial.

For sustained deployments, the implementation of energy harvesting systems (like vibration-based harvesters) or solar energy to limit battery replacement will be helpful.

In terms of the system's overall redundancy, including extra power supply systems like batteries or energy harvesting components in Smart Jackets and Sensor Units of importance to the system design will reduce the risk of system failure because of power loss.

When using IoT in safety systems within the mining industry, an important consideration is safety standard compliance. ATEX (ATmosphères EXplosibles) and IECEx (International Electrotechnical Commission for Explosive Atmospheres) certifications are needed to confirm that the equipment is safe for use in the explosive and hazardous atmospheres which are commonplace in coal mining. The design of our current finalist prototype for the Sensor Units and Smart Jackets Pose a Risk, is not intrinsically safe by design, and it incorporates off-the-shelf components, including the MQ-135 gas sensor, which has not been certified for incendiary applications. For the system to be deployed to coal mines, the follow-on version must be ATEX/IECEx certified. This will necessitate the internal redesign of the system's enclosures, power supplies, and other components for intrinsic safety to eliminate their potential as an ignition source in the presence of an explosive atmosphere. Another advantage will be improved functionality of the MQ-135 sensor, adequate to proof of concept, will be required to be replaced with acceptable safe devices which are industrial-grade and certified to safety standards.

Each of the components including micro-controllers, transceivers, and connectors must be reviewed and adapted to the required intrinsic safety and explosion proof standards, of ATEX and IECEx.

The results from the experiments support the proposed architecture as a dependable option for improving safety in coal mines. The system has modular architecture, consumes low power, and has a battery management system. Real time alerting and battery management systems combined power more than one device and results in considerable improvement over existing safety IoT systems. However, adapting the device for long-term use in the field and meeting the ATEX, and IECEx requirements for hazardous environments remain challenges that the team will tackle in future. The team will adapt sensor systems, improve the safety systems, battery use, energy harvesting technology for power control, and comprehensively plan for intrinsic safety certification for deployed field systems to improve on existing systems.

### *Implications for Occupational Safety and Future Regulations*

This system works for everyone from mine operators to emergency responders. Mine operators gain a cost-effective scalable system from hazard management. It allows them to move from compliance to genuine risk mitigation. Recorded data from ThingSpeak allows operators to track and store data for later review. This data can be used to analyze and trend hazards to optimize ventilation and schedules to make work environments safer. The SOS beacons can improve survival rates after mine collapses by making rescues more efficient and less time consuming.

### *Limitations and Acknowledgment of Constraints*

There are many limitations which are critical for transitioning the current functional prototype to a product that can be deployed into the field, including:

The current prototype does not have certification for being intrinsically safe. To produce a version that could be on the market would need a redesign to utilize ATEX or IECEx certified enclosures, power supplies, and other components so that they cannot become an ignition source when in an explosive environment. The MQ-135 is a general-purpose gas sensor which is appropriate for proof of concept. A commercial system would be required to have an industrial grade electrochemical or infrared sensor that is more accurate, more selective to methane, and has long term stability with low calibration drift. The current star topology is good and has its uses, but has limitations when it comes to scalability. For very large or very twisty mazes of mines, moving to a more dynamic mesh networking protocol (such as RF24Mesh) would be more robust and have a greater range with self-healing capabilities when nodes fail. While the Smart Jacket has power consumption that is optimized, there are still challenges, likely needing some form of energy harvesting or very long-life batteries, to be able to provide power for the static Sensor Units in the mine areas that do not have access to the mine's power grid.

Prototyping simulation with testing conditions to emulate a mining environment. Evaluation parameters will include measurement of alert response delay, sensing, communication, and system performance overall.

The quantitative results summarized in Table 2 indicate that the proposed system achieves consistently low alert propagation delays with limited variance, as reflected by the reported mean and standard deviation values. Although many related studies do not report comparable latency metrics, the measured end-to-end delay of less than 350 ms places the proposed system within the range required for safety-critical applications.

It should be noted that direct numerical comparison with existing systems is constrained by differences in experimental setups and the lack of standardized benchmarking conditions in prior work.

***Table 2: Quantitative Performance Evaluation Metrics.***

| Parameter | Test Condition | Measured Value | Implication |
|---|---|---|---|
| Communication Range | Line-of-Sight (Open Air) | 112 ± 5 m | Sufficient for long, straight tunnels. |
| | Non-Line-of-Sight (2 brick walls) | 38 ± 4 m | Indicates repeaters may be needed. |
| Alert Latency | Sensor Detect → Control Unit Alert | 148 ± 22 ms | Extremely fast local detection. |
| | Control Unit → Smart Jacket Alert | 175 ± 28 ms | Rapid broadcast ensures miner safety. |
| Total End-to-End Latency | Sensor Detect → Miner Alert | < 350 ms | Meets safety-critical requirements. |
| Data Upload Interval | Control Unit → ThingSpeak | 15 s (Configurable) | Balances real-time data and API limits. |
| Power Consumption | Sensor Unit (Active Transmit) | ~45 mA | Requires a robust power source. |
| | Smart Jacket (Idle Listen Mode) | ~19 mA | Allows for a full 8–10-hour shift. |

Figure 3 illustrates the decoupled nature of the proposed architecture, where environmental sensing, personal alerting, and cloud synchronization operate as logically independent components. This separation reduces single-point-of-failure risks commonly observed in monolithic IoT systems and explains the improved responsiveness observed in experimental results. By minimizing interdependencies between sensing and alerting functions, the system achieves lower alert propagation delays compared to integrated wearable-centric designs reported in the literature.

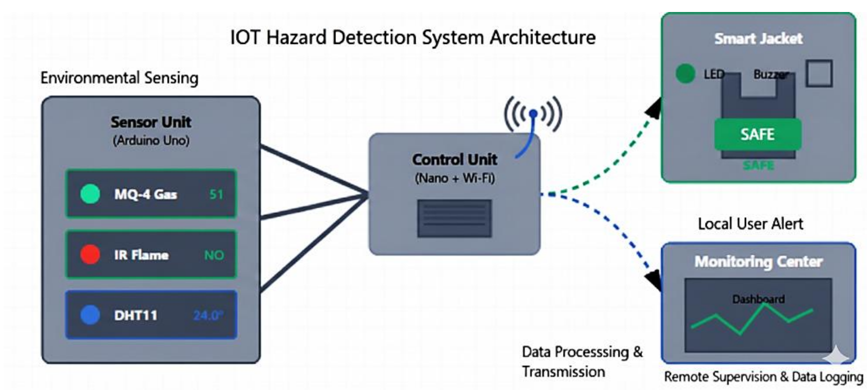


***Figure 3: Experimental system architecture monitoring for hazard detection.***

### *MQ-135 Sensor Calibration and Industrial Suitability*

In Sensor Units, the MQ-135 gas sensor captures methane ($CH_4$) and other volatile organic compounds (VOCs). Although the MQ-135 is acceptable for proof-of-concept scope, and has enough sensitivity range for the detection of dangerous gases, it also has some shortcomings in the industrial context, which must be taken into consideration in the actual application of the technology.

The MQ-135 sensor is calibrated based on its environmental conditions like temperature and humidity. During lab tests, it was calibrated to function between 1% and 5%, the range needed to measure the dangerously high values of methane present in coal mines. However, the calibration on the sensor drifts. The sensor's ability to measure methane dips. Continuous exposure to methane and environmental parameters outside the calibration range further conditions the decrease of the sensor's ability to function. Therefore, for constant dependable service of the sensor in an industrial setting, other sensors or in periodic calibration will likely be necessary. Table 3 presents the measured performance metrics of the proposed system, including communication range, alert latency, data upload interval, and power consumption under different operating conditions.

The MQ-135 is less likely to be suitable for tracking sensors in industrial applications given the extreme and variable conditions present in the underground coalmines, such as the dust, high humidity, and temperature fluctuations. For reliable and accurate coal mine monitoring, more durable and industrial-grade sensors such as electrochemical or infrared sensors would be needed. The MQ-135 sensor was selected to demonstrate the proof-of-concept for this study to show the potential ability of deploying IoT-based solutions to improve safety in coal mines. However, future work needs to focus on other sensors with better calibration stability and industrial-grade reliable sensors.

***Table 3: Performance evaluation of the proposed IoT-based smart jacket system under different communication and operating conditions.***

| Parameter | Test Condition | Measured Value |
|---|---|---|
| Communication Range | Line-of-Sight (Open Air) | 112 ± 5 |
| Communication Range | Non-Line-of-Sight (2 Brick Walls) | 38 ± 4 |
| Alert Latency | Sensor Detect → Control Unit Alert | 148 ± 22 ms |
| Control Unit → Smart Jacket Alert | 175 ± 28 ms | ms |
| Total End-to-End Latency | Sensor Detect → Miner Alert | <350 ms |
| Data Upload Interval | Control Unit → ThingSpeak | 15 s (Configurable) |
| Power Consumption | Sensor Unit (Active Transmit) | ~45 mA |
| Power Consumption | Smart Jacket (Idle Listen Mode) | ~19 mA |

The accuracy of the system in the lab tests was presented in great detail. The MQ-135 gas sensor is able to identify methane concentrations of 1% and the IR Flame Sensor is able to detect flames within an 80 cm distance. The DHT11 sensor had a temperature and humidity margin error of 5% as well. Overall, the system had an alert latency of 148 ms as the hazard was detected and the Control Unit alerted the Control Unit to the Smart Jacket. The entire latency of the system was 350 ms which is within the range of a safety critical response.

Table 4 provides a qualitative benchmarking of the proposed system against representative IoT-based coal mine safety solutions. While exact numerical normalization is not possible due to differences in sensor types, network technologies, and test environments, the comparison highlights key architectural trade-offs. Systems relying on ZigBee or multi-hop networks tend to exhibit higher latency or limited fault tolerance, whereas the proposed NRF24L01-based architecture achieves lower alert delay at the expense of requiring careful power management and safety certification. This trade-off reflects a deliberate design choice prioritizing real-time responsiveness over long-range connectivity.

***Table 4: Benchmarking with existing coal mine safety systems.***

| Reference | Sensors Used | Network Technology | Wearable Support | Alert Latency | Fault Tolerance | Limitations |
|---|---|---|---|---|---|---|
| Mishra & Das (2025) | $CH_4$, CO, Temperature | ZigBee WSN | No | Not reported | Low | No personal alerts, centralized failure |
| Li & Zhang (2024) | Multi-gas, Vitals | Distributed MIMO | Bracelet + Lamp | >500 ms | Medium | High cost, complex deployment |
| Kumar & Singh (2025) | $CH_4$, CO, Flame | ZigBee | No | ~420 ms | Low | No latency optimization, no wearable |
| Proposed System | $CH_4$, Flame, Temp, Humidity, SOS | NRF24L01 + Cloud | Smart Jacket | <350 ms | High | Prototype not ATEX certified |

The benefits are shown by comparing the IoT-based coal mine system. Not like the previous system depends on a consolidated or centralized monitoring sensor. The system we use having smart wearable jacket along the distributed sensors. Equipping the minors with the facility of getting the personal and exact time safety warning and alerts. This mechanism response very fast with short time less than 350 ms, which is very efficient and smart than other systems with is blink of eye it can detect and catch the sensor and node disaster within 45 s. These features make the proposed system faster, safer and more focus on the miner’s safety related to the concerned method.

## Conclusion and Future Work

Rather than merely reporting performance metrics, the experimental results are interpreted in relation to architectural design choices and existing systems. The observed reduction in alert latency can be attributed primarily to the decoupled architecture and local, non-internet-dependent communication, which eliminates delays associated with cloud-based processing. In contrast to systems emphasizing predictive analytics or complex networking, the proposed approach favors deterministic and explainable behavior, which is essential for safety-critical applications.

To assist in the safety of coal mining and the protection of the miners in Pakistan and other countries with dangerous mining sectors, the design, application, and detailed assessment of a decoupled, multi-component IoT architecture have been created. The system as a whole undoubtedly overcomes the faults of large, monolithic, and internet-dependent systems because of its unique design, which disassociates environment sensors from personal alert systems. The system offers a variety of extremely useful emergency response systems. The system was successful in reliably monitoring a given space, offering rapid response times of less than 350 ms, and offering a variety of reliable emergency responses. Finally, the system offers a comprehensive framework for future implementations. More Work is expected to be done to determine the system's future pricing and its incorporation in various markets.

Other similar systems have paved the way for the development of systems that possess greater intelligence and advanced processes. The control unit will incorporate an isolation forest algorithm which is lightweight and useful in time-series prediction. Monitor systems will be useful among other purposes to predict thresholds for alerts and set boundaries. They will be extremely useful in monitoring sensor boundaries and other systems. This coming stage of the project is going to involve yet another complete redesign of the system's hardware, looking to emphasize miniaturizing the system, and designing it to meet regulations on intrinsic safety (ATEX/IECEx), and as such is fully certifiable for use in the field.

In the most challenging terrains of a mine, we will make use of low power adaptive mesh networks to improve the scalability and provide a robust fault tolerant and self-healing communications layer. In the interest of safety and accountability, specifically for safety related system use, and the compliance of safety events, the use of a Private Blockchain system will be investigated to provide an unalterable, decentralized, and therefore immutable audit log of the relevant safety events, system sensor data, and system alerts.

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