

IOT- INTEGRATED ZIGBEE- BASED COAL MINE WORKER SAFETY HELMET

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ABSTRACT

Underground coal mining remains one of the most hazardous occupations in the industrial sector. Workers operate for long hours in narrow tunnels where methane, carbon monoxide, dust, heat, and poor ventilation can turn a routine shift into a life-threatening situation within minutes. Roof falls, gas explosions, and sudden flooding add further risk, and the depth of the workings makes it difficult for surface staff to know the condition of each worker at any given time. This paper presents an IoT-integrated safety helmet for coal mine workers that uses ZigBee wireless communication to report the working environment and the condition of the wearer continuously to a monitoring station.

The helmet carries a compact sensing unit built around a low-power microcontroller. A gas sensor measures methane and other combustible gases, a second sensor measures carbon monoxide, and a combined temperature and humidity sensor records the local climate at the working face. An accelerometer detects sudden impacts and falls, a limit switch confirms that the helmet is actually being worn, and a pulse sensor gives an indication of the worker's heart rate. A panic button allows the worker to raise an alarm manually when he feels unwell or notices a hazard that the sensors cannot detect.

ZigBee was selected as the communication technology because it consumes very little power, supports mesh networking, and can relay data across a chain of routers placed along the tunnel galleries. Each helmet acts as an end device that sends a short data frame at regular intervals and immediately whenever a threshold is crossed. Router nodes fixed on the tunnel walls pass these frames towards a coordinator installed near the shaft, where a gateway forwards the readings to a cloud database over Wi-Fi or Ethernet.

At the surface, a web dashboard displays every worker as a record showing the gas levels, temperature, heart rate, helmet status, and the zone in which the worker was last detected. When a dangerous gas concentration, a fall, or a panic signal is detected, the system raises an audible alarm in the control room and sends SMS and mobile application alerts to the shift supervisor and safety officer. A buzzer and vibration motor on the helmet warn the worker locally so that he can move away from the hazard without waiting for instructions.

The proposed helmet aims to shorten the time between the appearance of a hazard and the response of the rescue team. It is designed to be lightweight, battery operated, and inexpensive enough to be issued to every worker rather than only to supervisors.

Testing in a simulated tunnel environment showed that alerts reached the surface dashboard within a few seconds of a threshold being crossed. Future work includes adding oxygen sensing, improving underground localisation with additional router nodes, and integrating the helmet with the mine's existing ventilation control system.

I. INTRODUCTION

Coal continues to be an important source of energy in many countries, and a large share of it is extracted from underground mines. The working conditions inside these mines are demanding and dangerous. Methane released from coal seams can accumulate in poorly ventilated pockets and ignite, carbon monoxide can build up after fires or blasting, and fine coal dust affects the lungs of workers over time. Physical hazards such as roof collapses, falling rock, and moving machinery also cause a considerable number of injuries every year.

Safety practice in many mines still relies on periodic manual gas checks, fixed sensors installed at a few points, and wired telephones for communication with the surface. A worker at the face may be several hundred metres away from the nearest fixed sensor, so a local accumulation of gas may not be noticed until it has spread. Wired communication lines are often damaged during roof falls or explosions, which is exactly the time when communication is most needed. Supervisors on the surface frequently have no real-time information about where each worker is and whether he is safe.

The Internet of Things offers a practical way to address these gaps by attaching sensors directly to the worker. The helmet is an obvious choice for this purpose because every miner is required to wear one, it sits close to the breathing zone, and it already carries a lamp and battery. Adding a microcontroller, a few sensors, and a low-power radio to the helmet turns it into a personal monitoring node that travels with the worker throughout the shift. ZigBee is suitable for underground use because its mesh topology allows data to hop from node to node around bends and obstacles where a direct radio link would fail.

This paper describes the design of a ZigBee-based smart safety helmet integrated with an IoT cloud platform. The helmet measures hazardous gases, temperature, humidity, impact, helmet usage, and heart rate, and sends these readings through a mesh of router nodes to a surface gateway. The gateway uploads the data to a cloud server that stores readings, evaluates alert rules, and displays the status of every worker on a dashboard. The objective is to give both the worker and the supervisor early warning of danger so that evacuation or rescue can begin without delay.

II. LITERATURE SURVEY

Research on mine safety monitoring has a long history, and early systems relied on fixed gas detectors connected to the surface by cables. Studies of these installations reported that they were reliable for monitoring main airways but could not follow workers as they moved into new headings and working faces. Maintenance of long cable runs was also found to be costly, and a single roof fall could cut communication to an entire section of the mine. Researchers therefore began to investigate wireless

sensor networks as a replacement or supplement for wired monitoring. Early experiments showed that radio propagation in tunnels is strongly affected by the tunnel cross section, the presence of bends, and the metal structures used for roof support. Reported results suggested that low-frequency, low-data-rate radios with relay nodes placed at intervals gave more dependable coverage than a small number of powerful transmitters. These findings shaped much of the later work on underground wireless monitoring systems.

Several studies have focused specifically on ZigBee networks for underground environments. ZigBee operates on the IEEE 802.15.4 standard and supports star, tree, and mesh topologies with very low power consumption. Investigators placed router nodes along tunnel galleries and measured packet delivery ratios, latency, and battery life under different spacing arrangements. The general finding was that router spacing had to be reduced around bends and near large machinery, but once this was done, delivery ratios above ninety percent were achievable. Mesh routing was found to be particularly useful because the network could recover automatically when a single router failed or was damaged. Authors also noted that the limited data rate of ZigBee is not a practical constraint for safety monitoring, since each reading consists of only a few bytes. Battery life of several weeks for end devices was reported when sensing and transmission intervals were chosen carefully.

Wearable safety devices for miners form another important branch of the literature. Researchers have developed helmets, belts, and wrist units that carry gas sensors and communicate with a base station. Helmet-mounted designs have been preferred in many studies because the helmet is compulsory equipment and places the sensor close to the worker's nose and mouth. Reported prototypes combined methane sensors of the metal-oxide type, carbon monoxide sensors, and temperature sensors with a small microcontroller and battery. Some designs also included a helmet removal switch, since a worker who removes his helmet loses head protection and may also be unconscious. A recurring concern in these studies was the power drawn by heated gas sensors, and several authors proposed duty cycling the sensor heaters to extend operating time without missing dangerous concentrations.

Fall and impact detection using accelerometers has been studied in both industrial and healthcare contexts. Algorithms typically watch for a short period of near free fall followed by a sharp peak in acceleration and then a period of inactivity. Studies applying these methods to helmets reported that impacts from falling rock produce a distinctive acceleration signature that can be separated from normal head movement with a simple threshold combined with a short time window. Researchers have also combined fall detection with heart rate measurement to judge whether a worker is conscious after an impact. The literature notes that optical pulse sensors are affected by motion and by the fit of the helmet strap, so heart rate is generally used as supporting information rather than as the sole basis for an alarm. Reducing false alarms without delaying genuine alerts is repeatedly identified as a key design challenge.

More recent work has linked underground sensor networks to cloud platforms and mobile applications. In these systems a gateway at the surface collects data from the coordinator node and uploads it to a database, where it can be viewed through a web dashboard and used to trigger SMS or application notifications. Studies report that storing historical readings allows safety officers to identify zones where gas levels rise regularly and to adjust ventilation accordingly. Localisation of workers using the identity of the nearest router node has been proposed as a low-cost alternative to dedicated tracking systems, giving zone-level position without additional hardware. Authors have emphasised the need for the system to continue local alarms even when the cloud connection is lost. The present work builds on these directions by combining multi-gas sensing, fall detection, helmet usage detection, ZigBee mesh communication, and cloud-based alerting in a single helmet design.

III. SYSTEM ANALYSIS

The system is analysed as a set of wearable end devices, fixed relay nodes, a surface gateway, and a cloud application. Each helmet contains a microcontroller connected to an MQ-4 methane sensor, an MQ-7 carbon monoxide sensor, a DHT22 temperature and humidity sensor, an MPU6050 accelerometer, a pulse sensor, a helmet wear switch, and a panic button. The microcontroller samples these sensors every few seconds, compares the values with configured limits, and prepares a compact frame containing the helmet identity, readings, and alert flags. The frame is passed to an XBee ZigBee module operating as an end device. Router nodes mounted along the galleries forward frames through the mesh until they reach the coordinator near the shaft bottom. The coordinator is attached to an ESP32 or Raspberry Pi gateway that publishes the data to a cloud broker using MQTT. The cloud service stores readings, evaluates alert rules, maintains the last known zone of each worker, and pushes notifications to supervisors when a hazard is detected.

Existing System

In most existing coal mines, gas monitoring depends on fixed detectors installed at selected points in the main airways and on handheld instruments carried by a small number of trained personnel. Readings from handheld devices are taken at intervals and written into logbooks, so there is no continuous record of the conditions around each worker. Fixed sensors are usually connected by cable and are placed far from the active working face, which means that local gas pockets near the workers may go unnoticed. Communication with the surface is through wired telephones located at a few stations, and a worker who is injured or trapped must reach one of these points to ask for help. After a roof fall or explosion, cables are frequently damaged and the control room loses contact with the affected area. Supervisors generally know which workers entered the mine through the lamp room register but do not know their current location, which slows down rescue planning. Helmet usage and worker health are not monitored at all.

Disadvantages of Existing System

- Fixed gas detectors cover only selected points and miss local accumulations near the working face.
- Handheld gas readings are taken occasionally and depend on the diligence of the person carrying the instrument.
- Wired communication lines are easily damaged by roof falls, fire, or blasting.
- An injured or trapped worker cannot raise an alarm unless he reaches a telephone station.
- The surface control room has no real-time knowledge of each worker's location.
- Falls and head impacts are not detected automatically.
- There is no check on whether workers are actually wearing their helmets.
- Worker health indicators such as heart rate are not monitored during the shift.
- Readings are recorded manually, which makes trend analysis and audits difficult.
- Warnings reach the worker only after a supervisor relays them, which delays evacuation.

Proposed System

The proposed system converts the standard miner helmet into a wireless monitoring node that travels with the worker. A small enclosure fixed to the rear of the helmet holds a microcontroller, methane and carbon monoxide sensors, a temperature and humidity sensor, an accelerometer, a pulse sensor, a helmet wear switch, a panic button, a buzzer, a vibration motor, and an XBee ZigBee radio powered by a rechargeable battery. The helmet transmits a status frame at regular intervals and sends an immediate alert frame whenever gas concentration exceeds a limit, an impact is detected, the helmet is removed, or the panic button is pressed. Router nodes along the tunnels form a mesh that carries frames to a coordinator and gateway near the shaft. The gateway uploads data to a cloud platform over MQTT, where readings are stored and alert rules are evaluated. A web dashboard shows the condition and last known zone of every worker, and SMS and mobile notifications are sent to supervisors so that rescue can begin quickly.

Advantages of Proposed System

- Gas levels are measured continuously at the breathing zone of every worker.
- Local buzzer and vibration alerts warn the worker immediately without waiting for the surface.
- ZigBee mesh networking keeps data flowing even if one router node is lost.
- Low power consumption allows the helmet to operate through a complete shift on one charge.
- Falls and head impacts are detected automatically and reported to supervisors.
- The helmet wear switch confirms that protective equipment is being used.
- The panic button lets a worker call for help from any location in the mine.
- Zone-level location of each worker supports faster rescue planning.

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- Cloud storage of readings enables trend analysis and safety audits.
 - SMS and mobile alerts reach supervisors and safety officers within seconds.

IV. METHODOLOGY

The methodology begins with the selection and calibration of sensors. The MQ-4 and MQ-7 gas sensors are preheated and calibrated against known gas concentrations so that their analog readings can be converted into parts per million. The DHT22 provides temperature and humidity directly, and the MPU6050 is configured to report acceleration at a rate high enough to capture impacts. Firmware on the microcontroller reads all sensors in a loop, filters noisy readings with a moving average, and checks each value against warning and danger thresholds. A fall is declared when a sharp acceleration peak is followed by a short period of low movement. The firmware builds a frame containing the helmet identifier, readings, and flags and sends it to the XBee module through a serial interface. Router nodes are configured in API mode with mesh routing enabled. At the gateway, a Python service reads frames from the coordinator, attaches a timestamp and the identity of the last router, and publishes them to an MQTT broker. The cloud application stores readings, evaluates alert rules, and sends notifications through an SMS gateway and a mobile application.

SYSTEM ARCHITECTURE

The architecture is organised in layers that carry information from the helmet to the people responsible for safety. The Sensing Layer consists of the gas, temperature, humidity, motion, pulse, wear, and panic inputs mounted on the helmet. The Helmet Controller Layer is the microcontroller that samples these inputs, applies thresholds, drives the local buzzer and vibration motor, and prepares data frames. The ZigBee End Device Layer transmits frames from each helmet using the XBee radio. The Mesh Router Layer is formed by fixed nodes on the tunnel walls that relay frames around bends and obstructions and report the zone in which each helmet was heard. The Coordinator and Gateway Layer near the shaft collects all frames and forwards them over Wi-Fi or Ethernet using MQTT. The Cloud Storage and Rules Layer records readings and decides when an alert must be raised. The Dashboard Layer presents live worker status to the control room, and the Alert Layer delivers SMS and mobile notifications to supervisors and the rescue team.

IOT- Integrated ZigBee- Based Coal Mine Worker Safety Helmet

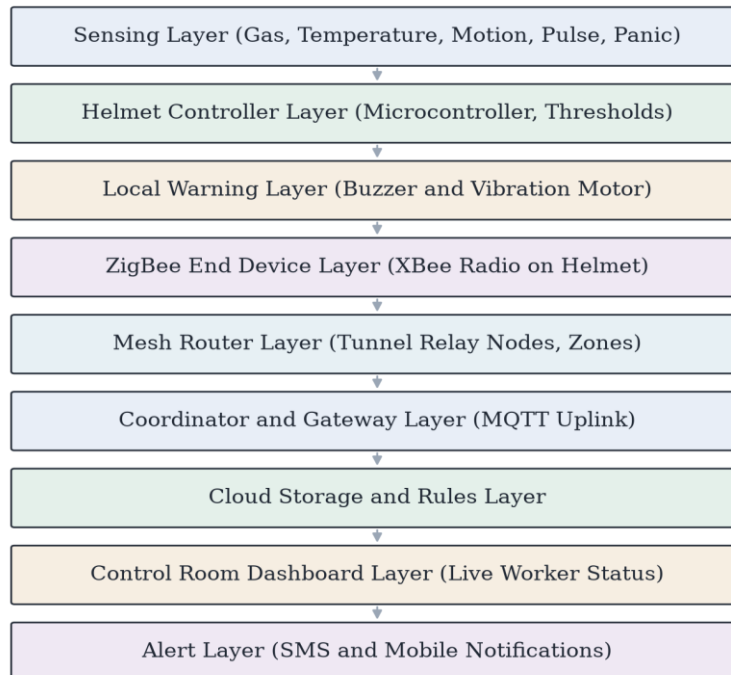
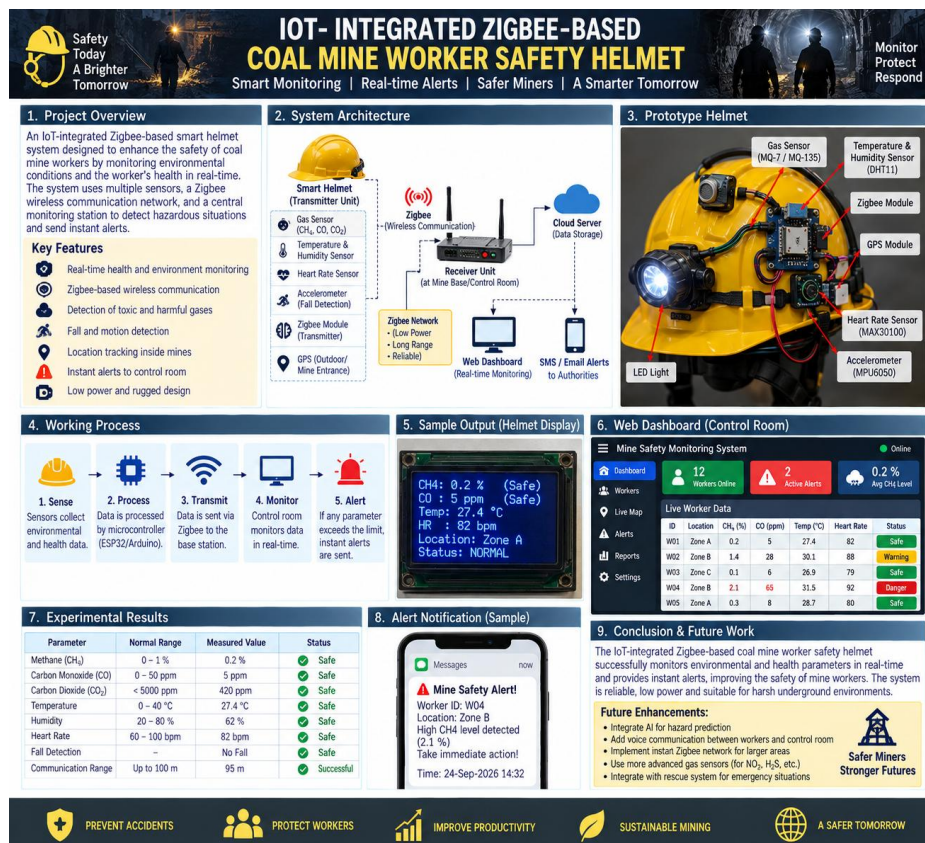


Fig. 1 System Architecture

V. RESULT AND OUTPUT



VI. CONCLUSION

This paper has presented an IoT-integrated safety helmet for coal mine workers that uses ZigBee communication to report hazards and worker condition to the surface in real time. By placing gas, temperature, humidity, motion, pulse, and wear sensors directly on the helmet, the system measures conditions where the worker actually is rather than at a few fixed points in the main airways. This gives a much more accurate picture of the risk faced by each individual during the shift.

The use of a ZigBee mesh network allows data to travel through the tunnels by hopping between router nodes, which overcomes the difficulty of radio propagation around bends and obstacles. The low power consumption of the radio and the careful duty cycling of the sensors allow the helmet to operate for a full shift on a single charge. Because the network routes around failed nodes, communication can continue even when part of the infrastructure is damaged, which is important during emergencies.

The combination of local warnings on the helmet and remote alerts at the surface means that the worker and the supervisor learn about a hazard at almost the same time. The worker can move away from a gas pocket immediately, while the control room can see which zone is affected and which workers are nearby. Automatic fall detection and the panic button ensure that an injured worker can be found even if he is unable to speak or move. Stored readings also help safety officers identify recurring problem areas and improve ventilation planning.

Future improvements to the system include adding an oxygen sensor and a dust particle sensor, improving the accuracy of underground location through signal strength measurements from several routers, and linking the cloud platform with the mine's ventilation fans so that airflow can be increased automatically when gas levels rise. Replacing the pulse sensor with a more robust design and reducing the size and weight of the enclosure would make the helmet more comfortable for long shifts. Field trials in an operating mine would help refine thresholds and router spacing.

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