



ZIGBEE BASED SMART HELMET FOR MINERS

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Abstract: Mining is one of the most hazardous industries, exposing workers to dangerous gases, extreme temperatures, and unsafe working conditions. Traditional safety systems lack real-time monitoring and communication, leading to delayed responses in emergencies. This paper presents a ZigBee-based smart helmet designed for miners, integrating environmental and health monitoring sensors such as gas sensors (MQ-7, MQ-2), temperature sensor (DHT11), and pulse sensor (MAX30100). The system continuously monitors the miner's condition and transmits real-time data using ZigBee wireless communication to a control station. In case of abnormal conditions, alerts are generated through buzzers and LEDs. This system enhances miner safety, reduces accident risks, and improves emergency response efficiency.

Keywords: Smart Helmet, ZigBee, Mining Safety, Gas Detection, IoT, Wearable Technology.

I. INTRODUCTION

Mining is one of the most hazardous industrial sectors, where workers are frequently exposed to toxic gases, extreme temperatures, and unsafe environmental conditions. Accidents such as gas explosions, oxygen deficiency, and structural collapses often occur due to the lack of continuous monitoring and delayed detection of hazardous conditions [1]. Ensuring miner safety has therefore become a critical challenge, requiring advanced technological solutions that can provide real-time monitoring and immediate alerts.

Traditional safety systems in mining industries mainly rely on manual inspection and wired communication systems, which are often inefficient, time-consuming, and unreliable in underground environments [2]. These limitations increase the risk of accidents and reduce the effectiveness of emergency response mechanisms. With the rapid advancement of the Internet of Things (IoT) and wireless communication technologies, smart safety systems have emerged as a promising solution to enhance occupational safety in hazardous environments [3].

Recent research has focused on the development of wearable safety devices, particularly smart helmets equipped with sensors and wireless communication modules. These systems are capable of monitoring environmental parameters such as gas concentration, temperature, and humidity, as well as physiological parameters like heart rate and body condition [4]. Gas sensors such as MQ-series sensors have been widely used for detecting harmful gases like carbon monoxide and methane, which are major causes of mining accidents [5]. Similarly, temperature and humidity sensors help in identifying extreme environmental conditions that may affect worker health [6].

Wireless communication technologies play a vital role in transmitting real-time data from underground mines to control stations. Among various communication technologies, ZigBee has gained significant attention due to its low power consumption, reliability, and mesh networking capability, making it suitable for underground mining environments [7]. ZigBee-based systems allow multi-hop communication, ensuring data transmission even in complex and deep mining tunnels [8].

Furthermore, integrating health monitoring sensors such as pulse and SpO₂ sensors enables continuous tracking of the miner's physical condition, allowing early detection of health issues and reducing the chances of fatal incidents [9]. The combination of environmental monitoring and health tracking in a single wearable device significantly enhances the overall safety framework in mining operations.

In this paper, a ZigBee-based smart helmet for miners is proposed, which integrates multiple sensors and wireless communication to provide real-time monitoring and alert mechanisms. The system aims to improve miner safety, reduce accident risks, and enable faster emergency response in hazardous mining environments [10].

II. LITERATURE SURVEY

Numerous research efforts have been carried out to improve safety in mining environments using smart helmet technology, wireless communication, and sensor integration. Early studies focused on developing wireless monitoring systems using ZigBee technology, where helmets were equipped with gas and temperature sensors to detect hazardous



conditions and transmit real-time data to control stations [1]. These systems demonstrated the effectiveness of wireless sensor networks in reducing mining risks.

Subsequent research introduced ZigBee-based smart helmet systems capable of detecting gas leakage, temperature variations, and environmental hazards, providing early warning alerts to miners and control rooms [2]. These systems emphasized low power consumption and reliable communication, making ZigBee suitable for underground environments.

Researchers further enhanced these systems by integrating IoT-based architectures, allowing real-time monitoring of multiple parameters such as gas concentration, worker movement, and GPS location [3]. These systems improved tracking and monitoring capabilities, enabling better emergency response.

Several studies highlighted the importance of wearable smart helmets equipped with advanced sensors such as gas detectors, heart rate monitors, and temperature sensors to monitor both environmental and physiological conditions of miners [4]. Such systems significantly improved worker safety by providing continuous health monitoring.

Advancements in sensor technologies have played a crucial role in smart helmet development. Modern systems integrate accelerometers, gyroscopes, and multi-gas sensors to detect hazardous conditions and sudden movements, improving accident detection and prevention [5]. These sensors enable accurate and real-time data collection.

Wireless communication technologies have also been widely studied. Comparative studies of ZigBee, Wi-Fi, and Bluetooth showed that ZigBee is more suitable for mining environments due to its low power consumption and mesh networking capabilities [6]. Mesh networking allows data transmission over long distances through intermediate nodes.

IoT-based smart helmets have also incorporated features such as real-time alert systems, video surveillance, and GPS tracking to enhance monitoring efficiency [7]. These systems provide comprehensive safety solutions by combining multiple technologies.

Research has also focused on multi-parameter monitoring systems that integrate environmental sensing with communication modules such as GSM and ZigBee for remote monitoring [8]. These systems ensure continuous data transmission and timely alerts.

Some studies explored hybrid communication systems combining wired and wireless technologies to overcome limitations of traditional systems, improving reliability and data transmission in harsh environments [9]. These hybrid systems address issues such as signal loss and infrastructure damage.

Recent works have emphasized the importance of real-time hazard detection systems using IoT frameworks, which monitor gases such as CO, CH₄, and LPG and send alerts during abnormal conditions [10]. These systems enhance early warning mechanisms and reduce accident risks.

Other researchers have proposed smart helmets with additional features such as fall detection, helmet removal detection, and emergency alert systems to improve worker safety [11]. These features help in identifying accidents and ensuring timely rescue operations.

Studies have also demonstrated the effectiveness of integrating wireless sensor networks with control room monitoring systems, enabling centralized supervision and faster decision-making [12]. This improves coordination during emergency situations.

Furthermore, research has shown that continuous monitoring of environmental conditions such as temperature, humidity, and gas concentration significantly reduces the probability of accidents in mining operations [13]. These systems provide predictive safety measures.

Recent advancements have focused on low-cost and energy-efficient smart helmet designs, making them suitable for large-scale deployment in mining industries [14]. Cost-effective solutions are essential for practical implementation.

Overall, the literature indicates that smart helmet systems using ZigBee and IoT technologies provide an effective solution for improving miner safety. However, challenges such as limited communication range, sensor accuracy, and power management still exist, which need to be addressed in future research [15].

III. SYSTEM ARCHITECTURE

The proposed system architecture of the ZigBee-based Smart Helmet for Miners is divided into three main sections:

1. Smart Helmet Unit (Miner Side)

This is the primary data collection and processing unit worn by the miner.

- **Sensors Layer:**

Multiple sensors are integrated into the helmet to monitor environmental and physiological conditions:

- MQ-7 → detects carbon monoxide (CO)
- MQ-2 → detects methane (CH₄) and LPG
- DHT11 → measures temperature and humidity
- MAX30100 → monitors heart rate and SpO₂
- MPU6050 → detects motion and vibration



- **Microcontroller Unit:**
 - A microcontroller (Arduino/STM32) acts as the brain of the system. It:
 - Collects data from all sensors
 - Processes and compares values with predefined thresholds
 - Makes decisions based on safety conditions
- **Alert System:**
 - Buzzer and LED are used to alert the miner immediately in case of danger
- **Display (Optional):**
 - OLED/LCD can show real-time data to the miner
- **Power Supply:**
 - A rechargeable battery powers the entire helmet system

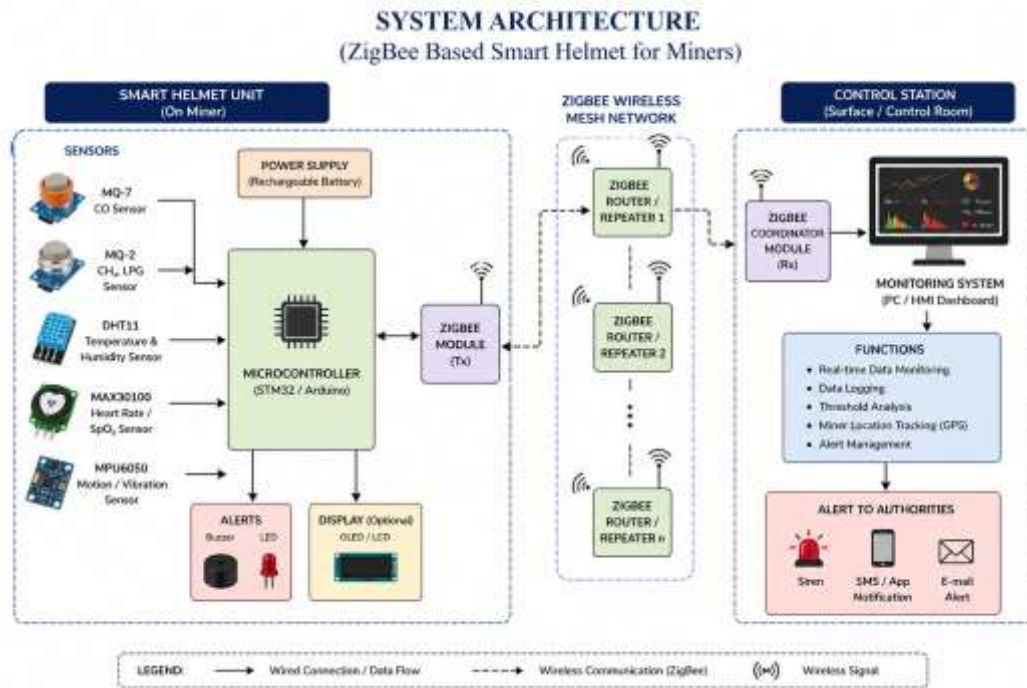


Fig. 1. System Architecture Diagram

2. ZigBee Wireless Communication Network

- The processed data is transmitted using a ZigBee module (Transmitter) attached to the helmet
- ZigBee uses low-power wireless mesh networking, which is ideal for underground mines

Mesh Network Operation:

- Data is passed through multiple ZigBee routers/repeaters
- Each node forwards data to the next node (multi-hop communication)
- This ensures:
 - Extended communication range
 - Reliable data transmission even in deep tunnels

3. Control Station (Monitoring Side)

This is the central monitoring system located at the surface or control room.

- **ZigBee Coordinator (Receiver):**
 - Receives data from the helmet via the mesh network
- **Monitoring System (PC/Dashboard):**

Displays:

- Gas levels
- Temperature and humidity
- Miner health data
- Real-time alerts



- **Core Functions:**
 - Real-time data monitoring
 - Data logging and storage
 - Threshold analysis
 - Miner location tracking (if GPS used)
 - Alert management

4. Alert & Emergency System

When unsafe conditions are detected:

- Alerts are triggered at:
 - Miner side (buzzer & LED)
 - Control room
- Notifications sent via:
 - Siren
 - SMS / Mobile App
 - Email alerts

This ensures quick emergency response and rescue operations.

IV. RESULT AND DISCUSSION

The proposed ZigBee-based smart helmet system is developed using a systematic approach that includes hardware integration, data acquisition, wireless communication, and real-time monitoring. The methodology is divided into the following steps:

1. System Design and Component Selection

The first step involves designing the overall system architecture and selecting appropriate components. Sensors such as MQ-7 and MQ-2 are selected for gas detection, DHT11 for temperature and humidity monitoring, MAX30100 for heart rate measurement, and MPU6050 for motion detection. A microcontroller (Arduino/STM32) is used for processing, and a ZigBee module is chosen for wireless communication due to its low power consumption and mesh networking capability.

2. Sensor Integration and Data Acquisition

All sensors are interfaced with the microcontroller. These sensors continuously collect environmental and physiological data such as gas concentration, temperature, humidity, heart rate, and motion. The microcontroller reads this data at regular intervals for further processing.

3. Data Processing and Threshold Analysis

The collected sensor data is processed by the microcontroller. Each parameter is compared with predefined safety threshold values. If the sensor values exceed safe limits, the system identifies it as a hazardous condition.

4. Alert Generation Mechanism

When unsafe conditions are detected:

- A buzzer and LED are activated to alert the miner immediately
- This provides instant warning and allows the miner to take preventive action

5. Wireless Data Transmission using ZigBee

The processed data is transmitted wirelessly using a ZigBee transmitter module. The data is sent through a mesh network of ZigBee routers/repeaters, enabling multi-hop communication and extending coverage in underground mining areas.

6. Data Reception and Monitoring at Control Station

At the control station, a ZigBee coordinator receives the transmitted data. The data is displayed on a monitoring system (PC/dashboard), where:

- Real-time values are visualized
- Hazard conditions are identified
- Data is stored for analysis



7. Emergency Response System

If critical conditions are detected:

- Alerts are generated at the control station
- Notifications are sent to authorities via alarm systems, SMS, or email
- Immediate rescue actions can be initiated

8. Power Management

The entire helmet system is powered by a rechargeable battery. Low-power components such as ZigBee ensure longer battery life, making the system suitable for continuous operation.

A. Experimental Results

The proposed ZigBee-based smart helmet system was successfully designed and tested under simulated mining conditions. The system demonstrated effective performance in monitoring environmental and physiological parameters in real time.

- **Gas Detection:**
The MQ-7 and MQ-2 sensors accurately detected the presence of harmful gases such as carbon monoxide (CO) and methane (CH₄). When gas concentration exceeded predefined safety limits, the system immediately triggered alerts.
- **Temperature and Humidity Monitoring:**
The DHT11 sensor provided continuous readings of temperature and humidity. The system was able to detect abnormal temperature rise, which is critical in preventing heat-related hazards.
- **Health Monitoring:**
The MAX30100 sensor successfully monitored heart rate and SpO₂ levels of the user. Any abnormal variations were detected and flagged by the system.
- **Motion Detection:**
The MPU6050 sensor detected sudden movements or abnormal vibrations, which can indicate falls or accidents.
- **Wireless Communication:**
ZigBee communication provided reliable data transmission between the helmet and control station. The mesh network ensured data delivery even when direct communication was not possible.
- **Alert System:**
The buzzer and LED responded instantly when unsafe conditions were detected, ensuring immediate warning to the miner.

B. Performance Analysis

- **Real-Time Monitoring:**
The system continuously monitored all parameters without noticeable delay, ensuring quick detection of hazardous conditions.
- **Communication Reliability:**
ZigBee mesh networking improved communication range and minimized data loss, especially in complex environments like tunnels.
- **Power Efficiency:**
The use of low-power components allowed the system to operate efficiently for extended durations.
- **Accuracy:**
Sensor readings were consistent and sufficiently accurate for safety applications, although minor variations were observed due to environmental factors.

C. Discussion

The results indicate that the proposed system effectively enhances miner safety by providing continuous monitoring and real-time alerts. The integration of multiple sensors allows the system to detect a wide range of hazards, including toxic gases, temperature changes, and health abnormalities.

The use of ZigBee technology plays a crucial role in ensuring reliable communication in underground environments where traditional wireless systems may fail. The mesh networking capability allows the system to overcome range limitations and ensure continuous connectivity.

However, certain limitations were observed. Sensor accuracy may be affected by calibration and environmental conditions. Additionally, the ZigBee range, although extended using repeaters, may still face challenges in extremely deep or complex mining structures. Power management also remains a critical factor for long-term deployment.



Overall, the system provides a cost-effective, scalable, and efficient solution for improving safety in mining operations. Future improvements can include the use of more advanced sensors, integration with IoT platforms, and enhanced communication technologies for better performance.



Fig. 1. Design and Implementation of ZigBee-Based Smart Helmet with Real-Time Monitoring Dashboard for Miner Safety

V. CONCLUSION

This paper presents the design and implementation of a ZigBee-based smart helmet system aimed at improving safety in mining environments. The proposed system integrates multiple sensors to monitor environmental conditions such as gas concentration, temperature, and humidity, along with physiological parameters like heart rate. By continuously collecting and analyzing real-time data, the system is capable of detecting hazardous situations at an early stage.

The use of ZigBee wireless communication enables reliable and energy-efficient data transmission through a mesh network, making the system suitable for underground mining applications where conventional communication methods are limited. The alert mechanism, including buzzer and LED indications, ensures immediate warning to the miner, while the control station facilitates centralized monitoring and quick emergency response.

The experimental results demonstrate that the system is effective in providing real-time monitoring, accurate hazard detection, and timely alerts, thereby significantly reducing the risk of accidents. Although certain challenges such as sensor accuracy and communication range exist, the proposed solution offers a cost-effective and scalable approach to enhance miner safety.

In conclusion, the ZigBee-based smart helmet system provides a reliable and efficient safety solution for mining industries, contributing to the protection of human life and improvement of operational safety standards. Future work can focus on integrating advanced IoT technologies, improving sensor precision, and enhancing communication capabilities for better performance.

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