Review Paper:

ZigBee based Real Time System for Environmental Parameters Monitoring in Model Mine: An Experimental Study

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Abstract

The global mining industry, known for extracting valuable minerals like coal, iron ore, gold, silver, copper and zinc, primarily operates through underground mining. These underground mine environments are influenced by various environmental factors including toxic and flammable gases, increased carbon dioxide (CO_2) levels and decreased oxygen (O_2) concentrations. These factors significantly impact the productivity and safety of mine workers, making monitoring harmful gases crucial. Various methods exist to measure gas concentrations and respond appropriately when these levels exceed safe thresholds. However, each method has its own set of limitations. In underground mines, wireless monitoring systems are essential to monitor environmental parameters in real time. This study focuses on the assessment of ZigBee-based wireless techniques for their application in underground mines. The developed ZigBee wireless communication system was tested and validated at the surface level and in a model mine laboratory at the Mining Engineering Department of the National Institute of Technology Karnataka (NITK), Surathkal, India. This laboratory replicates an underground mine setting.

The ZigBee-based system is designed to wirelessly monitor environmental parameters. Experiment results suggest that the ZigBee network is suitable for real-time monitoring of environmental conditions in underground mines. Further details regarding the functioning, effectiveness and potential applications of the ZigBee-based system in underground mining are discussed in the study.

Keywords: Wireless Communication, ZigBee, Underground Mine, Automation, Environmental Parameters Monitoring.

Introduction

The mining industry extracts valuable minerals like gold and diamonds using open pit and underground mining methods. Underground mining is riskier due to toxic gases, dust and particulates, roof collapses and other hazards. Long-term exposure to gases like carbon monoxide (CO), methane (CH_4), hydrogen sulfide (H_2S), nitric oxide (NO), nitrogen dioxide (NO_2), aldehydes and increase in carbon dioxide (CO_2) is particularly harmful which leads to health problems for mine workers. Safety is a significant concern and while efforts are made to improve conditions, mining remains unpredictable and dangerous. Monitoring air quality and implementing safety measures including worker training and advanced technology like gas detectors and wireless communication, are essential for worker health and safety. The dynamic and complex nature of underground mines makes communication challenging yet vital for ensuring safety.

The Directorate General of Mines Safety (DGMS) in India recommends environmental monitoring systems in mines to address these risks, with specific standards for diesel equipment to mitigate hazards like emissions and explosions[8]. To safeguard the health and safety of mine workers in underground mines, there is a critical need for an effective and economical system that can monitor environmental conditions in real-time. The risks in these mines are heightened due to the use of diesel equipment and the deeper excavation of mine workings[3]. Workers face significant dangers from inhaling harmful gases, dust and increased CO_2 which can lead to chronic health issues. Additionally, exposure to diesel-operated machinery elevates the risk of developing cancer and respiratory diseases.

Therefore, it is vital to continuously track and maintain toxic gas levels within safe thresholds, necessitating the use of energy-efficient wireless communication technologies[5,6]. The complex and varying layout of underground mines, with their bends and intersections, poses challenges in communication. Implementing an advanced communication system is essential for effectively sharing information about environmental conditions, locating workers and signaling danger zones[12,14,16,18]. Employing automated systems can notably enhance worker safety by establishing a dependable and strong communication network[9,10,21]

The DGMS circular outlines specific minimum ventilation requirements for various noxious and inflammable gases[4,20]. These limits are detailed as follows:

a) **Carbon Dioxide (CO_2):** The maximum allowable concentration is 5000 parts per million (PPM).
b) **Carbon Monoxide (CO):** The threshold limit is 50 PPM.

c) **Nitric Oxide (NO):** The permissible concentration is 25 PPM.
d) **Nitrogen Dioxide (NO_2):** The threshold limit is 5 PPM.
e) **Sulphur Oxide (SO_2):** The maximum allowable concentration is 5 PPM.
f) **Hydrogen Sulfide (H_2S):** The threshold limit is 5 PPM.
g) **Aldehydes:** The allowable concentration is 10 PPM.

The review focuses on the influence of toxic mine gases on physiological health, underground mine disasters caused by gas accidents and the role of WSNs with ZigBee for monitoring environmental parameters in underground mines. An experimental setup using ZigBee modules and various sensors was tested at a surface level and a model mine replicating an underground mine site. The test results of the experimental setup are presented in the study.

This review synthesizes research on the impact of gas explosions, dust and toxic gases in underground mines, focusing on their contribution to accidents and fatalities[1,2,7]. It highlights various studies that have examined mine disasters across different regions, particularly in India, China, Canada, Iran, Russia, Brazil, Ghana, Poland and Pakistan[11,19]. Key findings include:

a) High rates of accidents and fatalities in underground mines, often due to gas explosions and the presence of toxic gases like CO, NOx, NO and H_2S.
b) Several case studies of mine disasters in India, including incidents caused by asphyxiation, gas leaks and explosions[13,15].
c) Analysis of gas hazards in Indian coal mines and the effectiveness of workplace risk assessment and control techniques.
d) Studies on the health impacts of diesel engine exposure and carbon dioxide gas on mine workers, highlighting increased risks of cancer, cardiopulmonary diseases, lung diseases and pneumoconiosis.
e) Investigations into the causes of methane gas explosions in Russian coal mines and the implementation of the "24Model" technique in Chinese coal mines to prevent gas explosions.
f) Recommendations for continuous monitoring of gas parameters, increased ventilation in mines and the need for real-time monitoring systems to enhance safety[22,23].

The research collectively emphasizes the necessity of improving safety measures, managing production and ensuring the health of underground mine workers. It emphasizes controlling gas parameters, providing necessary medical support and adopting technological solutions to prevent hazardous gas formation and maintain safe mine environmental conditions. This review examines the effects of harmful gases in mines on health, the occurrence of mining disasters due to gas-related accidents and how Wireless Sensor Networks (WSNs) with ZigBee technology are used to monitor environmental conditions in underground mines. It includes an experimental study where ZigBee modules and sensors were tested both at surface level and within a simulated underground mine environment. The outcomes of these tests and their implications are detailed in the study.

ZigBee based Real-Time System in Underground Mines

The mining industry is progressively integrating wireless communication technologies to enable real-time monitoring of critical environmental parameters such as gas levels, temperature and humidity, as well as to deliver timely emergency alerts to mine workers. This transition from conventional methods influences Wireless Sensor Networks (WSNs), which are composed of multiple sensor nodes and a central base station. These sensor nodes relay data to the base station, however, they are constrained by challenges such as limited power supply, processing capabilities and computational efficiency. ZigBee technology, which operates on license-free ISM radio frequency bands, is widely used for wireless communication in this context. Numerous studies have investigated the application of WSNs and ZigBee technology in underground mining environments:

Experiments demonstrated that ZigBee nodes could communicate up to 100 meters in straight tunnels and 70 meters in curved ones, with signal loss observed in curves and non-line-of-sight areas. The influence of tunnel branches and curvature on radio wave propagation and packet loss was investigated. Several studies analyzed radio wave propagation in mines to enhance signal reception, sensor node localization and miner tracking, highlighting variations in results depending on mine structures. ZigBee-based systems were developed for monitoring gas concentrations and other environmental parameters, although some studies lacked detailed implementation information. ZigBee-enabled smart helmets were tested for gas detection and object sensing, but primarily at the laboratory level.

Environmental monitoring was explored using Proteus simulation software and ZigBee modules, with most implementations confined to simulations or lab environments. Different sensor node arrangements in ZigBee networks were examined through conceptual models based on simulation outcomes. Systems for real-time environmental monitoring were also developed, however, detailed reports on actual mine-site implementations were often limited. ZigBee-enabled IoT solutions, equipped with IP-enabled gateways, achieved real-time environmental monitoring with coverage of up to 140 meters between routers. Additionally, a portable ZigBee-enabled system designed for hazardous gas detection was tested on miners' helmets, though evaluations were conducted only at the surface level.

Overall, these studies demonstrate significant advancements in safety and efficiency in underground mining through the development of various communication protocols and

algorithms. However, many of these innovations are still at the conceptual, simulation, or laboratory stage, indicating a need for further development and implementation in actual mining environments.

The integration of ZigBee technology in underground mines has been extensively researched. Studies have shown that ZigBee systems are affected by path loss in branched and curved tunnels and in non-line-of-sight conditions. Despite these challenges, ZigBee-based systems have proven effective for monitoring environmental conditions and detecting hazardous gases in underground mines. Mesh topology is identified as the most suitable design for Wireless Sensor Networks (WSNs) in these environments.

Establishment of Zigbee based Wireless Communication for Environmental Parameters Monitoring

ZigBee is an IEEE 802.15.4 standard wireless protocol known for its low power usage, low data rate and cost-effectiveness. It supports mesh networks, enhancing communication reach between transmitters and receivers. In a ZigBee setup, the transceiver module can function as a coordinator, router, or end device, forming a personal area network (PAN). This network, comprising of a coordinator, routers, or end devices, facilitates data communication. The coordinator in a ZigBee network plays a pivotal role in setting up the network, allowing new devices or routers to join and managing data routing. Each ZigBee device is configurable via the XCTU graphical user interface, with a unique 64-bit MAC address and a 16-bit network address. For instance, in a mine safety system, as depicted in figure 1, the block diagram shows both transmitter and receiver modules.

The transmitter ZigBee module is configured as the coordinator node for effective wireless communication while the receiver module is set as a router node[17]. The transmitter section is integrated with an 8-bit microcontroller Arduino board, sensors to monitor environmental parameters and a ZigBee transceiver module. The microcontroller is connected to a temperature and humidity sensor, CH_4, CO, CO_2 and H_2S sensors. In the receiver unit, there is another microcontroller paired with a ZigBee module. This setup includes a display unit for showcasing data gathered from the sensors and an alert buzzer. The buzzer serves as an early warning system, activating when gas levels surpass predefined threshold limits.

The transmitter section represents the Arduino UNO board connected to sensors and the industrial type of XBEE_S2C PRO ZigBee module. The sensors DHT 11 temperature and humidity sensor, MQ-8 is H_2 sensor, MQ-9 is CO and MQ-135 is air quality sensors are integrated with an Arduino 8-bit microcontroller. The receiver circuit represents the Arduino UNO board and the XBEE_S2C PRO ZigBee module acts as a router node. The display unit can be integrated to view the gas parameter values on a display board, as shown in figure 2.

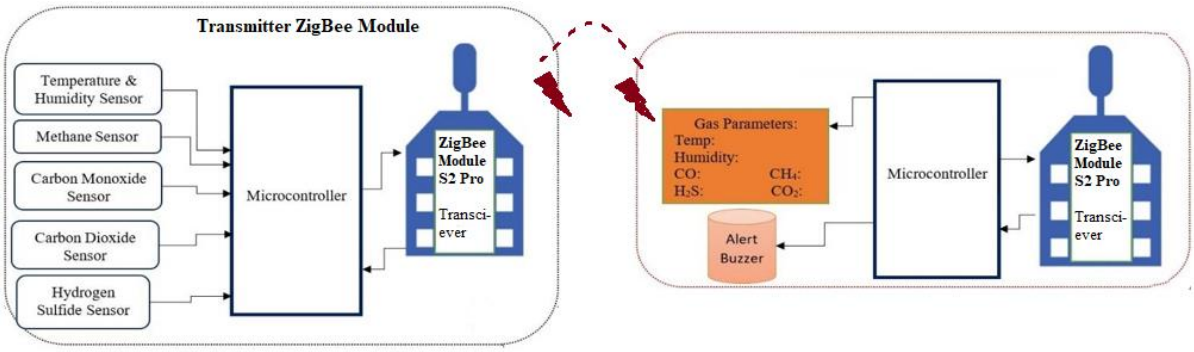

Figure 1: Block diagram of ZigBee modules enabled mine safety system

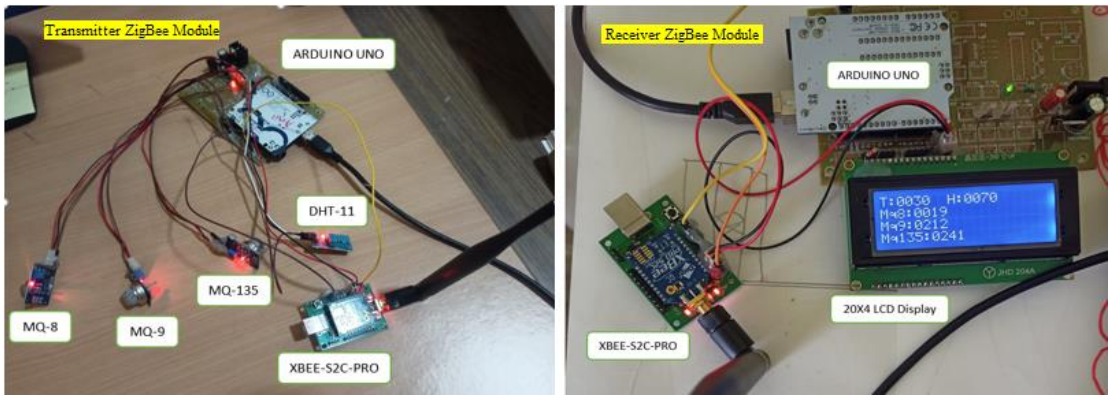

Figure 2: Prototype of Integration of Sensors to Transmitter ZigBee Module and Receiver ZigBee Module connected with LCD Display

The ZigBee radio module is XBee Pro S2C type and the design of these sensors features electrodes coated with a reactive material, which becomes more sensitive to gas when heated. When the sensor detects its target gas, there is a change in its resistance. This resistance decreases with higher gas concentrations and increases with lower concentrations. Different sensors have specific sensitivities: the MQ-8 is highly responsive to hydrogen gas (H_2) and can also detect alcohol. The MQ-9 sensor is particularly sensitive to CO and CH_4 gases and can also sense LPG gas. The MQ-135 air quality sensor identifies gases such as ammonia (NH_3), nitrogen oxides (Nox), alcohol, benzene and smoke. The DHT-11 sensor is equipped with NTC temperature and humidity measurement components for temperature and humidity measurements.

Implementation of Developed ZigBee based Wireless Communication System in a Model Mine

The implementation of the developed ZigBee-based real-time system experimentation was carried out on a model mine. The ZigBee-based real-time environmental monitoring system is tested in a model mine laboratory of the Mining Engineering Department of the NITK, Surathkal, India, which replicates the real underground mine. The transmitter and receiver side ZigBee radio modules are fixed in an enclosure, as shown in figure 3. Figure 4 depicts the layout of the model mine at the NITK, Surathkal, India. The model mine includes:

a) Belt Conveyor of 23 m length, which operates with a 3 HP motor capacity, 58 RPM motor speed.
b) The Direct Rope Haulage track length of 25 m, the track width of 0.66 m with a tub capacity of 1.5t, which operates on 2 HP motor power and 15 RPM motor speed.
c) Variable speed fan with proper ventilation condition and power supply.

The deployment of the ZigBee transmitter module in a model mine at the corner point is represented as shown in figure 5. The location of experimentation carried out at the Mining Engineering Department and model mine laboratory of the NITK, Surathkal, India, are cited in a google map as shown in figure 6. The data collected from sensors using ZigBee modules at the model mine are represented in figure 7. The data is collected from 12:28 (hour: minute) to 14:54 (hour: minute) using the ZigBee-based system. The transmitter and receiver are deployed at various distances and a distance of 51 m between the transmitter (model mine) and receiver (Mining Engineering Department) established a reliable signal strength to monitor data at the receiver.

Figure 3: Transmitter and Receiver ZigBee Modules to monitor the data from a model mine are fixed in an enclosure

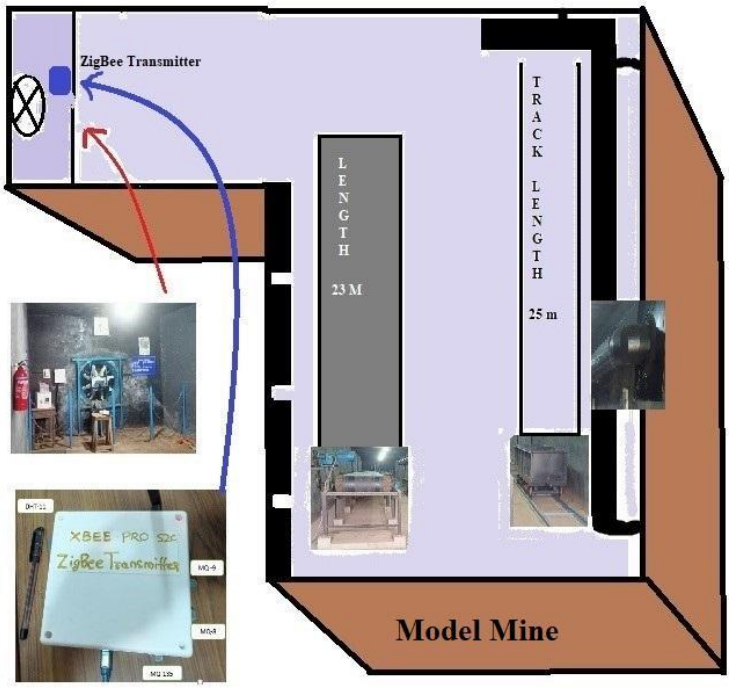

Figure 4: A Schematic plan view of the model mine at the NITK Surathkal, India

Figure 5: Deployment of Transmitter ZigBee Module in a model mine and Receiver at the Mining Engineering Department, NITK Surathkal. a) ZigBee transmitter deployed at model mine, b) ZigBee receiver deployed at the mining engineering department, c) Inside view of model mine, d) Front view of model view

Conclusion and Future Work

The ZigBee-based real-time system was developed to monitor the environmental parameters in underground mines. The system is tested and evaluated in an underground model mine at a surface level. The developed system is reliable, power efficient and cost-effective for monitoring the concentration of gases and temperature and humidity. The ZigBee system is portable and data is collected in real-time. The system was tested at different locations and achieved a wireless communication distance between transmitter and receiver of more than 110 m within the NITK, Surathkal campus, surrounded by college buildings and around 500 m in open space without any obstacles.

The system was tested in a model mine that replicates the underground mine structure. The transmitter and receiver are placed 51 m apart to monitor real-time data from the model mine to the Mining Engineering Department of NITK, Surathkal. The developed system will benefit underground mine workers and organizations in terms of safety and productivity concerns.

Figure 6: Deployment of the Transmitter ZigBee Module in a model mine and Receiver at the Mining Engineering Department, NITK Surathkal is represented as in a Google map

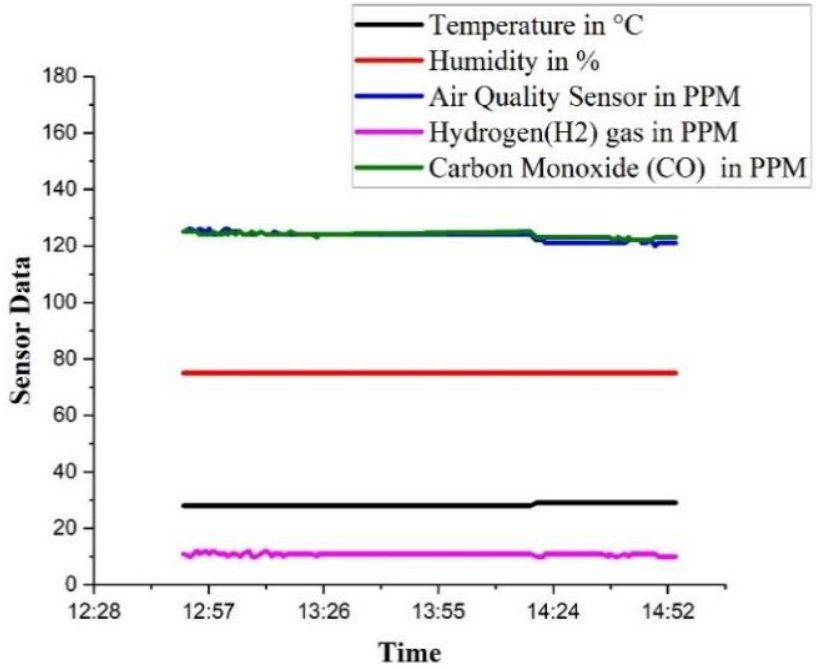

Figure 7: Data collection from sensors using ZigBee modules from model mine

As a part of future work, the system can also be enhanced by embedding a gateway node at the receiver side of the ZigBee system to transmit data to the cloud platform to monitor the data in real time from anywhere and at any time. The developed system has been designed to be cost-effective and energy-efficient, making it accessible to smaller and less affluent underground mines.

Acknowledgement

The authors are grateful to the National Institute of Technology Karnataka, Surathkal, India and the Mining Engineering Department for permission to conduct a study in a model mine that replicates an underground mine. Vision Group on Science and Technology (VGST), Government of Karnataka, India, sponsored the project to carry out the research work.

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(Received 21st November 2024, accepted 25th December 2024)