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DESIGN AND DEVELOPMENT OF A LoRa-BASED SMART SAFETY HELMET FOR REAL-TIME MONITORING OF UNDERGROUND MINE WORKERS

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Abstract: Underground mine workers operate in environments where hazardous atmospheric conditions and worker-related emergencies require timely monitoring. This paper describes the design and prototype implementation of a wearable smart safety helmet integrating environmental and selected physiological sensing with wireless data communication. An ESP32 transmitter acquires information from MQ-4, MQ-135, DHT11, MAX30100 and a GPS receiver. An SX1278-based LoRa module transmits the data to an Arduino Nano receiver, and a laptop dashboard displays the received fields. A buzzer provides a local alert output according to configured firmware conditions. The assembled prototype was demonstrated with a dashboard showing sample sensor readings and helmet status. The displayed readings are preliminary observations, and further sensor calibration, repeated testing, underground radio characterization, and mine-safety certification are required to establish the system's reliability and suitability for practical mining applications.

Keywords: Smart mining helmet, underground mine safety, LoRa, ESP32, wireless sensor network, environmental monitoring.

I. INTRODUCTION

Underground coal mining presents environmental and operational hazards that can affect worker safety. Changes in gas concentration, air quality, temperature and humidity may require timely detection and communication. Worker-related events and location information can also be useful to a monitoring station. A wearable sensing system can place selected sensors near the worker and transmit measurements to a remote receiver.

This work describes a prototype smart helmet using an ESP32-based transmitter and an SX1278-based LoRa radio link. The receiver uses an Arduino Nano and forwards the received information for laptop-based monitoring. A buzzer is included as a local alert output. The project is intended to demonstrate sensor integration, wireless transfer and display of the received information.

The scope of this paper focuses on the developed prototype arrangement and its available demonstration results. The system monitors environmental and physiological parameters and transmits sensor data using LoRa communication. It does not claim medical-grade physiological measurements, guaranteed underground radio range, or mine-wide positioning. MQ sensor readings are considered raw values rather than ppm without proper calibration, while conventional GPS reception is generally unavailable deep underground.

A. Objectives

The objectives are to integrate environmental sensors on a wearable helmet; acquire selected worker-related measurements; transmit sensor information through LoRa; display received data on a laptop; and provide a local audible warning output according to the configured firmware conditions.

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II. RELATED WORK

Research on smart helmets for mining has investigated wearable environmental sensing, worker monitoring and warning mechanisms. Mamatha and co-authors reported a coal-mine safety monitoring and alerting system using a smart helmet in IJARCCE. The work is relevant to the application and target journal because it considers helmet-based mine-hazard monitoring. The present prototype uses a different hardware arrangement based on ESP32, SX1278 LoRa and Arduino Nano.

Naik, Reddy and Mandela presented a real-time environmental parameter monitoring system using LoRa-based wireless communication technology in underground mines. Their work provides relevant background for the use of LoRa in mine telemetry. Ray Chowdhury and co-authors examined a LoRa-based industrial IoT network for underground coal-mine environments. These studies support the importance of assessing radio communication in mine-specific layouts. Zhao and Zhu described a LoRa-based temperature and humidity monitoring and communication system for coal-mine workings. Liang and co-authors reviewed intelligent monitoring and protection equipment for vital signs of underground personnel in coal mines. These publications are relevant to the environmental and worker-related sensing objectives of the present helmet.

A further smart-helmet study by Aireddy and co-authors presented an integrated safety monitoring system for coal miners. Its sensing and communication arrangement is a related-work reference, not a description of the present prototype. The present implementation is distinguished by its ESP32 transmitter, Ra-02 LoRa radio link, Arduino Nano receiver and laptop dashboard.

A. Research motivation

The reviewed literature indicates continuing interest in wearable mine safety, environmental monitoring, worker-related measurements and wireless communication. The present project combines these functions in a prototype demonstrator. No direct performance comparison with the cited systems is claimed because equivalent test datasets and measurement conditions are not available.

III. SYSTEM ARCHITECTURE

The system contains a helmet-mounted transmitter and a receiver station. Sensors are interfaced to the ESP32. The controller acquires readings, forms a data record and sends it through the Ra-02 LoRa module. A second Ra-02 module at the receiver is connected to an Arduino Nano. The Nano receives the radio data, which is displayed on a laptop dashboard. The ESP32 also controls the local buzzer output.

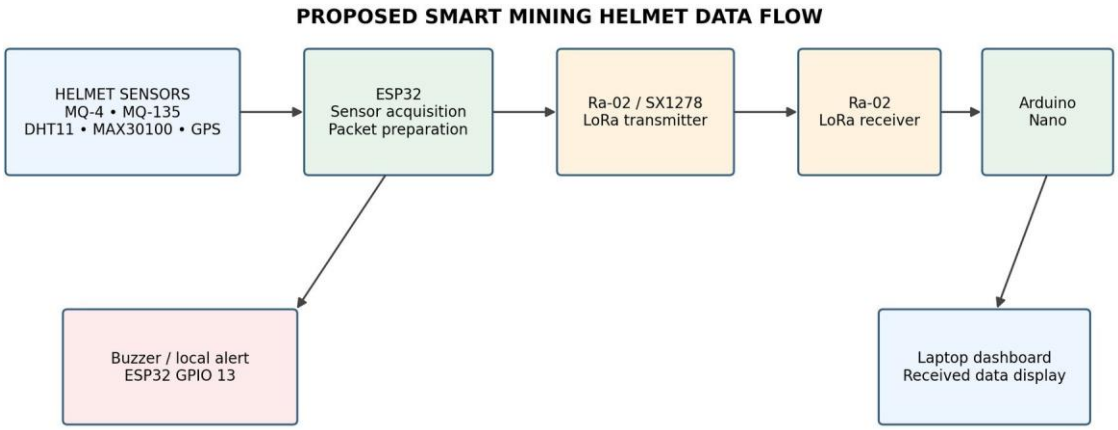


Fig. 1. Overall architecture of the proposed smart mining helmet monitoring system.

The dashboard data fields include MQ-4 response, MQ-135 response, temperature, humidity, heart rate, SpO_2, GPS coordinates, worker identifier and helmet status. The exact data-packet structure and validation method must be confirmed against the final firmware.

A. LoRa-based communication for underground mining

Conventional internet connectivity may be unavailable or unreliable in underground mining tunnels. The LoRa link in

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this project is intended to provide local wireless data transfer between the helmet unit and a receiver without requiring an internet connection. In the implemented prototype, the ESP32 sends the sensor record through the helmet-side Ra-02 (SX1278) module. A second Ra-02 receives the packet and passes it to the Arduino Nano, which makes the information available on the laptop dashboard. This is a single-hop, point-to-point communication arrangement.

For communication over a longer tunnel, the architecture may be extended by deploying additional LoRa relay nodes at suitable locations. Each relay node would receive a packet and forward it to the next node towards a gateway or monitoring station. This arrangement is described as a linear multi-hop wireless sensor network. It is not a bus topology; a mesh topology would require multiple interconnections and alternative paths between nodes. The relay nodes and forwarding firmware are proposed extensions and are not demonstrated by the current two-radio prototype.

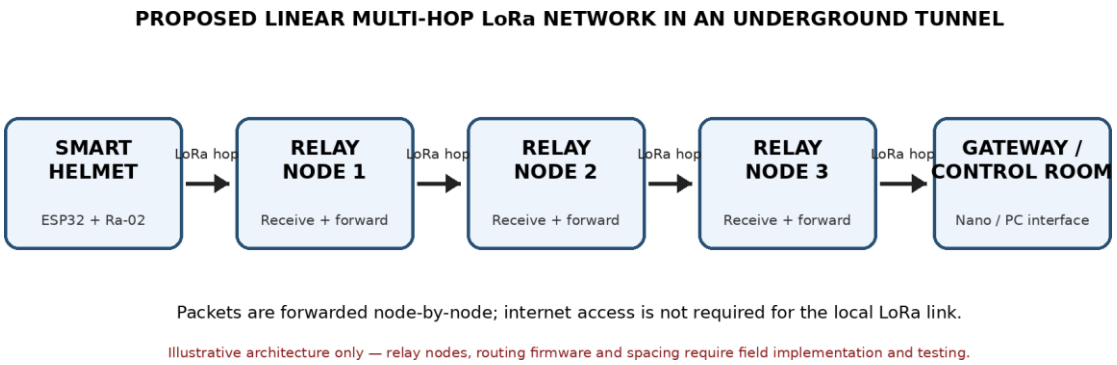


Fig. 5. Proposed linear multi-hop LoRa network for forwarding helmet data along an underground tunnel; the relay arrangement is conceptual and requires implementation and field testing.

An approximate 2 km distance between relay nodes may be considered only as an initial deployment idea. It must not be presented as a measured or guaranteed underground range. Actual spacing must be established through tests in representative tunnels because bends, rock strata, equipment, antenna placement, antenna orientation, transmit power and LoRa radio settings affect the link. Testing should record packet reception, packet loss, RSSI, SNR and end-to-end latency before fixing the relay locations.

IV. HARDWARE DESIGN AND INTERFACING

A. Main hardware components

Component	Function in prototype
ESP32	Sensor acquisition, packet preparation and transmitter control.
Ra-02 (SX1278)	LoRa wireless transmitter and receiver modules.
Arduino Nano	Receiver-side controller.
MQ-4	Methane-sensitive gas sensor module; calibration required.
MQ-135	Broad-response air-quality sensor module; not gas selective.
DHT11	Temperature and relative-humidity measurement.
MAX30100	Optical pulse-rate and SpO_2-related estimation.
GPS receiver	Coordinate acquisition when satellite reception is available.
Buzzer	Local audible warning output.
MT3608	Boost converter used in the prototype supply arrangement.

B. ESP32 transmitter pin mapping

Interface	ESP32 connection
DHT11 data	GPIO 25
MQ-4 analog output	GPIO 35
MQ-135 analog output	GPIO 34
Buzzer control	GPIO 13
MAX30100 SDA / SCL	GPIO 21 / GPIO 22
MAX30100 INT	GPIO 26
LoRa SCK / MISO / MOSI	GPIO 18 / GPIO 19 / GPIO 23
LoRa NSS / RESET / DIO0	GPIO 5 / GPIO 14 / GPIO 27
GPS UART2 RX / TX	GPIO 16 / GPIO 17

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C. Arduino Nano receiver pin mapping

Ra-02 signal	Arduino Nano pin
SCK	D13
MISO	D12
MOSI	D11
NSS / CS	D10
RESET	D9
DIO0	D2
VCC / GND	3.3 V / GND

The Ra-02 is a 3.3 V radio module. Its supply must not be connected to 5 V. The Nano uses 5 V logic; compatible level shifting is required on Nano-to-radio signal lines where appropriate. The final physical wiring, regulator current capability and common-ground arrangement must be checked against the actual assembled circuit.

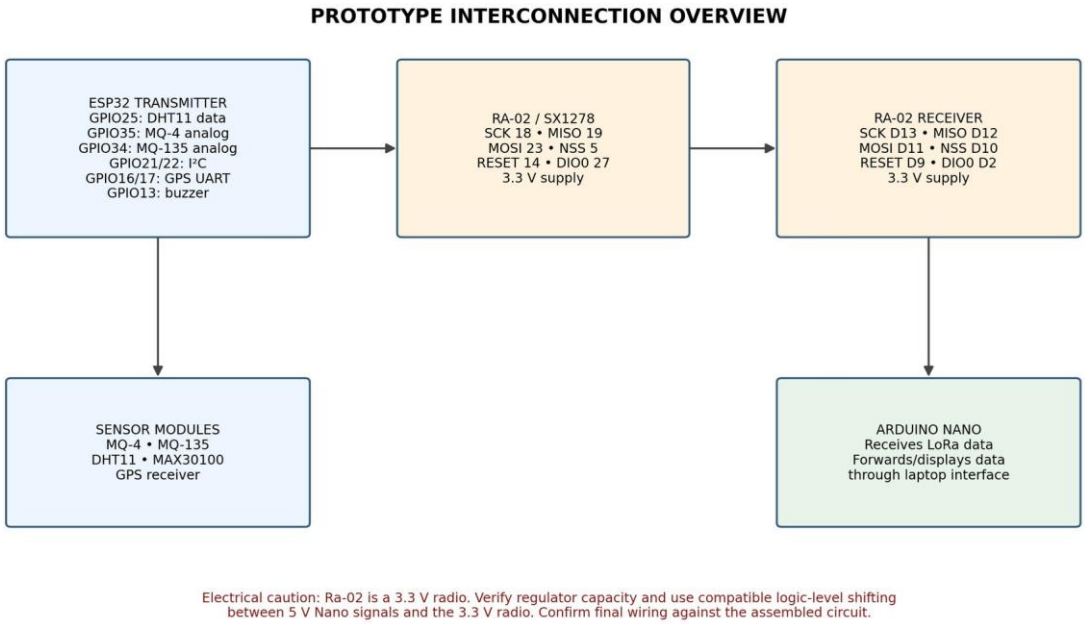


Fig. 2.Prototype interconnection diagram based on the pin assignments documented during development; verify level shifting and final wiring before fabrication.

V. METHODOLOGY AND SOFTWARE IMPLEMENTATION

A. Sensor data acquisition

The ESP32 reads the DHT11 temperature and humidity values and samples the analog outputs of the MQ-4 and MQ-135 modules. The MAX30100 communicates through the IZC interface and is intended to provide pulse-rate and SpO_2-related estimates when valid optical contact is available. The GPS receiver communicates through a UART interface and supplies coordinates only when satellite reception is possible.

MQ-series sensor response depends on warm-up, calibration, environmental conditions and cross-sensitivity. Therefore, the values displayed by the prototype are treated as sensor-response or ADC values. They are not expressed as ppm because no verified calibration curve or reference-gas procedure has been supplied. The MAX30100 is not a medical-grade instrument. GPS should not be described as an underground positioning solution.

B. Data transmission and reception

After sensor acquisition, the ESP32 prepares a record containing fields for MQ-4, MQ-135, temperature, humidity, heart rate, SpO_2, latitude, longitude and status. The record is transmitted through the Ra-02 LoRa module. The receiver-side Ra-02 passes the received information to the Arduino Nano, which makes the data available to the laptop dashboard. Radio frequency, spreading factor, bandwidth, coding rate, transmit power, antenna and packet validation details must be taken from the final firmware and hardware configuration.

C. Proposed multi-hop forwarding operation

In the proposed expanded network, each relay node should identify the received packet, check its integrity and sequence

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information, and forward it to the next configured node when required. A gateway at the monitoring station would deliver the packet to the laptop interface. The forwarding implementation should include node identifiers, packet sequence numbers, duplicate-packet handling and a defined response to a failed or unavailable next hop. These functions require additional LoRa hardware and relay firmware; they are not part of the currently demonstrated point-to-point link.

C. Monitoring dashboard

The laptop interface displays the worker identifier, helmet status and sensor fields. The photograph of the final prototype shows a worker identifier of 01 and the status "HELMET NOT WORN." The physical mechanism used to detect helmetwear must be confirmed. If the status is manually assigned or software-generated, it must not be represented as automatic sensor-based detection.

D. Local alert mechanism

A buzzer is connected to ESP32 GPIO 13. It provides a local audible warning according to configured firmware conditions. The final paper should state exact alert thresholds and timing only after they are verified from the source code and test records. A software status output is not a certified safety decision.

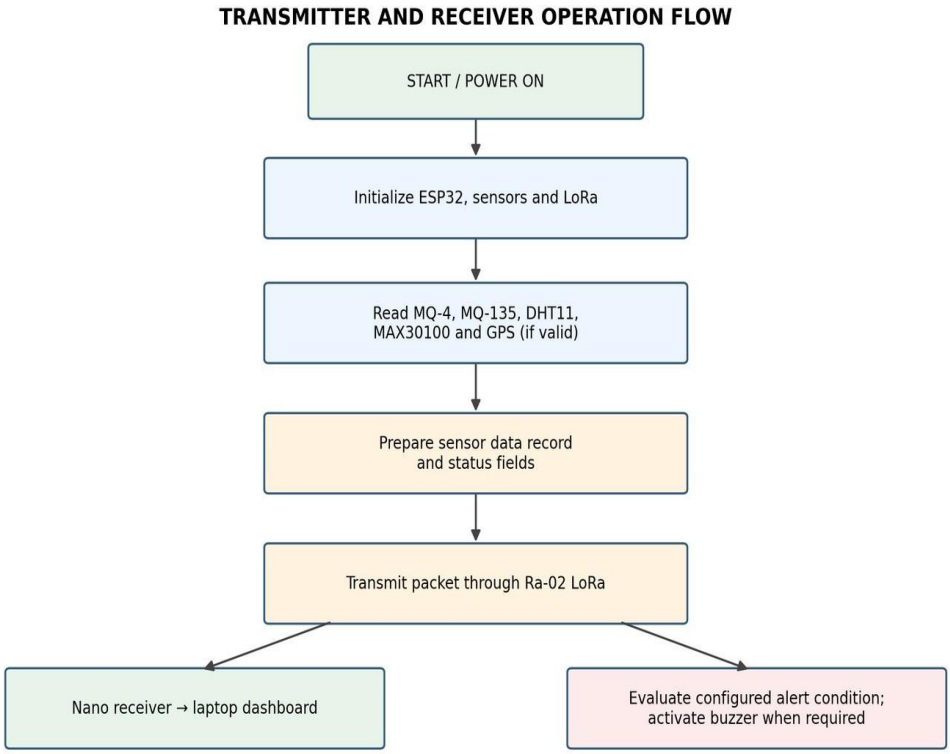


Fig. 3. Operational flow of the transmitter, LoRa receiver and laptop monitoring process.

VI. PROTOTYPE IMPLEMENTATION AND OUTPUT

The final prototype combines the helmet-mounted electronic assembly with a laptop-based monitoring dashboard. The helmet carries the sensing and transmitter modules. The receiver arrangement delivers the received information for display on the laptop. The photograph documents the assembled prototype and the monitoring interface used during the demonstration.

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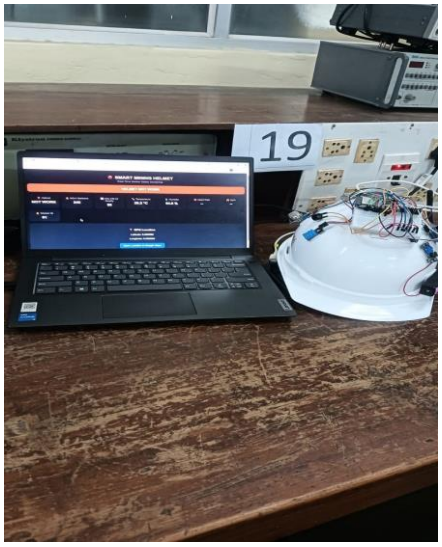


Fig. 4. Final smart mining helmet prototype with laptop-based monitoring dashboard.

A. Observed dashboard output

Dashboard parameter	Value visible in photograph	Interpretation
Worker ID	01	Identifier shown in dashboard.
Helmet status	HELMET NOT WORN	Displayed status; detection mechanism needs confirmation.
MQ-4 response	240	Raw/displayed sensor response; not calibrated ppm.
MQ-135 response	99	Raw/displayed sensor response; not gas-specific concentration.
Temperature	Approx. 28.2 °C	Single displayed observation.
Humidity	Approx. 64.6%	Single displayed observation.
Heart rate / SpO_2	No valid numerical value visible	No physiological result can be reported from this snapshot.
GPS	Coordinates not clearly readable	No location value reported.

The values in Table I are transcribed from one photograph and represent a demonstration snapshot. The heart-rate and SpO_2 fields do not show valid numerical readings; this must not be interpreted as zero heart rate or zero oxygen saturation. The GPS values are not sufficiently legible to report.

B. Why comparative performance graphs are not included

A single dashboard photograph does not provide repeated time-series measurements, calibrated reference values, measured radio distances, packet delivery statistics or latency records. Therefore, comparative graphs for gas response, accuracy, LoRa range, packet delivery or response time would be scientifically unsupported at this stage. The figures in this manuscript are system diagrams and the prototype photograph. Performance graphs should be added after collecting a repeatable dataset.

VII. RESULTS AND DISCUSSION

The demonstration confirms that the prototype hardware and laptop interface were assembled and that the dashboard presents fields for the selected environmental and worker-related parameters. The photograph shows example MQ sensor response values, temperature and humidity, as well as a helmet-status field. This is evidence of the monitoring interface and prototype integration, but it is not a controlled performance evaluation.

The MQ-4 response of 240 and MQ-135 response of 99 must not be compared with occupational exposure limits or reported as gas concentration without calibration. Repeated tests against suitable reference instruments are required. Temperature and humidity readings should also be compared with calibrated references to estimate measurement error.



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The absence of numerical heart-rate and SpO_2 readings in the captured dashboard indicates that valid measurements were not displayed in that image. The MAX30100 requires suitable contact and signal-quality checks. Repeated measurements against a suitable reference device are necessary before reporting physiological measurement performance.

GPS coordinates were not readable in the photograph, and GPS generally requires satellite visibility. Deep underground positioning requires another suitable localization infrastructure. LoRa performance is similarly dependent on mine geometry, obstacles, antenna placement and radio settings; no underground range or packet-delivery claim is made from the available evidence.

Accordingly, the current results support only the assembled prototype and its point-to-point LoRa data transfer. The proposed multi-hop tunnel network and the suggested relay spacing remain future work until they are implemented and evaluated under actual underground conditions.

A. Experimental metrics to collect

Test area	Required data for future evaluation
Gas sensing	Reference concentration, sensor output, calibration curve, response/recovery time, repeated trials.
Environmental sensing	Reference temperature/humidity, error, repeatability.
Physiological sensing	Valid readings, contact conditions, reference comparison, number of trials.
LoRa link	Distance, tunnel layout, packets sent/received, packet-loss ratio, latency, RSSI and SNR.
Power	Battery type/capacity, current consumption, operating duration.
Alert system	Firmware threshold, alert delay, repeatability and false-alarm observations.
Helmet-wear status	Sensor type, mounting location and validation method.

VIII. LIMITATIONS AND SAFETY CONSIDERATIONS

The prototype is not a certified mine-safety device. MQ-series modules are not substitutes for certified mine gas detectors. Sensor calibration, warm-up and cross-sensitivity must be considered. The MAX30100 is not a medical device. GPS is not expected to operate reliably deep underground. LoRa communication must be evaluated in representative mine tunnels. Battery and electronic assemblies require assessment for hazardous-area electrical safety, thermal behaviour, mechanical robustness and applicable intrinsic-safety requirements before any mine deployment.

IX. CONCLUSION

This paper presents the design and prototype implementation of a smart mining helmet that integrates environmental sensing, selected worker-related sensing and LoRa-based wireless communication. The transmitter uses an ESP32 to acquire data from MQ-4, MQ-135, DHT11, MAX30100 and GPS modules. An SX1278-based Ra-02 link transfers the data to an Arduino Nano receiver, and a laptop dashboard displays the received fields. A buzzer provides a local alert output. The final prototype photograph documents the assembled helmet and dashboard demonstration.

The available evidence supports the description of the prototype architecture and the sample dashboard fields. It does not establish calibrated gas concentration, medical-grade physiological measurement, underground GPS operation, measured underground radio range or mine-safety certification. These limitations define the next stage of engineering validation.

X. FUTURE WORK

Future work will focus on calibration of the gas sensors using reference instruments, repeated temperature and humidity measurements, validation of the MAX30100 readings, a dedicated and verified helmet-wear sensor, and underground localization. The LoRa link should be characterized in representative tunnels by recording packet delivery, latency, RSSI and SNR at measured distances. Battery runtime, alert thresholds, false-alarm behaviour, mechanical robustness and electrical safety should also be evaluated. Only after these tests and applicable certification should the system be considered for operational mine use.

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