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EIDAS-Edge Linked Industrial Data Acquisition System for Mining Environments

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***Abstract*— In high-risk areas like mining, effective real-time environmental monitoring is crucial from a safety and operational standpoint. In this work, we propose EIDAS, which stands for Edge-Linked Industrial Data Acquisition System, an industrial-grade system built for hazardous environments with ESP32 microcontrollers and peer-to-peer wireless communication using the ESP-NOW protocol. The architecture is modular and comprises three nodes: a sensing unit with gas sensors, a local alert system, a relay node which expands the communication range, and a cloud-integrated node for data visualization and mobile applications. Remote monitoring is facilitated through ThingSpeak and the Blynk app, while local alerts are provided via LCD display and buzzer. Local data acquisition can be on-demand or scheduled. We tested the system under simulated conditions and found it to be reliable, responsive, and scalable. EIDAS shows great promise as an infrastructure agnostic industrial safety IIoT solution and can be adapted to support multi-parameter monitoring in many environments.**

***Index Terms*— Industrial Internet of Things (IIoT), ESP32, ESP-NOW, Mining Safety, Wireless Sensor Networks (WSN), Edge Computing, Gas Detection.**

I. INTRODUCTION

In the mining, chemical production, and waste management industries, monitoring environmental conditions, especially dangerous gas levels, is pivotal for the safety of personnel, compliance with regulations, and the reliability of operations.

Monitoring devices today use wires and stable Wi-Fi networks to transmit data to the cloud, which is a common limitation of existing monitoring systems. These systems face numerous problems: Inflexible wired technology is expensive to adopt and challenging to reconfigure in changing field conditions. Wi-Fi dependent systems are useless in remote, underground, or other regions with no network infrastructure.

Moreover, many conventional solutions offer rigid form factors that make changing sensors or adding new sensors modularity difficult without substantial changes to existing hardware or software. Also, most rely on periodic sampling and do not offer user-initiated real time updates, which add hybrid data acquisition methods. In addition, reliance on network connection generally renders these systems inoperable since they lack local alert mechanisms and offline data logging capabilities. Failure to include such components severely hampers functionality in critical situations.

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Consequently, there is a need for an economical, modular, and non-infrastructure-dependent system that can reliably function in low-communication environments, provide autonomous and request-based data collection, facilitate local and remote notification, and permit simple addition of extra sensors. The edge linked industrial data acquisition (system) EIDAS offers a new solution which includes wireless, microcontroller-based peer to peer monitoring structures around ESP32 microcontrollers The EIDAS system aims to address the technological gap by integrating ESP-NOW peer-to-peer communication, local alert mechanisms, and optional cloud services to leverage Industrial IoT for environmental monitoring, thus creating a more adaptable and resilient multidisciplinary Industrial IoT ecosystem.

Founded deep into EIDAS lies the microcontroller which serves as the core component. Integrating Wi-Fi and Bluetooth serves the purpose of keeping costs low, achieving dual core processing power, and enabling embedded edge intelligence. The system can be integrated with further advancements of the Industrial Internet of Things (IIoT) which has emerged as a remarkable shift in modern technology alongside cloud services. Multi-sensor technology can also be adapted in IIoT to boost safety requirements of industrial operations [1].

ESP32 serves a purpose of upgrading the mines infrastructure. Unlike traditional Wi-Fi-linked solutions, the current system can use proprietary low latency, connectionless protocols such as ESP-NOW which allows blocks of routers to be bypassed during data transfer.

The system is built on three nodes which provide different functionalities: (1) the first includes a sensor node for gas detection with local alerting mechanisms like buzzers and LCD screens, (2) the second node relays along with maintaining the stability of the system's infrastructure, (3) The final node of the setup enables storage of data onto the cloud based platform ThingSpeak.

As cost-effective and modular as it is, the EIDAS system is tailored for robust deployment. The cloud integration through nodes in underground locations, for instance, greatly impacts real-time data visualization and remote access and control on Blynk. Furthermore, there is impact-free historical data logging on ThingSpeak, which helps crews receive alerts in case of dangerous conditions. The challenges of communication are resolved by wireless communication ESP-NOW protocol developed by Espressif. It offers low power, low latency, device to device, secure communication at 2.4GHz with a maximum payload of 250bytes. One additional concern is that a single point of failure, such as disruption of ESP node, renders the entire system inoperative and incapable of cloud services, however it can still provide local alerts. The application of unregulated Wi-Fi renders sensitive sensor data accessible to hackers. Such constraints exemplify the necessity for the construction of secure protocols for command as well as offline data logging. These features, coupled with extreme range and low power prerequisites that ESP-NOW technologies offer, allow for superior and expandable industrial monitoring assistance.

II. Literature Survey and Limitations of Current Works

[2] sets up wireless sensor network spanning the mining area to monitor several parameters of working conditions. The data from all nodes are processed by distance vector hop localization algorithm to identify those area and parameters such as gas leakage exceeding threshold limit and notifying the ground station with alerts. This includes Edge computations to determine hazard prone zones, however real time environment surveillance is challenging. [3] explores the design of a wireless sensor network (WSN) for detecting dangerous gases like methane and carbon monoxide in underground mining environments. It uses ZigBee protocol which requires coordinators and is efficient for simple peer-to-peer networks. [4] proposes IoT based system is involved in monitoring mining area conditions using sensors and transmitting the data via Wi-Fi network to ground station. The systems lack real time monitoring and action due to lack of edge computation and rely on central station, unavailability of Wi-Fi network in mining area may cause failure of the system. [5] uses similar strategy of [4] for monitoring mining conditions however relays information through zigbee technology which limits communication range and increasing power consumption. The proposed system in [6] is similar to any conventional system however data transmission to the central control station uses ZigBee technology. The low power feature of ZigBee limits the data rate and range of communication thus increasing the complexity and the cost of monitoring system for mines. The GSM based alerting system may fail to provide real time emergency handling act. [7] The smart helmet for mine area monitoring embeds within it various sensors to alert the worker the breach of safety levels of gas emissions. The data transmission using Wi-Fi network is limited in underground mine environments due to non-line of sight communication and electromagnetic interference and solid barriers. The data communication challenges in mine environment is met in [8] by multiple communication interfaces with ZigBee, Bluetooth and Wi-Fi, however suffers from interoperability issues. To eliminate the risk of explosion due to toxic gas concentrations, artificial neural network (ANN) is employed for diagnosis,

prediction and early warning [9]. The communication between nodes in WSN is handled by long range (LoRA) which is low power wide are area technology, however is limited from low data rate, small payload and low quality of service(QoS) and high latency limiting real time monitoring. [10] proposes android app to visualize monitored data and store it for future reference, however data transmission requires appreciable bandwidth and Wi-Fi connectivity. The proposed system [11] integrates cloud computing for monitoring, control and alerts in case of emergency. However, the effectiveness relies on communication network. The comparison of various wireless technologies is illustrated in Table.I

TABLE I. COMPARISON OF VARIOUS WIRELESS TECHNOLOGIES FOR COMMUNICATION IN MINE ENVIRONMENT

Sl. No.	Range	Power consumption	Data security	Data rate	Cost	Latency
LoRa	Long range communication: 3-5 km (Urban) 15-20 km (Rural)	low	Moderate level of security due to Spread spectrum (forward error correction)	50kbps	Low	High
Zigbee	10-100m(LoS)	Low	Susceptible to interference and security issues	250kpbs	Low	Low
GSM	Extended range of communication	high	Comparatively high due to cellular network infrastructure	Comparatively high	High	High generation has less latency
ESP-NOW	Medium range communication (250m)	Low	Not built in, but user implemented	1 Mbps	Low	lowest

III. METHODOLOGY

A. Hardware

The hardware solution of the EIDAS (Edge-Linked Industrial Data Acquisition System) is designed to enable modular, wireless, and scalable industrial gas monitoring, especially in mining regions. The system design has three primary ESP32-based nodes—each with a different role of sensing, relaying, and data aggregation as shown in the Fig.1 These nodes form a wireless mesh of communication using the ESP-NOW protocol, which is free from a central router and facilitates strong peer-to-peer data transfer in areas where there is no conventional network setup.

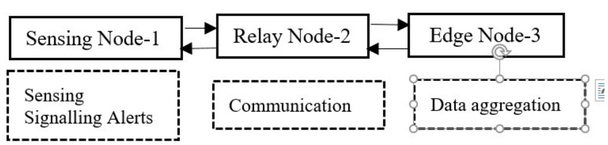

Figure 1. Block diagram depicting the architecture of the Data acquisition system.

A. ESP1 – Sensing Node

This node serves as the sensor front-end unit to provide environmental data acquisition. It is equipped with an MQ-series gas sensor (e.g., MQ-135), which is sensitive to combustible or poisonous gases like methane (CH_4), carbon monoxide (CO), and ammonia (NH_3). The analog output of the sensor is wired to an ADC (e.g., GPIO34) on the ESP32. A 16x2 I2C LCD is provided to display real-time gas concentration on a local scale, and a piezoelectric buzzer is used to provide instantaneous auditory warnings in case the gas concentration falls below a predetermined safety limit (e.g., 400 PPM). The node sends data at predefined intervals (after every 60 seconds) or when it receives on-demand request queries routed over the mobile interface.

B. ESP2 – Relay Node

The ESP2 node is a wireless bridge between the sensor (ESP1) and cloud gateway (ESP3) nodes. It does not sense or alert but is essential in maintaining communication between nodes when there are physical obstructions or extensive coverage areas. ESP2 gets data from ESP1 via ESP-NOW and forwards it to ESP3 without modifying the data payload. It also controls bidirectional communication for manual request of data propagation from ESP3 to ESP1 for ensuring low-latency and guaranteed message delivery.

C. ESP3 – Data Aggregation and Cloud Interface Node

ESP3 is the cloud gateway and control centre of the system. It is supplied with gas concentration information from ESP2 and performs some vital functions: data validation, data comparison with threshold levels, local alarm generation, and internet uploading of data. Another I2C LCD is present for the use in displaying current gas levels and system status. It contains a buzzer for alarming local staff in risk areas. ESP3 also manages Wi-Fi-based integration with ThingSpeak (cloud logging and analysis) and the Blynk IoT platform, which provides a user-friendly mobile interface. Remote users can view real-time data, request refreshes of sensors, and receive push notifications upon exceeding gas thresholds through the mobile application.

D. Power Supply and Housing

All ESP32 nodes are powered via USB (5V) or an external regulated power supply. For outdoor deployment in off-grid areas, rechargeable battery packs for Li-ion batteries or solar panels may be combined with battery management circuits. Enclosure is also an important factor—nodes to be deployed in mining sites must be enclosed within rugged, dust-proof, and perhaps explosion-proof enclosures for protection and durability.

E. Interfacing and Connections

Fig.2 illustrates descriptive block diagram and interfaces of the proposed EIDAS system. This hardware method makes the EIDAS system is light, energy-efficient, modular, and deployable across varied environments

B. Software

The software methodology for the EIDAS (Edge-Linked Industrial Data Acquisition System) is based on a distributed, event-driven architecture developed using the Arduino Integrated Development Environment (IDE) with C/C++ for all ESP32 microcontroller units. The code is modular and specifically designed to fit the individual functional tasks of each ESP32 node: ESP1 for sensor data acquisition, ESP2 as a communication relay, and ESP3 for data aggregation, alert triggering, and cloud interaction. The design prioritizes real-time responsiveness, light-weight communication, and flexible control logic, allowing effective operation in resource-constrained and infrastructure-poor industrial settings.

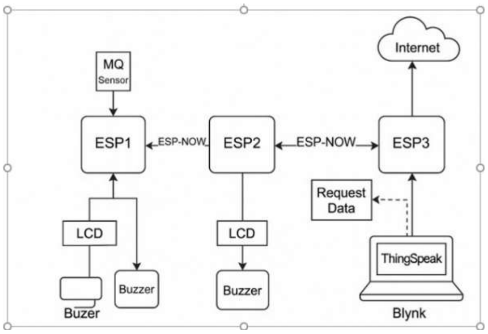

Figure 2. Block diagram of the Data acquisition system

All ESP32 boards are programmed using the Arduino IDE along with the incorporation of some major open-source libraries.

- esp_now.h to facilitate peer-to-peer communication with the use of the ESP-NOW protocol,
- WiFi.h for ESP3 networking,
- LiquidCrystal_I2C.h for I2C interface-based LCD display,
- BlynkSimpleEsp32.h for mobile dashboard control through the use of the Blynk IoT platform,
- HTTP-based routines or ThingSpeak.h to post data to the ThingSpeak cloud for visualization and storage.

C. Data flow diagram

The Fig.3. illustrates the functional blocks, interfaces and data flow and achievable objectives of the EIDAS system. On the ESP1 node, the firmware constantly checks for gas concentration with an MQ-series analog gas sensor on the ESP32 ADC. Every 60 seconds, or when a remote data request is received, ESP1 reads the gas value through analogRead(), checks it against a safety level (e.g., 400 PPM), and transmits the data to ESP2 via esp_now_send(). If the level of gas is less than the specified limit, the onboard buzzer gets activated and the display on LCD shows "ALERT" with the use of lcd.print(). ESP1 is also coded to receive messages from ESP2, for example, "REQ" commands from ESP3, and return with prompt sensor readings.

ESP2, acting as a relay node, has minimal code to enable bidirectional message passing between ESP1 and ESP3. It uses esp_now_recv_cb() to receive messages and differentiate between sensor data and remote requests. Based on the type of message, ESP2 forwards data to ESP3 or passes a request to ESP1 using esp_now_send().

This approach enables low-latency and efficient data processing with low processing overhead. ESP3 acts as the master controller, performing cloud integration and mobile interface updates. ESP3 receives sensor readings from ESP2 and checks the gas concentration for threshold violations. If unsafe levels are detected, ESP3 activates its buzzer and displays suitable warning messages on the local LCD. It also posts data to ThingSpeak through HTTP POST requests with WiFiClient and HTTPClient, enabling long-term data logging and visualization. In parallel, ESP3 is integrated with the Blynk system, where virtual pins are utilized for direct user interaction. All inter-device communication is based on the ESP-NOW protocol. A static MAC address is assigned to each ESP32 node, which enables directed and encrypted peer-to-peer message passing without the necessity of a conventional Wi-Fi router. The protocol also includes retries and acknowledgments to guarantee delivery of messages even in interference-rich industrial environments.

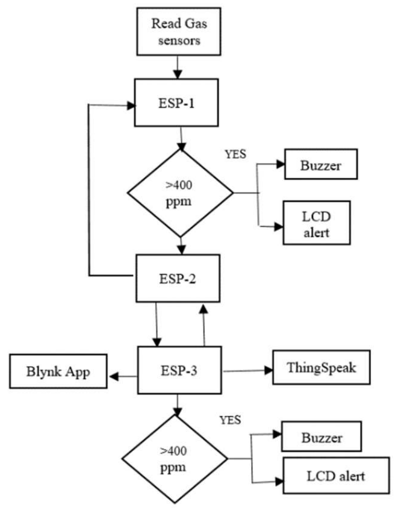

Figure 3. The data flow in EIDAS mine monitoring system

Alert handling is split between ESP1 and ESP3 to provide quick, local responses independent of internet connectivity. When the gas levels go below the set threshold, the local buzzers and LCD displays of both nodes come on instantly.

Manual data request capability is facilitated by a round-trip communication process. When the user clicks on the request button on the Blynk app, ESP3 sends an "REQ" command to ESP2, which then sends it to ESP1. ESP1 captures the reading of the gas level and sends it back via ESP2 to ESP3.

III. TEST RESULTS

The EIDAS hardware prototype shown in the Fig.4. was severely tested in a controlled setup to authenticate its performance, reliability, and promptness under diverse operating conditions that mimic real-world industrial environments. The Performance of wireless communication was tested using latency through range tests. The peer-to-peer communication using ESP-NOW proved extremely reliable, where average latency was around 10 to 30 milliseconds. The relay node (ESP2) successfully extended the communication distance and provided data integrity even when line-of-sight between ESP1 and ESP3 was blocked

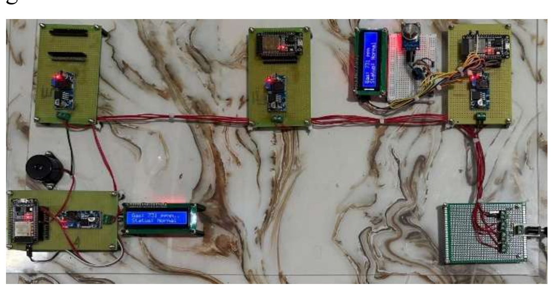

Figure 4. The hardware prototype of EIDAS

The system had good communication of over 25–30 meters within buildings and over 70 meters in the open area with Cloud integration and mobile dashboard functionality were extensively tested. Sensor readings received at ESP3 were successfully uploaded to ThingSpeak via HTTP POST requests with correct timestamps and correct formatting for graphical display. Real-time gas monitoring was done using a gauge widget and alert LED from the Blynk mobile app along with manual data requests using a virtual button as shown in the Fig.5. Notification alerts were consistently triggered when gas levels fell below the safety level (400 PPM), thereby validating the functionality of the dual alert mechanism of the system. The responsiveness of the manual data request feature was also tested by triggering data pulls through the Blynk application. The end-to-end request-response cycle from data acquisition by ESP1 to propagation through ESP2 to ESP3 took less than 2–3 seconds on average. This was achieved with near real-time responsiveness even during load.

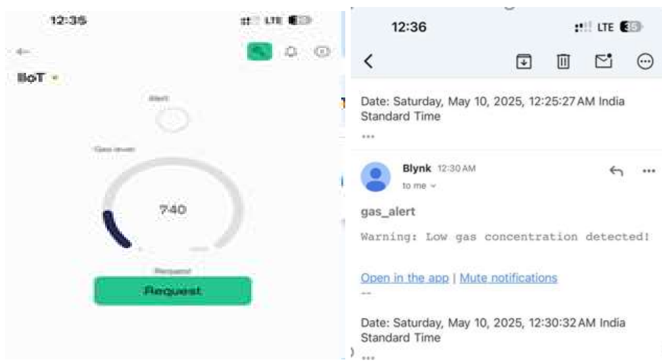

Figure 5. Illustration of alert message display on Blynk

IV. CONCLUSION

The EIDAS (Edge-Linked Industrial Data Acquisition System) effectively proves a low-cost, modular, and wireless real-time environmental monitoring solution for industrial environments, especially mining areas where traditional infrastructure is inadequate. Utilizing ESP32 microcontrollers and the ESP-NOW protocol, the system provides reliable peer-to-peer communication without the necessity of a central router, with the system still operating even in low-connectivity areas. The combination of MQ gas sensors, local notification devices (buzzers and LCDs), and cloud platforms like ThingSpeak and Blynk offers a robust monitoring and notification system supporting periodical and on-demand data collection. The operation of the system in testing proved its ability to provide timely notification, reliable communication, and efficient control. Its modular design also provides for future scalability, like the addition of extra sensors or long-range communication technology. In general, EIDAS provides a strong base for Industrial IoT use cases, increasing worker safety and operational efficiency through smart, real-time monitoring of dangerous environments. Further work is extended by incorporating the system with machine learning and artificial intelligence algorithms for predictive maintenance and anomaly detection would make the system highly intelligent and reliable

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