Comparative Analysis of IoT Architectures for Mine Environmental Monitoring: A Literature Review and Evaluation

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***Abstract*— The viability of mining operations and the safety of communities depend on environmental monitoring. This study looks at different Internet of Things architectures that are used to monitor the environment in mine environments, focusing on factors such as communication dependability, energy utilization, scalability, real-time observation, and cost effectiveness. The paper identifies problems with current monitoring methodologies, such as inconsistent monitoring and expensive maintenance costs, based on an examination of some scholarly articles and a case study with the Zambia Environmental Management Agency (ZEMA). As a response, the research proposes a hybrid IoT framework that combines cloud services, remote calibration features, and remote sensing networks while also factoring in climate adaptation. These findings highlight the revolutionary potential of IoT systems in boosting environmental surveillance in mine environments, which can result in sustainable practices and improved community health. These insights are vital for regulators and other interested parties.**

Keywords*— *Mine environmental monitoring, Internet of Things (IoT), IoT architectures, comparative analysis

I. INTRODUCTION

Mining operations play a vital role in economic development by providing essential resources, but they also present significant environmental challenges, including air pollution[1][2]. To address these concerns, effective environmental monitoring and management are crucial, with regulatory bodies like the Zambia Environmental Management Agency (ZEMA) responsible for ensuring compliance with environmental regulations and promoting sustainable mining practices [3]. Environmental monitoring is essential for collecting and analyzing data on various parameters, facilitating risk identification, evaluating mitigation measures, and informing decision-making [4][5]. However, traditional monitoring methods have limitations in providing real-time and comprehensive data. Fortunately, the emergence of Internet of Things (IoT) architectures has revolutionized environmental monitoring practices [5]. By leveraging IoT technologies, such as interconnected sensors, devices, and data analytics platforms, continuous and remote data collection, transmission, and analysis are made possible, offering benefits like real-time monitoring, scalability, improved accuracy, and cost-effectiveness [6]. Integrating IoT solutions in mining environments can significantly enhance environmental monitoring, regulatory oversight, and sustainability practices [5]. Therefore, this study aims to examine and evaluate the existing literature on IoT architectures for mine environmental monitoring, comparing various options to provide valuable insights and recommendations for the implementation of customized IoT solutions tailored to meet ZEMA's requirements and improve data collection. This, in turn, ensures the safety of communities living around mine environments and promotes sustainable mining practices[3]. The findings of this study will guide the development of advanced and effective IoT-based systems, ultimately improving environmental management and safeguarding the well-being of the surrounding communities.

II. METHODOLOGY

The research utilized a rigorous methodology to conduct a comparative analysis of various Internet of Things (IoT) systems specifically developed for environmental monitoring in mining regions. The procedure encompassed several important stages:

- Literature Search: An exploration of pertinent databases was conducted, employing specific keywords associated with Internet of Things (IoT) systems and environmental monitoring within the mining industry.
- Inclusion and Exclusion Criteria: To ensure the relevance of the collected literature, inclusion and exclusion criteria were applied. The literature reviewed encompassed primary research articles, conference papers, and reviews that particularly addressed the topic of IoT systems for mine environmental monitoring.
- Data Extraction: A structured data extraction form was utilized to extract pertinent information from the selected literature. This form captured essential parameters pertaining to architecture design, scalability, reliability, power management, cost effectiveness, and other pertinent variables.
- Data Analysis: The extracted data were subjected to a thematic analysis to identify prevailing trends, recurring patterns, and significant insights embedded within the literature.
- Comparative Analysis: Based on the analyzed data, a comparative analysis of the diverse IoT architectures was executed. This step entailed contrasting and juxtaposing the identified architectures against one another.
- Evaluation Criteria: Employing established evaluation criteria, the architectures were

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assessed. This criterion encompassed parameters such as communication reliability, power usage, scalability, real-time monitoring capabilities, and cost-effectiveness.

By adhering to this methodological framework, the study garnered a comprehensive understanding of the strengths and weaknesses of various IoT architectures tailored for mine environmental monitoring.

III. LITERATURE REVIEW

A. *Overview of Mine Environmental Monitoring Methods*

Mine environmental monitoring involves various methods and strategies to evaluate and mitigate the environmental effects of mining operations. Conventional approaches encompass manual sampling, periodic inspections, and the use of portable stack emission equipment[16]. Although these methods yield valuable data, they have drawbacks concerning real-time monitoring, continuous data acquisition, and a comprehensive assessment of environmental parameters such as air pollution.

B. *Introduction to IoT Architectures*

IoT architectures have emerged as a promising solution for improving environmental monitoring practices in various industries, including mining[3][5]. IoT architectures involve the integration of sensors[17], devices, communication networks[18], and data analytics platforms to enable continuous data collection, transmission, and analysis[6]. These architectures offer advantages such as real-time monitoring, remote accessibility, scalability, and data-driven decision-making.

C. *Existing Literature on IoT Architectures for Monitoring Mine Environments*

This section offers a synopsis of the prevailing research focused on IoT frameworks designed for the environmental surveillance of mining activities. These scholarly works investigate the utilization of IoT solutions in tracking various environmental metrics such as air quality and additional ecological aspects within mining settings. The research underscores the inherent advantages of IoT frameworks, including enhanced data precision, dependability, and operational efficiency, while tackling challenges unique to the mining sector. Through the examination of these scholarly contributions, we acquired a deeper understanding of the technological advancements in IoT and their prospective impact on refining environmental monitoring systems in mine environments.

TABLE I. SUMMARY OF EXISISTING LITERATURE

Paper	***Description***	***Key Findings***
[7]	A study on the use of Azure Machine Learning for predictive analytics in mining environments	Focuses on using Azure Machine Learning for predictive analytics. Employs ZigBee for communication.
[8]	A paper proposing a low-cost, wearable IoT device for monitoring ventilation parameters in underground mines.	Proposes a wearable IoT device for real-time monitoring of ventilation parameters like temperature, humidity, and pressure.
[9]	A development study of a low-cost, portable system for monitoring air quality in deep underground mines.	Develops a portable system for monitoring air quality. Uses Bluetooth for communication and Android app for data visualization.
[10]	Industrial IoT for enhancing safety in mining industries.	Discusses the application of Industrial IoT in enhancing safety. Uses MQTT over AWSIoT for communication.
[28]	IoT based coal mine safety and health monitoring system using LoRaWAN	A focus study on enhancing the safety and productivity of coal mining operations through an IoT system for enhancing safety and productivity through an IoT system.
[12]	A paper discussing a low-cost IoT system for monitoring environmental parameters in mines.	Discusses a low-cost IoT system for monitoring environmental parameters. Uses Wi-Fi for communication and is powered by solar panels and a rechargeable battery.
[13]	Event reporting and early warning in mines.	Proposes a system for event reporting and early warning. Uses Bluetooth for communication and provides real-time monitoring and alerts.
[14]	Predictive maintenance in mining equipment.	Utilizes CNN and LSTM for predictive maintenance in mining equipment.
[15]	A Remote Sensing Approach to Environmental Monitoring in a Reclaimed Mine Area.	The study aims to identify subsidence zones and vegetation productivity degradation using remote sensing and GIS techniques. .

1) *Key Components and Features of IoT Architectures*

IoT architectures for environmental monitoring comprises various entities, ranging from physical ones such as hardware and physical links for networks communication to logical ones[19] and the latter covers operating systems, software, and services provided by the cloud[19]. These architectures leverage wireless sensor networks[20], cloud computing, and big data analytics technologies to enable real-time monitoring, data aggregation, and decision support.

a) *Key Components*

- Sensors: Almost all architectures include various types of sensors to collect data on environmental conditions, equipment status, and other relevant parameters. For example, Santos et al [8]proposes a wearable IoT device with sensors for temperature, humidity, and pressure.
- Communication Protocols: Different papers propose the use of various communication protocols like ZigBee, Bluetooth, Wi-Fi, and

MQTT. For instance Jo et al.[13] employs ZigBee, while Prasad et al. [10] uses MQTT over AWSIoT.

- Data Processing Units: These are often microcontrollers or microprocessors that process the data collected by the sensors before sending it to the cloud or a central server.
- Cloud Services: Many architectures propose the use of cloud services for data storage, analytics, and visualization. Prasad et al. [10] , for example, uses AWSIoT for cloud storage and analytics.
- User Interface: This is usually a dashboard or an app where the end-users can monitor the conditions in real-time and receive alerts. Jo et al.[13] proposes a system that provides real-time monitoring and alerts.

2) *Summary of Existing Studies and Their Findings*

The literature on IoT architectures for mine environmental monitoring spans diverse studies tailored to the mining industry, highlighting real-time monitoring, precise data collection, and resource management benefits. One study features an Azure Machine Learning-based architecture employing ZigBee for real-time data transmission. Another introduces a wearable IoT device for low-cost ventilation monitoring, emphasizing real-time data and cost-effectiveness. Advanced algorithms like CNN and LSTM are explored for predictive maintenance, showcasing scalability and data analytics potential. Innovations include renewable energy-powered IoT systems and event reporting for safety using Bluetooth or Wi-Fi. Overall, these studies collectively inform on IoT's practical mining applications, shaping the foundation for evaluating and recommending optimal IoT architectures for environmental monitoring in mines.

IV. CURRENT LIMITATIONS OF ZEMA'S MONITORING METHODS

In a preliminary investigation presented at a conference [21], the study examines ZEMA's existing practices for mine environmental monitoring and identifies key limitations. While the current use of portable stack emission equipment and periodic inspections provides valuable data, it falls short in offering continuous, real-time monitoring. These limitations are compounded by the need for physical inspector presence, concerns over future equipment availability, and high maintenance costs [21]. These challenges have significant implications for effective environmental management, including data gaps, questions about long-term sustainability, and vulnerabilities during external challenges like the COVID-19 pandemic. This paper therefore advocates for the adoption of Internet of Things (IoT) architectures as a solution to these issues, enabling continuous monitoring, reducing maintenance costs, and improving data reliability.

V. COMPARATIVE ANALYSIS OF IOT ARCHITECTURES

A. *Criteria for Evaluation*

The objective of this comparative analysis is to evaluate various IoT architectures for their suitability in mine environmental monitoring, specifically tailored to the needs and challenges faced by the Zambia Environmental Management Agency (ZEMA). To gain a deeper understanding of ZEMA's current monitoring methods and requirements, a qualitative investigation was conducted, including interviews with ZEMA officials[21]. The insights from this investigation have informed the selection of the following criteria for evaluating IoT architectures:

- Communication Reliability: ZEMA's mobile caravan is responsible for transmitting real-time data to a central server [21]. Given the critical nature of environmental monitoring, it is imperative that the chosen IoT architecture ensures reliable and uninterrupted communication.
- Power Usage: ZEMA's monitoring caravan is fitted with solar units[21], emphasizing the importance of energy efficiency in remote or off-grid locations. Therefore, the power usage of the IoT architecture is a crucial factor in its evaluation.
- Scalability: As ZEMA's operational scope may expand or contract based on environmental needs and regulatory changes, the IoT architecture must be scalable to adapt to these varying conditions.
- Real-time Monitoring: The ability to provide real-time data is a key feature of ZEMA's current monitoring system. This criterion is essential for immediate decision-making and emergency response, making it a pivotal factor in the evaluation process.
- Cost-Effectiveness: Given that ZEMA operates under budget constraints and relies on external projects like ZMERIP for capacity building[21], the cost-effectiveness of the IoT architecture is a significant consideration. The architecture should offer a balance between performance and cost, without compromising on essential features.

These criteria have been selected to provide a comprehensive and practical framework for evaluating IoT architectures for mine environmental monitoring. They align closely with the real-world challenges and operational needs identified through our investigation into ZEMA's current practices.

B. *Evaluation of IoT Architectures*

TABLE II. EVALUATION OF IOT ARCHITECTURES FOR MINE ENVIRONMENTAL MONITORING

Paper	***Communication Reliability***	***Power Usage***	***Scalability***	***Real-Time Monitoring***	***Cost-Effectiveness***
[10]	Yes	High	High	Yes	Low
[22]	No	Low	High	Yes	Low
[23]	Yes	High	High	Yes	Low
[24]	Yes	Moderate	High	Yes	Moderate
[25]	Yes	Low	High	Yes	High
[26]	Yes	High	High	Yes	Low
[27]	Yes	High	High	Yes	Moderate
[11]	Yes	Low	High	Yes	Low
[9]	Yes	Low	High	Yes	Low
[8]	No	Moderate	High	Yes	Low
[15]	Yes	Moderate	High	Yes	Moderate
[12]	Yes	Low	High	Yes	Low
[13]	Yes	Moderate	High	Yes	Low
[28]	Yes	low	High	Yes	Low
[29]	Yes	low	High	Yes	moderate
[30]	Yes	low	High	Yes	Low
[31]	Yes	High	Low	Yes	moderate
[32]	Yes	Moderate	Moderate	Yes	Low
[33]	Yes	Low	Low	Yes	Low
[34]	Yes	Low	High	Yes	Moderate
[35]	Yes	High	High	No	Moderate
[36]	Yes	Moderate	High	Yes	Moderate
[37]	Yes	Moderate	High	Yes	Low
[14]	Yes	Moderate	High	Yes	Low

C. *Findings and discussion*

Based on the comparative analysis of the IoT architectures for mine environmental monitoring, as presented in the "Evaluation of IoT Architectures for Mine Environmental Monitoring" table, several key findings and discussions can be highlighted:

- Communication Reliability: Most of the evaluated IoT architectures exhibit good communication reliability, with a majority of them being capable of maintaining reliable communication. Communication reliability is a critical factor for ensuring that data from the mine environment is accurately transmitted and received for monitoring and analysis.
- Power Usage: The power usage of the evaluated IoT architectures varies across the board, with some architectures demonstrating high power consumption, while others are more power-efficient. Power usage is a significant consideration, as efficient power management is essential for prolonged deployment of monitoring systems in remote mining environments.
- Scalability: Scalability varies among the evaluated IoT architectures, with some architectures offering high scalability, while others are more limited in their scalability potential. Scalability is vital to accommodate future expansion of the monitoring system to cover larger mine areas or more monitoring points.
- Real-Time Monitoring Capabilities: The majority of the IoT architectures support real-time monitoring capabilities, allowing continuous data collection and analysis from the mine environment. Real-time monitoring is crucial for promptly detecting environmental risks, pollution incidents, or any anomalies that require immediate attention.
- Cost-Effectiveness: The cost-effectiveness of the evaluated IoT architectures varies, with some architectures being more cost-effective than others. Cost-effectiveness is a critical factor, as the regulators often need to balance the benefits of advanced monitoring with the associated costs.

The comparative analysis underscores the diversified attributes and capabilities intrinsic to various IoT architectures tailored for mine environmental monitoring. Most evaluated architectures emerge as particularly promising options due to their favorable performance across multiple evaluation criteria, including communication reliability, low power usage, scalability, real-time monitoring capabilities, and cost-effectiveness.

1.) *Recommendation of IoT Architecture for Mine Environmental Monitoring*

The assessment of IoT architectures for mine environmental monitoring, drawn from insights of 24 papers and a thorough comparative analysis, has uncovered crucial findings that illuminate the way forward arriving at a hybrid IoT architecture.

The choice to recommend a hybrid IoT architecture is grounded in the synthesis of insights derived from both the comparative analysis of IoT architectures and the distinctive challenges confronted by ZEMA in mine environmental monitoring. This decision is not only supported by the observed strengths of diverse architectures but also seamlessly aligns with the nuanced demands stemming from the constraints of current monitoring methods.

- Strengths Integration: The hybrid IoT architecture draws from the strengths exhibited by various architectures in the comparative analysis. It capitalizes on robust communication reliability, real-time monitoring capabilities, power efficiency, scalability options, and cost-effectiveness observed across different IoT architectures. The hybrid approach forms a unified framework that maximizes the various technologies and methodologies presented by each constituent.

- Customized for Specific Challenges: ZEMA's current monitoring limitations encompass a diverse range of facets, necessitating an approach capable of harmoniously addressing each challenge. The tailored hybrid architecture encompasses remote sensor networks, redundant systems, multi-modal Sensors that can collect data on various pollutants, cloud-based platforms, data redundancy, and remote calibration capabilities. It adeptly caters to the distinctive intricacies of these challenges, providing an all-encompassing solution.
- Enhanced Resilience: The hybrid architecture transcends being a mere consolidation of features but it is a methodically crafted solution designed to fortify the monitoring system's resilience. Through the introduction of data redundancy, the hybrid architecture ensures consistent data collection, accuracy, and real-time insights, even amidst external disruptions.
- Future-Ready Adaptability: The dynamic nature of mining operations and environmental monitoring demands an adaptable solution that can evolve in tandem with changing circumstances. The hybrid architecture's scalability provisions lay a foundation for seamless expansion, accommodating future growth and technological advancements without necessitating a complete overhaul.
- Balance of Efficiency and Affordability: The hybrid approach adeptly strikes a harmonious balance between cost-effectiveness and efficacy. By integrating cost-efficient features and harnessing existing strengths from diverse architectures, the hybrid solution adeptly addresses budget constraints while delivering peak monitoring performance.

In conclusion, the adoption of the hybrid IoT architecture is not just a theoretical concept but a strategic response that takes into account the specific findings from the comparative analysis, ZEMA's limitations, and the overarching objective of achieving comprehensive, continuous, and resilient mine environmental monitoring. The hybrid approach will also allow for real-time monitoring of critical environmental parameters such as sulfur dioxide, carbon monoxide, and particulate matter, aligning with ZEMA's current monitoring capabilities and guideline limits.

VI. FUTURE WORKS

In the upcoming phase of our research, our team is poised to transition from theoretical analysis to the tangible implementation of the recommended IoT architecture tailored for mine environmental monitoring. This ambitious endeavor will encompass a multifaceted approach that not only addresses the findings from our comparative analysis but also takes into account the unique challenges posed by tropical climates particularly pertinent in regions like Zambia.

Our holistic implementation strategy will span various critical domains, including project planning, robust system design, seamless hardware-software integration, strategic field deployment, rigorous data collection protocols, performance evaluation, and active collaboration with stakeholders. It is through this consolidation of efforts that we intend to transcend the limitations inherent in ZEMA's current monitoring methods.

Central to our approach is the fusion of innovative technological solutions with climate-specific adaptations. Recognizing the significance of the tropical climate prevalent in Zambia, we are committed to enhancing the architecture's resilience by introducing climate-specific sensors and materials. These elements will enable the architecture to withstand the challenges posed by high humidity, temperature variations, and other climate-induced factors that can potentially impact data accuracy and system longevity.

Ultimately, our goal remains unwavering and that is to realize an IoT architecture that seamlessly combines cutting-edge technology with the adaptive capacity necessary to thrive in Zambia's tropical climate. Through this fusion, we aspire to usher in a new era of continuous, resilient, and effective mine environmental monitoring. By addressing the intricacies of both technology and climate, we aim to empower environmental management within mining environments, catalyzing positive change while embracing the challenges unique to our geographical context.

VII. CONCLUSION

The study set out to critically evaluate various IoT architectures for their applicability in mine environmental monitoring, with a particular focus on the needs of the Zambia Environmental Management Agency (ZEMA). Through a rigorous comparative analysis, the paper highlighted the shortcomings of traditional monitoring methods, most notably their inability to provide continuous, real-time data and their high operational costs. Our investigation led us to advocate for a hybrid IoT architecture that combines the strengths of remote sensor networks, cloud-based data analytics, data redundancy, remote calibration capabilities, and climate-specific adaptations.

This architecture not only addresses the gaps in current monitoring practices but also offers the flexibility to adapt to future technological advancements and environmental regulations, while also accounting for the unique challenges posed by tropical climates prevalent in the region. Moreover, the study serves as a foundational work for future research in the optimization of IoT architectures for environmental monitoring, encompassing both technological and climate-specific considerations. It opens the door for more in-depth studies focusing on the technical and economic feasibility of implementing the recommended hybrid architecture in tropical climates.

In summary, this paper contributes to the growing body of knowledge on the transformative potential of IoT technologies in enhancing environmental monitoring practices in mining environments. It offers a viable pathway for achieving a more sustainable and socially responsible mining industry that is attuned to the nuances of both technology and the environment.

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