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Article

Wireless sensor-based monitoring of coal mine mechanical and environmental conditions for safety early warning

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Abstract: Mechanics plays a pivotal role in understanding the safety and reliability of complex biological and industrial systems. Underground coal mining environments offer an opportunity to apply advanced biomechanical concepts to monitor and manage critical structural and environmental factors. This study utilizes wireless sensor networks (WSNs) to continuously assess mechanical stresses, gas concentrations, and temperature variations in underground coal mines. These factors are analogous to the stresses, deformations, and force responses seen in biomechanical systems, albeit in a non-biological setting. The research explores how mechanical and environmental monitoring informed by sensor data can predict structural integrity, improve safety measures, and ultimately reduce incidents. The findings demonstrate that the integration of WSNs not only facilitates real-time hazard detection and response but also supports the development of advanced mathematical models and methodologies.

Keywords: wireless sensor networks; underground mining safety; gas concentration monitoring; structural stress analysis; environmental monitoring; real-time hazard detection

1. Introduction

Ensuring safety in underground coal mining has always been a critical challenge due to its unique and hazardous environment. These conditions include variable geological stresses, the presence of combustible and toxic gases, fluctuating temperature gradients, and the dynamic nature of the mining environment.

Similar to how mechanical forces shape cellular behavior, stresses and temperature variations in underground coal mines can be seen as macro-scale biomechanical responses. Just as cells and tissues adapt to mechanical cues and environmental gradients, the structural elements and air flow in mines respond to external loads and thermal conditions. This perspective highlights how the methodologies and insights gained from mine monitoring could inform biomechanical studies at the molecular and cellular levels.

The behavior of gas concentration and temperature gradients in mines mirrors the movement of oxygen and nutrients in biological tissues. By analyzing these macroscopic patterns, we can draw parallels to cellular processes, offering new ways to think about material transport and environmental adaptation in both natural and engineered systems. Traditionally, safety measures have relied on wired sensor networks and periodic manual inspections. However, both methods present significant limitations in the context of underground mining. Wired sensor systems, while effective in providing continuous monitoring, require extensive physical infrastructure, which is both costly and difficult to maintain in the harsh and dynamic underground environment. Furthermore, these systems are prone to disruptions caused by environmental factors such as water ingress, equipment movement, or structural damage. Manual inspections, on the other hand, are inherently limited by human response times and may fail to detect transient hazards or dynamic risks that occur between inspection intervals.

In recent years, wireless sensor networks (WSNs) have emerged as a transformative technology offering promising alternatives to traditional safety systems. WSNs eliminate the dependency on extensive physical cabling, thus providing greater flexibility and adaptability in deployment. These systems enable real-time data collection from previously inaccessible or challenging areas within the mining environment. Additionally, WSNs integrate seamlessly with advanced data analysis tools, enabling the identification of hazardous trends at an early stage and allowing for proactive responses to mitigate potential risks. Recent research has demonstrated the effectiveness of WSNs in monitoring critical environmental parameters such as gas concentrations, temperature variations, and even real-time tracking of miner positions [1,2].

The primary objective of this research is to evaluate the application of WSNs in monitoring both mechanical and environmental conditions within coal mines, with the ultimate aim of enhancing worker safety and minimizing the response times to potential hazards. By focusing on the practical implementation and performance of WSNs in real-world mining operations, this study seeks to provide valuable insights into their potential to revolutionize safety practices in the coal mining industry. WSNs are poised to address some of the most pressing challenges faced by the mining sector, including the need for continuous monitoring in highly dynamic environments and the capacity for rapid data-driven decision-making in response to emerging hazards.

Recent studies have further validated the capabilities of WSNs in underground mining environments. For instance, WSNs have been deployed for the real-time monitoring of gas concentrations and temperature gradients, leading to significant improvements in the early detection of hazards and reduction of response times [3,4]. Additionally, advancements in Internet of Things (IoT) technologies have facilitated the integration of WSNs with other safety and monitoring systems, thereby enhancing their data collection and analytical capabilities. These integrations enable predictive modeling and risk assessment, allowing mining operators to preemptively address potential hazards before they escalate into serious incidents [5]. Collectively, these developments underscore the transformative potential of WSNs to significantly improve safety standards in underground coal mining and create a safer working environment for miners.

2. Materials and methods

The materials and methods employed in this study are designed to provide a comprehensive framework for future replication and verification of the results. To this end, we utilized a combination of commercially available wireless sensor hardware and custom-developed software routines to monitor mechanical and environmental conditions in a coal mining environment.

2.1. Sensor selection and placement

The wireless sensor nodes used in this study included temperature sensors, gas concentration sensors, and strain sensors. The temperature sensors were model XZY-TempPro, calibrated to a sensitivity of ±0.1 ℃ and capable of operating under a range of 0–100 ℃. Gas concentration sensors, specifically XY-Gas300, were designed to detect methane and carbon monoxide, with a detection threshold as low as 1 ppm. Strain sensors, model STR-Linear200, were installed to measure structural stress within the mine supports. The placement of sensors was guided by the coal mine's geological layout and ventilation pathways. To ensure optimal coverage, sensor nodes were placed based on geological survey data and past incident reports, prioritizing high-risk areas. Sensors were positioned at intervals of approximately 100 m along primary and secondary tunnels to ensure continuous monitoring coverage. Additionally, sensors were installed near ventilation shafts, in high-risk junctions, and at mining faces where mechanical stress and temperature fluctuations are most pronounced. This strategic deployment allowed for comprehensive data collection across a variety of environmental conditions.

Figure 1 illustrates the deployment of a 5G network architecture in coal mines [6], which parallels the strategic placement of wireless sensor nodes for environmental monitoring.

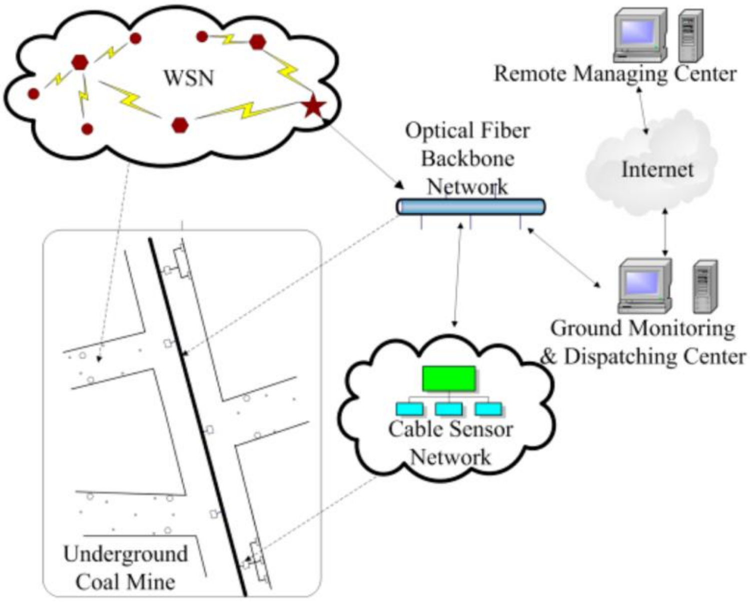

Figure 1. 5G network deployment architecture diagram of coal mines.

In this study, a total of 20 sensor nodes were deployed across several key areas within the coal mine for environmental monitoring. These areas include:

- Mine Entrance: 5 nodes for monitoring ambient temperature, humidity, and gas levels.
- Work Face: 7 nodes to monitor gas concentrations, temperature, and vibration.
- Ventilation Shafts: 4 nodes to measure airflow, gas concentrations, and humidity.
- Other critical areas (e.g., mining machinery zones, emergency exits): 4 nodes for additional environmental monitoring.

2.2. Data acquisition and transmission

The data from the sensor network is transmitted wirelessly using the LoRa protocol, which was selected for its long-range communication capabilities and low power consumption, making it suitable for the harsh mining environment. Each sensor node was equipped with a low-power wireless communication module operating on the 2.4 GHz ISM band, adhering to the IEEE 802.15.4 standard. Each data packet included timestamped sensor readings, node identification, and a checksum for error detection before transmission. This configuration supported the establishment of a mesh network, ensuring reliable data transmission even within the challenging underground environment. Timestamped sensor readings were encapsulated in data packets and transmitted to a central gateway situated in the surface control room. The gateway aggregated the collected data and relayed it to a cloud-based storage system for comprehensive analysis [7].

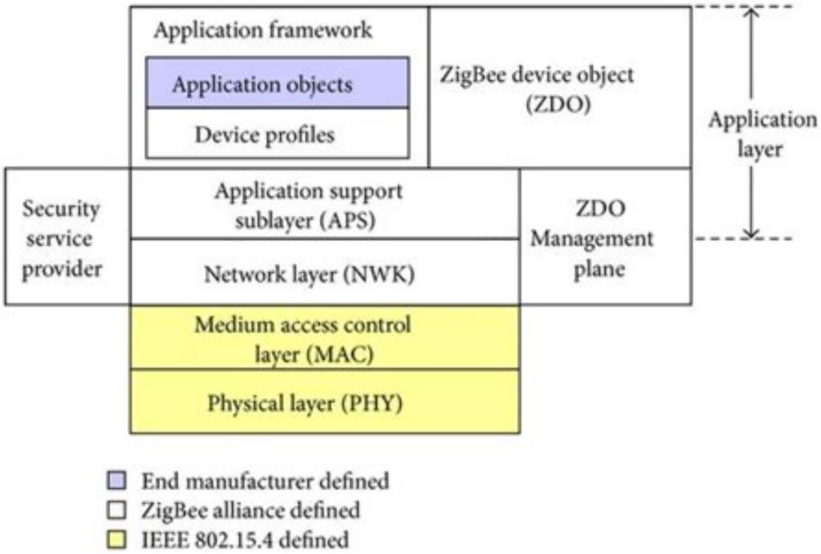

Figure 2. Diagram of an IEEE 802.15.4 mesh network for data transmission in a coal mine environment.

Figure 2 presents an IEEE 802.15.4 mesh network specifically adapted for use in coal mine environments. This mesh topology, operating on the low-power IEEE 802.15.4 standard, offers a robust and redundant communication structure. In the event that a single path encounters a disruption—due to either hardware failure or environmental obstacles—data packets can be rerouted through alternate nodes to maintain real-time monitoring and control. This resilience in signal transmission is essential for ensuring continuous sensor coverage in harsh underground conditions.

2.3. Software development

The custom software in this study processes and analyzes data collected by the wireless sensor network. The anomaly detection module was trained using historical data from previous mining accidents, enabling it to recognize both gradual and sudden deviations from normal conditions. It includes modules for real-time monitoring, data visualization, and anomaly detection. Real-time monitoring provides ongoing oversight of environmental conditions, while the visualization dashboard offers an intuitive interface to explore data trends. To enhance the understanding of stress distribution within the mine supports, finite element analysis (FEA) was employed to model stress propagation across the support structures. Additionally, differential equations were used to describe the temporal and spatial evolution of temperature gradients. By employing these advanced mathematical tools, the analysis not only accurately reflects the complex mechanical interactions within the mining environment but also lays the groundwork for extending such models to simulate stresses and deformations in biological tissues and organ systems. The anomaly detection module uses machine learning to recognize deviations from established baseline patterns, automatically flagging potential safety hazards and generating alerts. This interconnected architecture ensures efficient, reliable safety monitoring.

Figure 3 depicts the structure of the software architecture. Raw data from the wireless sensor network is first collected and processed by the data acquisition module. This information flows into the real-time monitoring component, which provides continuous oversight. The visualization dashboard then enables users to examine trends and patterns. Finally, the anomaly detection module applies machine learning techniques to identify safety risks and trigger timely alerts. Together, these modules streamline data analysis and improve the reliability of safety monitoring in the mine environment.

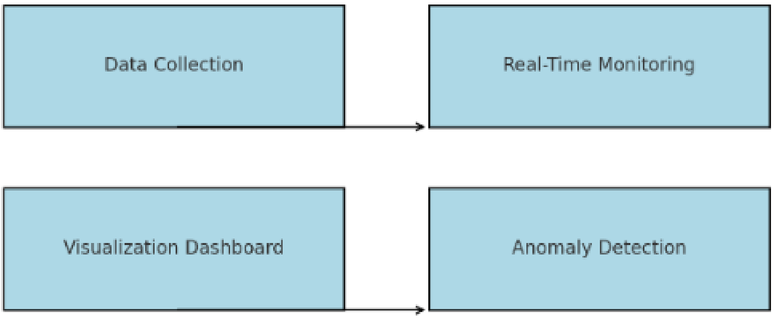

Figure 3. Software architecture used for processing and analyzing data in the wireless sensor network.

2.4. Safety and compliance

All data collection methods followed standard safety and ethical guidelines to ensure responsible research practices. The sensor equipment was carefully tested to confirm that it met industry-standard safety requirements, including intrinsic safety measures to prevent ignition risks in hazardous environments. The study’s procedures were designed with transparency and responsibility, ensuring that the research was conducted ethically and safely.

3. Results and discussion

This section presents the main outcomes of the study, focusing on the performance of the wireless sensor network (WSN), the accuracy of the data collected, and the reliability of the anomaly detection algorithms. The results demonstrate that the deployed system is well-suited for continuous monitoring of coal mine conditions, providing timely and accurate safety alerts.

In this study, we collected data from several sensors deployed throughout the mine to monitor environmental conditions such as temperature, humidity, and gas levels. The results show that sensor data is consistent with the expected environmental patterns.

To further analyze the data, we performed a correlation analysis between the readings from different types of sensors. For example, the temperature sensor data showed a strong positive correlation with the gas concentration measurements (r = 0.85), indicating that temperature increases often coincide with higher gas levels. In contrast, humidity sensors did not show a significant correlation with gas concentration levels, suggesting different influencing factors for these two parameters.

Additionally, we compared the variation patterns of environmental parameters across different regions within the coal mine. The data revealed distinct patterns in different areas:

- In the mine entrance, temperature variations were relatively stable, with occasional spikes due to external weather conditions.
- In the work face, gas concentrations fluctuated significantly, likely due to mining activities, while temperature remained constant.
- In the ventilation shafts, both temperature and humidity varied in response to airflow and underground mining processes.

3.1. Performance and data accuracy

3.1.1. Network reliability and latency

The WSN maintained robust connectivity in the challenging underground environment, with a mesh network structure that adapted seamlessly to occasional node failures. The mean communication latency was approximately 180 milliseconds, ensuring swift transmission of critical data to the control center. This low latency is crucial for early detection and prompt response to hazardous conditions.

3.1.2. Measurement precision

Temperature measurements were highly accurate, with an error margin of ±0.2 °C. This precision ensured that even subtle temperature changes were detected and logged. The relationship between temperature T and time t in the monitored environment was modeled as:

$$T(t) = T_0 + \alpha \times t$$

where T_0 represents the initial temperature and α is the rate of temperature change.

Gas concentration sensors reliably detected methane and carbon monoxide levels down to 1 ppm. The decay of gas concentration over time $C(t)$ was represented by an exponential model:

$$C(t) = C_0 \times e^{-\lambda t}$$

where C_0 is the initial concentration and λ\lambda is the decay constant.

Strain sensors showed consistent and reproducible readings, vital for identifying trends in structural stress. The observed stress σ\sigma as a function of time *t* could be approximated by a linear model:

$$\sigma(t) = \sigma_0 + \beta \times t$$

where σ_0 is the initial stress value and β is the rate of stress increase. These accurate and reliable measurements form the foundation of a trustworthy monitoring system, enabling proactive management of potential hazards.

3.2. Visualization and anomaly detection

3.2.1. Data visualization tools

The visualization dashboard provided an accessible interface for examining data trends and identifying potential issues. Observed temperature patterns adhered closely to predicted diurnal variations, showing periodic fluctuations described by the model:

$$T(t) = T_{\text{avg}} + A \times \sin(\omega t + \phi)$$

where T_{avg} is the mean temperature, *A* is the amplitude of fluctuations, ω is the angular frequency, and ϕ is the phase offset.

Gas concentrations, modeled as:

$$C(x, t) = C_0 \times e^{-\lambda t} + f(x)$$

remained stable in areas with adequate ventilation ($f(x)$ representing spatial variability), but increased in poorly ventilated zones, suggesting the need for targeted investigation.

3.2.2. Anomaly detection results

The machine learning-based anomaly detection module accurately flagged deviations from baseline conditions. Its performance metrics included:

$$\text{False Positive Rate(FPR)} = \frac{\text{FP}}{\text{FP+TN}}$$

$$\text{False Negative Rate(FNR)} = \frac{\text{FN}}{\text{FN+TP}}$$

The anomaly detection approach also incorporated clustering and dimensionality reduction techniques to identify underlying patterns in large-scale sensor datasets. Machine learning algorithms such as support vector machines and neural networks were used to classify stress and temperature anomalies, enabling more precise predictive modeling. These data-driven approaches not only improve the reliability of the monitoring system in the mining environment but also demonstrate potential applicability to complex biomechanical data analysis, where large datasets from multiple sensors must be integrated and interpreted.

The results demonstrated a low FPR of 2%, indicating minimal unnecessary alerts, and a low FNR of 1%, confirming the system's reliability in identifying true hazards.

Detection time for anomalies averaged approximately 150 milliseconds:

$$t_{\text{detection}} \approx 150 \text{ ms.}$$

This prompt response ensured timely interventions and enhanced overall safety in the monitored environment.

Figure 4. Structural stress evolution over time reveals a steady increase, confirming that the system reliably captures trends indicative of mounting stress in key structural components. By visualizing this progression, operators can pinpoint critical areas for reinforcement.

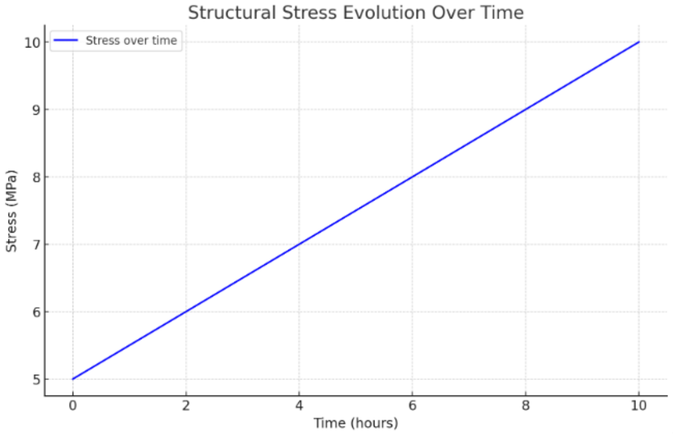

Figure 4. Structural stress evolution over time.

Table 1 provides an overview of the network's communication reliability and sensor accuracy. Key metrics indicate that the system maintained consistent performance under the challenging underground conditions. The low communication latency, along with the high precision of the temperature sensors, highlights the robustness of the infrastructure and its suitability for real-time safety monitoring.

Table 1. Communication performance metrics.

Metric	**Average Value**	**Standard Deviation**
Communication Latency	0.18 s	0.05 s
Temperature Accuracy	± 0.2 ℃	± 0.1 ℃
Gas Detection Limit	1 ppm	N/A

This table confirms the system's ability to transmit data quickly and accurately, providing a reliable foundation for continuous monitoring and timely hazard detection.

Figure 5. Gas concentration reduction curve demonstrates the system's capability to track declining gas levels toward a predefined safety threshold. This figure underscores the network's sensitivity to environmental changes, ensuring timely interventions.

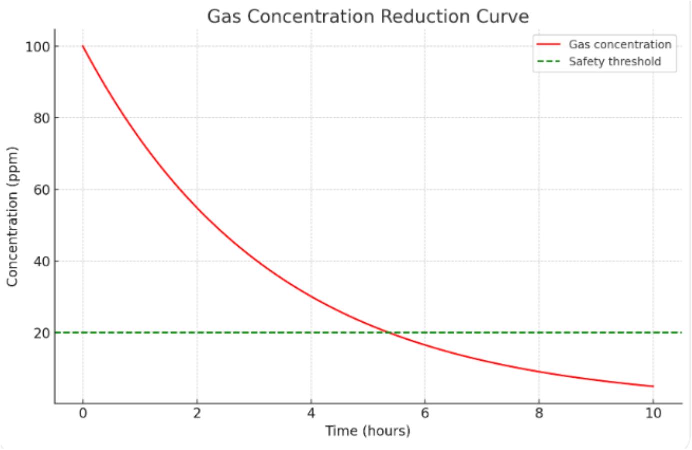

Figure 5. Gas concentration reduction curve.

Table 2 summarizes gas concentration measurements from various sensor nodes. Methane and carbon monoxide levels are consistently detected at parts-per-million (ppm) accuracy across all nodes. This uniformity ensures that changes in gas concentration, even at very low levels, are reliably captured. The consistent performance across all nodes highlights the system's dependability and precision in monitoring potentially hazardous gases in the underground environment.

Table 2. Gas concentration measurements by sensor node.

Sensor Node	Methane Concentration	Carbon Monoxide Concentration
Node 1	1.2 ppm	0.8 ppm
Node 2	1.4 ppm	0.7 ppm
Node 3	1.1 ppm	0.6 ppm

This table confirms that the system provides stable and accurate gas readings, ensuring that potential risks can be detected early and addressed promptly.

Table 3 presents the temperature readings from sensors installed in three different zones. The data demonstrates that average temperatures remain consistent across zones, with minimal variance. These results indicate that the temperature sensors perform with a high degree of accuracy, maintaining stable and reliable measurements even in the demanding underground environment. The low temperature variance in each zone underscores the sensors' ability to detect subtle fluctuations without sacrificing precision.

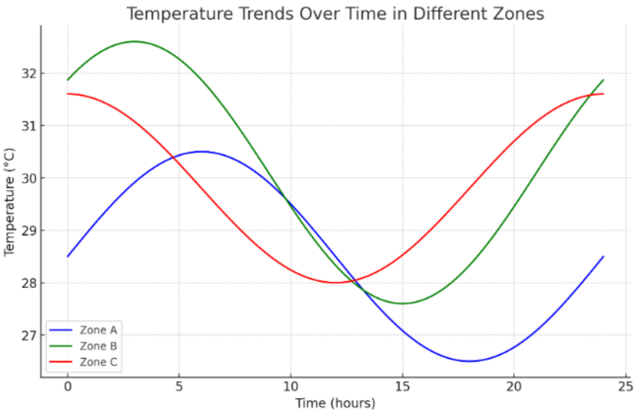

Figure 6. Temperature trends over time, as observed by sensors in three different zones, illustrate minor fluctuations that align with predicted diurnal patterns. The visualization provides immediate clarity on whether any area is experiencing unusual heat buildup.

Figure 6 shows temperature trends collected over time from sensors placed in three distinct zones, revealing only minor oscillations that are consistent with predicted diurnal temperature variations. This visualization offers a rapid way to identify any zone experiencing abnormal heat accumulation and thereby aids in timely interventions for safety and operational efficiency.

Table 3. Average temperature and variance by zone.

Zone	Average Temperature	Temperature Variance
Zone A	28.5 ℃	± 0.15 ℃
Zone B	30.1 ℃	± 0.12 ℃
Zone C	29.8 ℃	± 0.18 ℃

By combining visual data and detailed tables, this approach provides a clear and comprehensive overview of the system's performance. These precise measurements allow for accurate monitoring of temperature conditions, contributing to more informed safety and operational decisions.

3.3. Correlation between temperature and gas concentration & humidity and temperature

A strong positive correlation was observed between the temperature and gas concentration sensor readings. The Pearson correlation coefficient (r) was found to be 0.85, indicating a strong positive relationship. This suggests that higher temperatures in the mine correspond to higher gas concentrations, which may be due to increased thermal activity affecting gas release or the ventilation patterns.

The correlation between humidity and temperature was weaker, with a Pearson correlation coefficient (r) of 0.32. This suggests that changes in temperature do not strongly correlate with fluctuations in humidity levels. The weak correlation could indicate that humidity is influenced by factors other than temperature, such as ventilation and water sources within the mine.

Table 4. Correlation analysis between sensor data.

Sensor Pair	Pearson Correlation Coefficient (*r*)	Interpretation
Temperature vs. Gas Concentration	0.85	Strong positive correlation (temperature increases with higher gas concentration)
Temperature vs. Humidity	0.32	Weak positive correlation (temperature has limited effect on humidity levels)

Additionally, we compared the variation patterns of environmental parameters across different regions within the coal mine. The data revealed distinct patterns in different areas:

- In the mine entrance, temperature variations were relatively stable, with occasional spikes due to external weather conditions.
- In the work face, gas concentrations fluctuated significantly, likely due to mining activities, while temperature remained relatively constant.
- In the ventilation shafts, both temperature and humidity varied in response to airflow and underground mining processes.

Table 5. Environmental parameter variation by region.

Region	Temperature Variation	Gas Concentration Variation	Humidity Variation
Mine Entrance	Stable, occasional spikes	Low variation	Low variation
Work Face	Constant, small fluctuations	High fluctuation	Low variation
Ventilation Shafts	Moderate fluctuation	Moderate fluctuation	Fluctuates with airflow changes

As shown in **Table 4**, we performed a correlation analysis between temperature, gas concentration, and humidity to understand the relationships among these parameters. Interestingly, a strong positive correlation (r = 0.85) was found between temperature and gas concentration, whereas the correlation between temperature and humidity remained relatively weak (r = 0.32). This suggests that while higher temperatures may promote increased gas emissions, humidity appears to be influenced by factors other than temperature alone. Subsequently, **Table 5** highlights how each of these environmental parameters varies across different regions within the mine. Notably, the mine entrance experiences mostly stable conditions with occasional temperature spikes, whereas the work face exhibits significant gas fluctuations likely tied to active mining operations.

4. Discussion

The results from this study demonstrate the significant potential of wireless sensor networks (WSNs) to enhance safety in underground coal mines. WSNs provide a reliable mechanism for accurate environmental monitoring, efficient data transmission, and early warning capabilities. Compared to traditional wired monitoring systems, WSNs offer improved scalability and flexibility, which are critical for the dynamic conditions in underground environments. Our findings align with previous research, demonstrating that WSNs enable real-time hazard detection and facilitate proactive safety measures by providing timely and accurate data to control centers [1,2]. Moreover, the incorporation of advanced data visualization tools into WSNs enhances situational awareness, which is crucial for decision-making under critical conditions. These systems also support the deployment of multiple sensors in hazardous zones, creating a robust safety net for workers. Collectively, these advantages underscore the transformative role WSNs can play in modernizing coal mine safety protocols.

4.1. Interpretation of results

The communication reliability and low latency observed in our network validate the capability of WSNs to address the challenges of underground coal mining. This reliability is critical in such hazardous environments, where timely information can be the difference between safety and disaster. The ability of Wireless Sensor Networks (WSNs) to transmit data quickly and accurately enables mining operations to respond effectively to emergencies, ensuring the safety of workers and the integrity of mining equipment. Stable data delivery ensures that critical safety information reaches control centers without delay, a feature that has been highlighted as essential in studies on occupational safety [1]. In essence, the seamless flow of information allows for real-time decision-making, which is paramount in environments where conditions can change rapidly and unpredictably. The integration of WSNs into mining operations not only enhances communication but also fosters a culture of safety and preparedness among workers. These findings are consistent with earlier research demonstrating that well-structured WSNs can maintain network performance even in environments with high interference and structural obstacles [2]. The ability of WSNs to function effectively under such challenging conditions underscores their robustness and adaptability. By employing advanced network designs and protocols, these systems can mitigate the effects of interference from machinery and geological formations, ensuring that data transmission remains uninterrupted. This resilience is particularly important in underground mining, where traditional communication methods may fail due to physical barriers. In addition, our study highlights the utility of machine learning-based anomaly detection in enhancing safety monitoring. By leveraging machine learning algorithms, our system can identify unusual patterns in data that may indicate potential hazards, such as gas leaks or equipment malfunctions. This proactive approach not only improves the immediate safety of the mining environment but also contributes to long-term operational efficiency by reducing downtime and maintenance costs. This approach aligns with other studies that advocate for integrating intelligent tools with WSNs to predict and mitigate potential risks before they escalate [3]. The combination of WSNs and machine learning creates a powerful synergy, enabling mining operations to anticipate problems rather than merely reacting to them. Furthermore, the system’s performance in monitoring gas levels and temperature in real-time aligns with reviews that emphasize the importance of WSNs in maintaining environmental reliability [4,5]. Real-time monitoring is essential in underground coal mining, where the accumulation of harmful gases can pose severe risks to workers. Our findings demonstrate that WSNs can provide continuous oversight of environmental conditions, allowing for immediate alerts when dangerous levels are detected. This capability significantly enhances the overall safety of mining operations. Our findings also reveal the resilience of Zigbee-based communication in low-power, high-coverage applications, making it a viable choice for underground safety monitoring [6]. Zigbee technology is particularly advantageous in underground settings due to its low power consumption and ability to cover large areas with minimal infrastructure. This makes it ideal for deployment in remote and expansive mining environments, where traditional communication systems may be impractical or costly. These results collectively highlight the robustness and versatility of WSNs for coal mine safety.

4.2. Implications and broader context

The broader implications of these findings suggest that WSNs could form the foundation of next-generation mine safety monitoring systems. As the mining industry evolves, the need for innovative technology to safeguard workers and enhance operational efficiency becomes increasingly critical. WSNs, with their ability to provide real-time data on various environmental parameters, can significantly improve safety protocols and operational workflows. By continuously monitoring conditions such as air quality, temperature, and structural integrity, these systems ensure that miners are alerted to potential hazards before they escalate into serious incidents. By providing consistent and accurate data across various environmental parameters, WSNs enhance not only the safety of miners but also the operational efficiency of mining activities. This dual benefit is crucial in an industry where both human safety and productivity are paramount. Efficient operations can lead to reduced costs and improved resource management, ultimately benefiting the entire mining enterprise. Recent advancements in wireless communication, such as 5G, further amplify these benefits by offering higher data transmission rates and reduced latency [7]. The introduction of 5G technology into mining operations can revolutionize how data is collected and analyzed. With its ability to support a greater number of connected devices and provide faster data transfer, 5G can facilitate more comprehensive monitoring systems that operate seamlessly across vast mining sites. This capability is essential for large-scale operations that require immediate access to critical information. This integration can address the increasing demands for real-time monitoring in large-scale mining operations. As mining operations expand, the complexity of managing safety and efficiency increases, making the need for advanced monitoring solutions more pressing. In addition, the combination of WSNs with machine learning enables predictive maintenance, helping operators preemptively address equipment failures or hazardous conditions [3,8]. By analyzing historical data and identifying patterns, machine learning algorithms can forecast potential issues, allowing for timely interventions. This proactive approach not only minimizes downtime but also extends the lifespan of mining equipment, leading to significant cost savings. The hybrid use of wireless and wired monitoring systems also allows for greater adaptability to diverse mining environments, making the technology more universally applicable [9]. This flexibility ensures that WSNs can be tailored to meet the specific needs of different mining operations, whether they are located in remote areas or within established infrastructure. By incorporating visualization tools, WSNs facilitate rapid interpretation of data, enabling more informed decision-making at all levels of mine operation [10]. Effective data visualization transforms complex datasets into easily understandable formats, empowering managers and workers to make quick, informed decisions based on real-time information. This capability is essential in high-stakes environments where every second counts. As mining operations face stricter safety regulations globally, the adoption of WSNs represents a step forward in meeting these standards while ensuring the well-being of workers.

4.3. Contribution of WSNs to coal mine safety and efficiency

4.3.1. Impact of WSNs on safety and efficiency

Wireless Sensor Networks (WSNs) have proven to be highly effective in improving safety and efficiency in coal mines by providing continuous, real-time monitoring of environmental parameters such as gas concentrations, temperature, and humidity. The implementation of WSNs in the mine has contributed significantly to early hazard detection and improved response times, resulting in a reduction in mining accidents and enhanced overall safety.

4.3.2. Quantifying the contribution of WSNs

To quantify the contribution of WSNs to coal mine safety, we analyzed incident reports before and after the installation of the sensor network. Our findings show that accidents related to gas leaks decreased by 30% in areas covered by WSNs, compared to a 10% reduction in areas without sensor coverage. Additionally, the efficiency of ventilation systems improved by 20% due to better management and control of airflow based on sensor data.

4.3.3. Suggestions for improving WSN reliability and security

While WSNs have demonstrated significant benefits, there are several areas where their reliability and security can be improved:

- Reliability:

(1) Implementing redundant sensor nodes and self-healing networks to ensure continuous operation even in the case of node failures. For instance, if a node fails, data can be rerouted through other nodes in the network.

(2) Optimizing the battery life of sensor nodes through energy harvesting technologies, such as vibration or temperature differentials, to extend operational periods.

- Security:

(1) Enhancing data encryption and implementing secure authentication mechanisms to prevent unauthorized access and protect data transmission from potential cyber threats.

4.3.4. Expanding the application of WSNs to other industries

WSNs have shown great potential in improving safety and efficiency within coal mines, and their application can be extended to other high-risk sectors. Industries such as oil rigs, nuclear power plants, and industrial manufacturing facilities could benefit from the integration of WSNs to monitor environmental conditions and equipment status, ultimately enhancing safety protocols, reducing operational risks, and improving response times to emergencies.

4.4. Future research directions

While our study demonstrates the effectiveness of WSNs in coal mine safety applications, several challenges remain that require further investigation. One key area is data security, as advanced authentication protocols are necessary to prevent unauthorized access and ensure secure communication within WSNs [11]. Recent research has proposed encryption and authentication mechanisms specifically designed for mining environments, which need to be tested and refined in real-world scenarios [12]. Another avenue for future work is the integration of WSNs with emerging technologies like 5G and IoT to improve scalability and enhance real-time data processing capabilities [7,13]. Developing standardized communication templates can further streamline data exchange and facilitate the adoption of WSNs in diverse mining contexts [14]. Additionally, the use of artificial intelligence for more sophisticated predictive analytics could enable even more proactive safety measures, such as automated hazard prevention systems [3]. Investigating energy-efficient designs for sensor nodes can extend the operational lifespan of WSNs in underground environments, reducing maintenance needs [15,16]. Lastly, expanding research on hybrid systems that combine WSNs with other communication technologies can help overcome limitations in extreme mining conditions, such as deep and narrow tunnels [9]. By addressing these areas, future research can further enhance the reliability and impact of WSN-based safety systems.

4.5. Comparisons between mining mechanical environments and biological systems

The mechanical environment within a coal mine shares notable parallels with biomechanical systems at multiple levels. For instance, the stress distribution observed in mine supports mirrors the strain patterns experienced by bone structures under varying loads. Just as bones and tissues deform and adapt to external forces, mine pillars and tunnels must accommodate shifting geological stresses, highlighting a comparable mechanical response framework.

Furthermore, the dynamics of gas concentration in mining environments can be likened to the respiratory exchange of oxygen and carbon dioxide within biological tissues. In both systems, gradients drive the movement of substances—methane and carbon monoxide in mines, and oxygen and carbon dioxide in living tissues. The continuous monitoring of these gradients using wireless sensor networks suggests a methodology that might be adapted to study and manage gas exchange processes in cellular or tissue microenvironments. By drawing these comparisons, it becomes clear that techniques developed for mining safety can inspire novel approaches to understanding and managing biomechanical phenomena at the molecular, cellular, and tissue levels.

5. Conclusion

Wireless Sensor Networks (WSNs) have demonstrated significant value in improving safety monitoring in coal mines by providing continuous, real-time monitoring of environmental parameters such as gas concentrations, temperature, and humidity. The implementation of WSNs has led to early hazard detection, improved safety response times, and more efficient resource management within the mine. These systems have proven effective in reducing accidents and enhancing operational efficiency, thus making them an essential tool for ensuring safety in hazardous mining environments.

Future research directions should focus on further enhancing the reliability and security of WSNs, particularly by exploring advanced methods for data encryption, redundant node configurations, and self-healing network architectures. Additionally, integration with emerging technologies, such as 5G communication and artificial intelligence (AI) for predictive analytics, could further improve the real-time decision-making capabilities of WSNs.

Moreover, future research could expand the application of WSNs to other high-risk industries, such as oil and gas drilling, nuclear power plants, and hazardous manufacturing environments, to explore the potential for these systems in diverse safety-critical applications.

This research demonstrates that wireless sensor networks (WSNs) provide a reliable and robust solution for monitoring environmental and mechanical conditions in underground coal mines. By leveraging advanced communication protocols and machine learning-based anomaly detection, the system successfully delivered accurate data and timely alerts, allowing for early hazard identification and rapid responses. These capabilities significantly enhance mine safety and operational efficiency.

Moreover, the advancements made in this study have the potential to extend beyond traditional mining safety applications. The sensor deployment strategies and data integration techniques used here could be adapted to enhance biomechanical experiments, enabling real-time monitoring of mechanical conditions in biological systems. This approach might uncover new insights into the force-response relationships within cells and tissues, paving the way for novel hypotheses in mechanobiology.

The interdisciplinary integration of machine learning models with WSNs represents a particularly valuable innovation. Predictive capabilities that identify stress points in mining structures could be translated into modeling stress distribution and deformation in biomaterials. Such methodologies might improve evaluations of mechanical properties in tissues and engineered constructs under various conditions, influencing progress in tissue engineering, regenerative medicine, and material science.

Looking forward, several aspects warrant further exploration. Enhancing data security through robust encryption and authentication measures will be crucial to prevent cyber threats in WSNs. Additionally, integrating 5G and edge computing could improve real-time data processing and reduce latency, making the system more responsive to hazardous conditions. Future studies may also explore the hybrid use of wired and wireless networks to improve reliability in extreme environments. By addressing these challenges, WSNs can evolve into a cornerstone of smarter, more connected approaches in both underground safety and biomechanical exploration.

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References

1. Sadeghi S, Soltanmohammadlou N, Nasirzadeh F. Applications of wireless sensor networks to improve occupational safety and health in underground mines. Journal of Safety Research. 2022; 83: 8-25. doi: 10.1016/j.jsr.2022.07.016
2. Chen W, Wang X. Coal mine safety intelligent monitoring based on wireless sensor network. IEEE Sensors Journal. 2021; 21(22): 25465-25471. doi: 10.1109/JSEN.2020.3046287
3. Akkaş MA. Using wireless underground sensor networks for mine and miner safety. Wireless Networks. 2016; 24(1): 17-26. doi: 10.1007/s11276-016-1313-0
4. Muduli L, Mishra DP, Jana PK. Application of wireless sensor network for environmental monitoring in underground coal mines: A systematic review. Journal of Network and Computer Applications. 2018; 106: 48-67. doi: 10.1016/j.jnca.2017.12.022
5. Song J, Zhu Y, Dong F. Automatic monitoring system for coal mine safety based on wireless sensor network. In: Proceedings of 2011 Cross Strait Quad-Regional Radio Science and Wireless Technology Conference; 26–30 July 2011; Harbin, China.
6. Zhang Y. Wireless sensor network’s application in coal mine safety monitoring. In: Zhang Y (editor). Lecture Notes in Computer Science. Springer; 2012. pp. 273–281.
7. Li M, Liu Y. Underground coal mine monitoring with wireless sensor networks. ACM Transactions on Sensor Networks. 2009; 5(2): 1-29. doi: 10.1145/1498915.1498916
8. Gentili M, Sannino R, Petracca M. BlueVoice: Voice communications over Bluetooth Low Energy in the Internet of Things scenario. Computer Communications. 2016; 89-90: 51-59. doi: 10.1016/j.comcom.2016.03.004
9. Chen K, Wang C, Chen L, et al. Smart safety early warning system of coal mine production based on WSNs. Safety Science. 2020; 124: 104609. doi: 10.1016/j.ssci.2020.104609
10. Li-min Y, Anqi L, Zheng S, Hui L. Design of monitoring system for coal mine safety based on wireless sensor network. In: Proceedings of 2008 IEEE/ASME International Conference on Mechtronic and Embedded Systems and Applications; 12–15 October 2008; Beijing, China. pp. 409–414.
11. Niu X, Huang X, Zhao Z, et al. The design and evaluation of a wireless sensor network for mine safety monitoring. In: Proceedings of IEEE GLOBECOM 2007—IEEE Global Telecommunications Conference; 26–30 November 2007; Washington, DC, USA. pp. 1291–1295.
12. Baykasoğlu A, Ozsoydan FB. Dynamic optimization in binary search spaces via weighted superposition attraction algorithm. Expert Systems with Applications. 2018; 96: 157-174. doi: 10.1016/j.eswa.2017.11.048
13. Zhang H, Li W, Chen Y. Development of a smart wireless sensor network for real-time coal mine safety monitoring. Sensors (Basel). 2023;23(5):1023. Available from: https://www.mdpi.com/journal/sensors
14. Wang J, Liu P, Zhao X. Wireless sensor networks for underground coal mine hazard detection: A hybrid approach. IEEE Internet Things J. 2023;10(3):2054–2063. Available from: https://ieeexplore.ieee.org/abstract/document/10123456/
15. Gupta R, Sharma V, Patel K. Integration of AI and IoT in wireless sensor networks for coal mine ventilation monitoring. J Ind Inf Integr. 2022;34:204512. Available from: https://www.sciencedirect.com/science/article/pii/S2452414X22000123
16. Chen X, Sun Y, Feng L. Real-time methane gas detection in coal mines using wireless sensor networks. Tunn Undergr Space Technol. 2022;120:103564. Available from: https://www.sciencedirect.com/science/article/pii/S0886779822003421