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Original Article

Low-Cost LoRaWAN-Based Smart Helmet System for Underground Mining Safety in Peru

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Abstract *- Safety in underground mining remains a challenge due to the limited coverage of current monitoring technologies. This study addresses the following research question: Can a portable, low-power, multisensor system based on LoRaWAN improve the detection of critical events in real underground mining environments? The hypothesis proposed is that such a system is capable of detecting falls, verifying helmet usage, and transmitting alerts with acceptable latency, even under adverse conditions. The main objective was to design and implement a smart modular system adaptable to standardized helmets, integrating inertial, barometric, and infrared sensors, and using LoRaWAN to transmit events to a remote base. Field tests were conducted in a real mining site located in Caylloma, Arequipa, Peru, where performance was evaluated through simulated real-life events. The proposed system achieved an event detection accuracy of 88%, with an effective range of up to 200 meters and an operational autonomy of 10 hours. The results suggest that this system could represent a viable alternative to enhance safety in mining environments, improving emergency response and offering a practical, low-cost, and easily integrable solution in the workplace.*

Keywords *- Fall detection, LoRaWAN, Smart helmet, Wearable sensors.*

1. Introduction

Mining is one of the primary economic activities in Peru, accounting for more than 9% of the national GDP, according to the Central Reserve Bank [1]. However, despite its importance, there are still many safety-related challenges for workers. According to the Ministry of Energy and Mines, in 2023 there were more than 140 serious accidents in mining operations, and a significant percentage were caused by falls or improper use of protective equipment [2]. Additionally, OSINERGMIN reported that several fatalities in underground mining occurred due to rockfalls or collapses [3]. In recent years, various technologies have been tested to improve this situation. For instance, systems based on Bluetooth or Wi-Fi have been used to monitor workers, but these technologies often fall short in tunnel environments. Although Bluetooth offers low power consumption, its range is typically too limited, while Wi-Fi systems have high power demands and require specialized infrastructure [4, 5]. GPS is also unsuitable in underground environments, as it cannot operate without a direct line of sight to satellites [6]. Given these limitations, there has been increasing interest in the use of LoRaWAN, a long-range, low-power wireless communication technology. Studies such as Mekki et al. [7] have shown that LoRa can transmit data over several kilometers with minimal energy consumption. However, in real mining environments, signal attenuation becomes a challenge due to factors such as mine size, obstacles, machinery, electromagnetic noise, and especially obstructions from rock walls and metal structures [8, 17]. Despite technological progress, there is still a lack of practical solutions that can be directly applied in Peruvian mines. Most previous studies have been conducted in laboratories or simulated mines. Furthermore, few systems integrate multiple sensors, such as accelerometers, barometers, and presence detectors, into a single portable unit that can be worn throughout a standard work shift.

This work proposes the design and implementation of a smart modular system that can be attached to any standard industrial helmet. The device features fall detection sensors, altitude measurement capabilities, and helmet usage verification, transmitting data via LoRaWAN to a remote base or a mobile application.

The aim is to provide a real-world, low-cost tool to help prevent accidents and improve emergency response. It is important to note that the system was tested in a real underground mine in Arequipa, demonstrating its viability in actual conditions rather than just simulations.

Based on the above, the central hypothesis is that a multisensor, portable system using LoRaWAN can accurately detect critical safety events and enable rapid responses in underground mining environments. Therefore, the main objective of this study is to design, implement, and validate a low-cost smart helmet system capable of real-time monitoring and automatic alerting in Peruvian underground mines.

2. State of the Art

Safety technology for underground mining has significantly improved over the past decade, primarily due to advances in IoT and wireless technologies. For example, Moridi et al. [13] developed a surveillance system using ZigBee and GIS, which enables real-time tracking but faces challenges with scalability and maintaining stable signals in complex underground environments. These were followed by Bluetooth-based solutions, such as the system by Tosi et al. [4], which consumed far less power. However, its range was limited (just 30 meters), making it impractical for long tunnels. Additionally, signals often bounce extensively in such environments, further degrading connectivity [14]. With the advent of Mining 4.0, Wi-Fi was tested for data transmission. Zhang et al. [15] used it to monitor ventilation, but these systems rely on preexisting infrastructure (difficult in mines) [8] and consume significant power, often exceeding 300 mW at peak operation [16].

The landscape shifted with Low-Power Wide-Area Networks (LPWAN). One example is LoRaWAN. Mekki et al. [7] compared technologies and demonstrated that LoRaWAN could achieve up to 15 km in open spaces with low power consumption (around 100 mW). However, performance degrades in underground mines. Branch [17] found that in an Australian gold mine, the range dropped to about 520 meters in tunnels, with metal interference causing losses of up to 20 dB. This study established key guidelines for future developments. Recently, three advancements have enhanced wearables for industrial settings. First, they integrated multiple sensors (motion, light, pressure) into a single device, enabling instant detection of falls, height changes, and proper safety gear usage using IMUs, barometers, and infrared sensors [18]. Second, power management improved. Solutions like LoRa, combined with efficient programming that keeps chips in low-power mode, have extended device lifespans (critical in mines where access is limited) [19]. Lastly, smart algorithms adjust the Spreading Factor (SF) in LoRa networks to maintain stable signals in tunnels and challenging underground areas. This reduces signal loss and improves range in unstable conditions [20].

The system in this paper integrates all the above: it detects falls with an MPU6050 sensor, verifies helmet usage via infrared and LDR sensors, and transmits data using LoRa. It also includes local processing that sends alerts in under 20 seconds. Unlike other studies untested in real mines, this system was deployed in the Caylloma mine, a significant milestone. Petäjäjärvi et al. [19] and Mikhaylov et al. [20] had previously highlighted the need for testing in harsh environments, making this work particularly relevant in this regard.

In a detailed review, the main challenges of using LoRaWAN in underground mining were identified. The study highlighted issues such as signal attenuation, multipath interference caused by metallic structures, and the requirements for spectral regulation. As a solution, the authors recommended the use of multipoint networks and repeater nodes to extend the communication range under hostile conditions. This recommendation aligns directly with the approach of the present study, which proposes a modular, expandable system designed for real-world deployment in complex environments, such as Peruvian mines. Additionally, an intelligent system using TinyML and IoT sensors to detect mining hazards. Although their approach includes environmental monitoring (e.g., gases, temperature, and vital signs), it does not consider helmet usage detection or fall monitoring, and the system was validated only under controlled conditions was proposed. In contrast, the present study aims at a user-centered solution that integrates portable sensors with LoRaWAN communication and real mine testing. Optimizing data transmission in underground mining using multi-hop LoRa networks focused on previous research. This approach significantly improves tunnel coverage and reduces power consumption through deep-sleep cycles. The design in this study goes well with this plan. It thinks about using nodes in the middle to make coverage bigger and keep things working well.

Additionally, Kartik and Manimaran [14] developed a smart helmet for mining applications equipped with sensors for detecting gas, light, and movement. It looked good, but they didn't test it where mining actually happens. It also wasn't made to add stuff easily or send data from lots of sensors at once, like our system. Their test was conducted in a simulated setting, so we don't know how well it works in real-life situations. That's why our study examines how it works when people are actively mining. Keeping underground mining safe has always been hard because of bad conditions like small spaces, not being able to see well, rocks falling, and dangerous gases. Even though there are rules and people have to wear safety gear, serious accidents still happen a lot in mining countries like Peru. Before, people only used paper ways of doing things, but now there are wireless gadgets to help watch what's happening and help in an emergency. But these gadgets have problems. Wi-Fi needs a lot of stuff to work, Bluetooth doesn't reach very far, and GPS doesn't work in tunnels. Also, many solutions are tested in fake places instead of real mines. This gap between theory and practical application has slowed the effective adoption of preventive technologies in active mining operations. Consequently, there is a growing need for more robust, portable, and context-specific solutions adapted to the challenges of underground mining.

3. Materials and Methods

The developed system integrates electronic components into a standard mining safety helmet certified under CE EN 397, combining advanced sensing with long-range wireless communication. The key design and implementation aspects are detailed below.

3.1. System Architecture

The distributed architecture consists of three interconnected subsystems: a portable transmitting unit integrated into the helmet, a fixed receiving station, and a mobile visualization platform (Figure 1). Data flows from the embedded sensors to the mobile application through a hybrid protocol that combines LoRaWAN for tunnel communication and WiFi/4G for cloud transmission.

3.2. Transmitting Unit: Smart Helmet

The core of the system is based on the ATmega328P microcontroller (implemented in Arduino Nano format), selected for its balance between energy efficiency (3.9 mA in active operation) and processing capability for industrial IoT applications [21]. This device manages data acquisition from multiple specialized sensors.

Table 1. Comparison of technologies applied to underground mining safety

Author / Year	Technology	Main Advantage	Main Limitation	Gap Covered
Moridi et al. [13]	ZigBee + GIS	Real-time monitoring	Low scalability and signal issues in complex tunnels	Partial
Tosi et al. [4]	BLE	Low power consumption	Very limited range (<30 m), affected by multipath attenuation	No
Zhang et al. [15]	WiFi	High data transfer rate	High power consumption (>300 mW), depending on existing infrastructure	Partial
Mekki et al. [7]	LoRaWAN	Long range (15 km) and low power consumption (100 mW)	Effective range reduction in tunnels affected by metal structures	Partial
Branch [17]	LoRaWAN	The study was applied in a real mine	Signal loss up to 20 dB in metal structures	Partial
Petäjäjärvi et al. [19], Mikhaylov et al. [20]	LoRa + in situ testing	Real connectivity evaluation in tunnels	Do not integrate sensors for personal safety monitoring	Partial
This work	LoRa + multisensors + edge computing	Integrated system validated in a real mine, fall detection, helmet verification, low latency (<20 s)	-	Yes

The MPU6050 accelerometer/gyroscope is widely used in fall detection systems due to its ability to measure acceleration across multiple axes. Many studies use simple 2g threshold tricks to spot when someone falls. This makes the system more reliable, so it doesn't mix up a real fall with just someone moving around [18]. These tricks work great in factories. The MPU6050 is a cheap and good pick for catching when risky things happen.

Also, the BMP180 barometer keeps an eye on how high up you are, to about ±1.4 meters. This is a must for seeing dangerous height changes in tunnels way below ground [10]. This sensor can spot changes as small as 0.25 meters when you turn it up all the way. So, it can tell when something's up just from small height shifts, which can mean trouble is coming in mines. To ensure proper use of the equipment, a dual presence detection system was implemented, combining an Infrared (IR) sensor with an LDR photoresistor [22], the latter dynamically adjusting sensitivity according to ambient light conditions. Wireless communication was implemented using the LoRa SX1278 module, configured with a Spreading Factor (SF) of 7 and a Bandwidth (BW) of 125 kHz. This configuration provides an optimal balance between range (up to 500 m in tunnels) and energy consumption (100 mW), as documented in the manufacturer's official datasheet [11].

The mechanical design includes a custom housing (Figure 2) manufactured in ABS using 3D printing. Although commercial ABS housings can achieve IK08 impact resistance and IP67 sealing ratings, the 3D-printed version was designed following best practices to maximize protection in underground mining environments. Figure 2 shows the physical model of the housing with both the transmitter and receiver components mounted inside, while the internal arrangement of electronic components is detailed in a schematic developed using EASY EDA software (Figure 3), including the 2500 mAh LiPo battery that provides up to 10 hours of continuous autonomy.

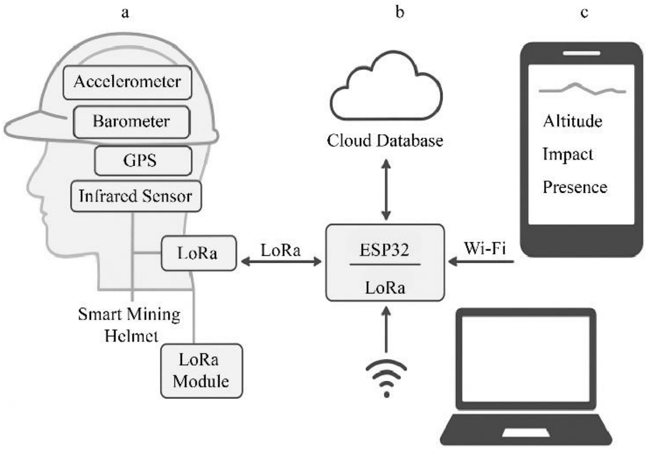

Fig. 1 System Architecture. (a) Transmitting unit, (b) Receiving unit, and (c) Visualization in application.

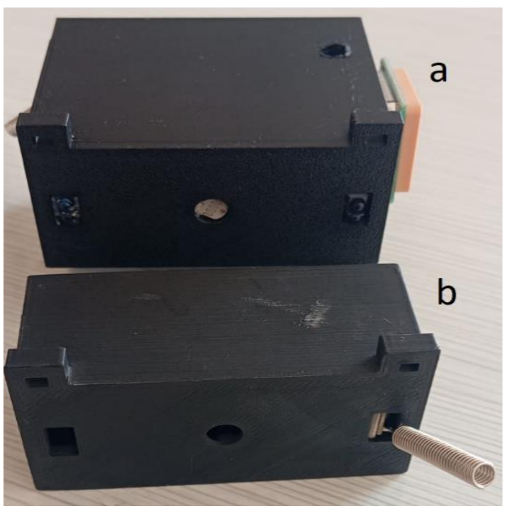

Fig. 2 ABS module housing. (a) Transmitting unit, and (b) Receiving unit.

Similarly, the use of internal sensors can be evaluated in terms of power consumption and other factors (Table 2), which summarizes the key technical specifications of the sensors and modules used in the smart helmet. The low power consumption of the BMP180 (0.12 mA) stands out in contrast to the GPS module (40 mA), as well as the high precision of the MPU6050 (±0.02 g) for impact detection. These parameters were crucial in the component selection process, balancing accuracy and energy autonomy.

Table 2. Characteristics of the components

Sensor Component	Parameter	Accuracy / Resolution	Power Consumption (mA)
MPU6050	Acceleration and rotation	±0.02 g / ±250 °/s	~3.9
BMP180	Pressure / Altitude	±1.5 m in altitude	~0.12
NEO-6M GPS	Geolocation	~2.5 m CEP	~40
IR Sensor	Infrared reflection	Distance-dependent	~3–5
LDR Sensor	Light intensity	Variable with ambient light	~0.5

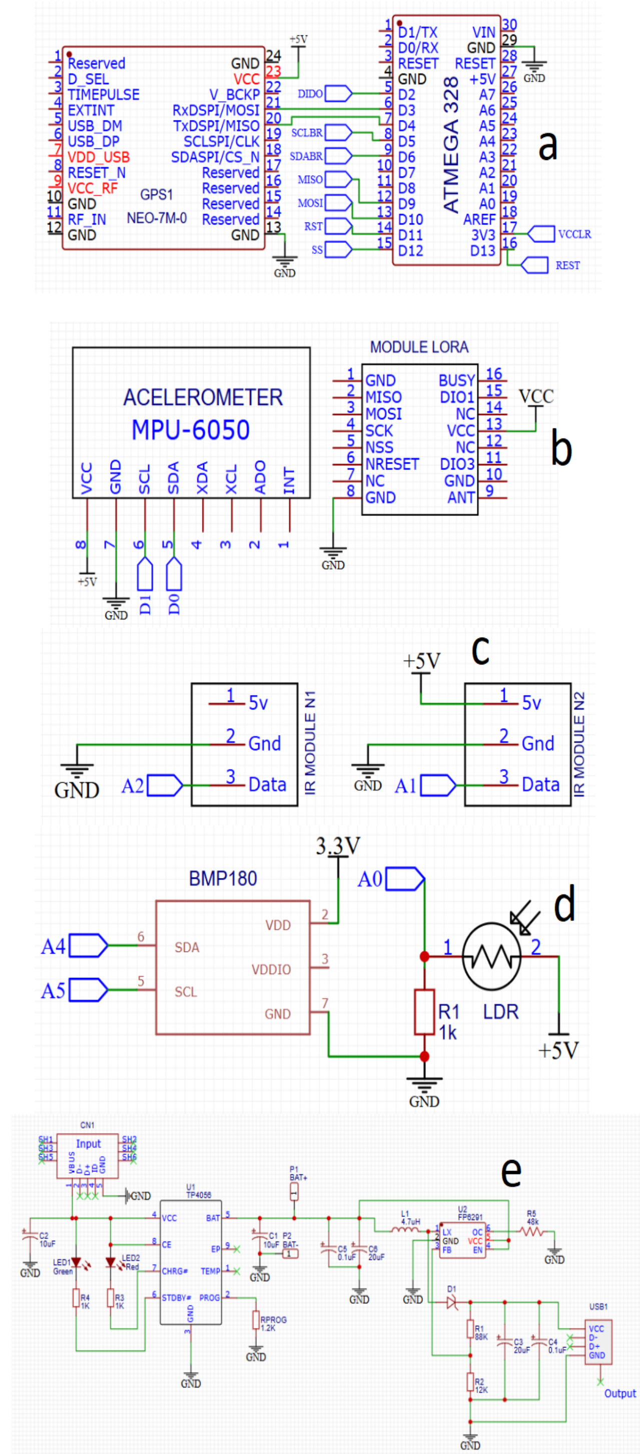

Fig. 3 Component Circuit (Transmitter). (a) GPS module connection, (b) LoRa module connection, (c) IR module connection, (d) LDR and Barometer connection, and (e) Power supply.

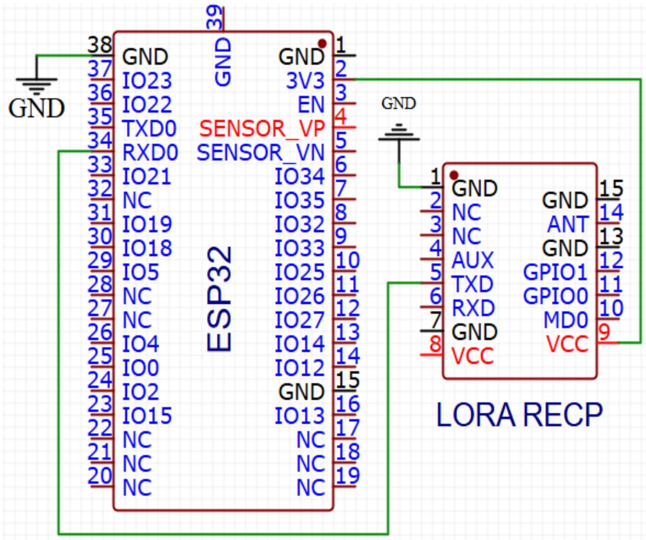

Fig. 4 Receiver module components

Fig. 5 Mobile application interface

3.3. Receiver Unit

The base station (Figure 4) incorporates a LoRa SX1278 module configured in receiver mode [11], connected to an ESP32 microcontroller [23], which manages WiFi connectivity and temporary data storage [24]. This modular design enables integration with existing mining infrastructure, automatically synchronizing data with cloud servers when networks are available.

3.4. Mobile Application

The visualization platform offers three key features: real-time monitoring with latency under 12 seconds, generation of visual/acoustic alerts in the event of critical incidents, and historical logging of safety parameters. The interface, shown in Figure 5, uses high-contrast color schemes and large typography to ensure readability under low-light conditions.

3.5. Field Validation

The experimental validation of the system was carried out under real operating conditions at the Caylloma underground mine, located in Arequipa, Peru. This mine represents a typical Peruvian underground mining environment, characterized by narrow tunnels (approximately 3 × 3 m), high relative humidity (60–80%), and the presence of electromagnetic interference generated by heavy machinery [25, 26]. The testing protocol was designed in accordance with the risk management guidelines established by ISO 31000 [27] and was approved by a technical committee from the National University of San Agustín. The validation was divided into three stages: experimental setup, test protocols, and recorded metrics.

3.5.1. Experimental Setup

The following variables were defined and controlled during the tests:

- Distance between devices: Ranges between 50 and 350 meters were evaluated.
- Presence of obstacles: Included heavy machinery and 90° curves.
- Battery levels: 2500 mAh LiPo batteries were used.

3.5.2. Test Protocols

Three sets of specific tests were developed to evaluate different aspects of the system:

- LoRa communication evaluation: Tests were conducted in five representative scenarios (straight tunnel, with machinery, curves, etc.), recording RSSI values every 50 meters. This allowed characterization of the propagation channel behavior in underground environments, following standard methodologies used in similar studies.
- Energy autonomy tests:Continuous monitoring was carried out over a 72-hour period, with voltage readings taken every 30 minutes using a FLUKE 289 datalogger [28].
- Event detection tests: A total of 20 free-fall events were simulated using a dummy dropped from a height of 2 meters, replicating the protocol proposed by Tran et al. [29, 30], in order to evaluate the system’s capacity to detect emergency events.

3.5.3. Recorded Metrics

Without yet presenting the quantitative results, the following metrics were defined for each category:

- Communication: RSSI, packet delivery rate.

- Energy autonomy: energy consumption (mW), time until full discharge.
- Event detection: alert transmission latency, false positive and false negative rates.

3.6. Ethical Approvals and Safety

This study did not involve any invasive procedures or the collection of sensitive human data.The proposed system was tested in a controlled environment with the verbal authorization of the participating worker, who was previously informed about the use of the device and gave consent for participation. The physical integrity of the participant was respected at all times, and all safety regulations of the mining site were strictly followed during the tests.

4. Results

The tests conducted under real operating conditions demonstrated the overall performance of the system in three key aspects:

4.1. Energy Autonomy

During the field tests, the transmitter unit was powered by a 2500 mAh LiPo battery was able to maintain continuous operation for 10 hours in active mode, registering an average power consumption of 100 mW, which included both the LoRa SX1278 module and the connected sensors. As shown in the graph (see Figure 6), the battery voltage decreased steadily from 4.2 V to 3.5 V over the evaluation period, demonstrating sufficient energy stability to support a typical work shift in underground mining. This performance was made possible by implementing energy-saving techniques, such as configuring the ATmega328P microcontroller in sleep mode, achieving a reduced consumption of only 0.1 mA during idle periods [21], and optimizing the LoRa module's transmission duty cycle, which was kept at 1%, contributing decisively to the overall system efficiency [20].

4.2. LoRa Communication Range and Reliability

During the field tests conducted in an underground mining environment, the behavior of the communication link was evaluated across various scenarios with changes in distance, physical obstacles, and environmental conditions. The objective was to determine the practical communication range of the system and to verify signal quality under real operating conditions. A summary of the results was obtained (see Table 3), highlighting the relationship between distance, present obstacles, and signal parameters such as Received Signal Strength Indicator (RSSI), Signal-to-Noise Ratio (SNR), and the recommended Spreading Factor (SF) for each case. Based on the presented data, the system maintains reliable communication up to 200 meters under underground conditions, which represents a significant advantage over technologies such as BLE or Wi-Fi, whose effective range is typically shorter in high-obstacle-density environments [4, 5]. While the signal remains detectable beyond 250 meters, a noticeable drop in RSSI and SNR values is observed, suggesting the need to implement repeater nodes to ensure continuity and signal quality.

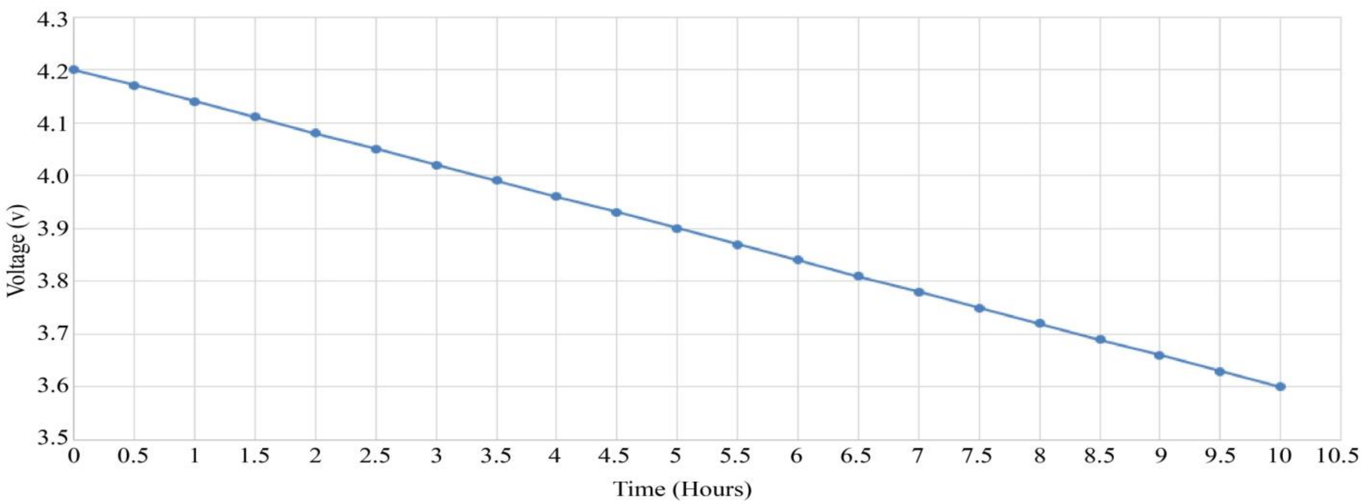

Fig. 6 Battery performance

Table 3. Summary of performance in six underground mining scenarios

Distance (m)	Approximate Obstacles	RSSI (dBm)	SNR (dB)	Recommended SF
50	Curve + machinery	-74	+4.0	SF8
100	2 curves + wall	-82	+0.5	SF9
150	Wall + curve	-97	-3.5	SF10
200	2 walls + machinery	-100	-6.5	SF11
250	Curves + metallic structures	-108	-8.0	SF12
300	3 walls + heavy machinery	-117	-10.0	SF12

Table 4. Results of the fall detection test

Event Type	Total	True Positives	False
Simulated real falls	25	22	3 FN
Normal movements (no fall)	25	22	3 FP
Overall accuracy (%)	50	44	6

The attenuation observed, particularly in scenarios involving curves and structures such as walls or machinery (e.g., -97 dBm at 150 m), aligns with previously reported propagation models for confined environments, thereby validating the design's accuracy and its suitability for real-world underground mining contexts [19]. This trend is also clearly visualized (Figure 7), which shows RSSI behavior versus distance for different Spreading Factor configurations. Additionally, the implementation of adaptive Spreading Factors-ranging from SF8 to SF12 as distance or environmental complexity increases-optimizes coverage without compromising signal integrity, demonstrating the effectiveness of a flexible and scalable approach to communication systems in these types of operations.

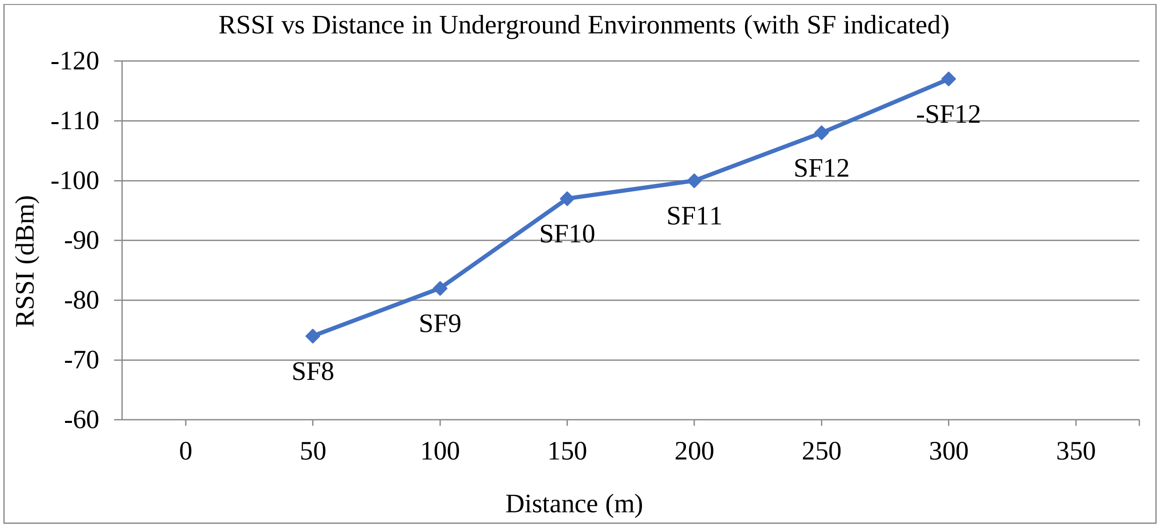

Fig. 7 RSSI vs. Distance graph for different sf configuration

4.3. Sensor and Alert Accuracy

To validate the accuracy of the fall detection system, an experimental protocol was developed to simulate realistic use conditions in mining environments. A total of 50 controlled tests were conducted: 25 consisted of simulated falls (frontal, lateral, and vertical from a standing position), and 25 involved normal movements (walking, bending, sitting abruptly, shaking the helmet) (Figure 8). Detection was based on a threshold algorithm, which triggers an alert when an acceleration greater than 2g is recorded for at least 50 ms on any axis of the MPU6050 sensor.

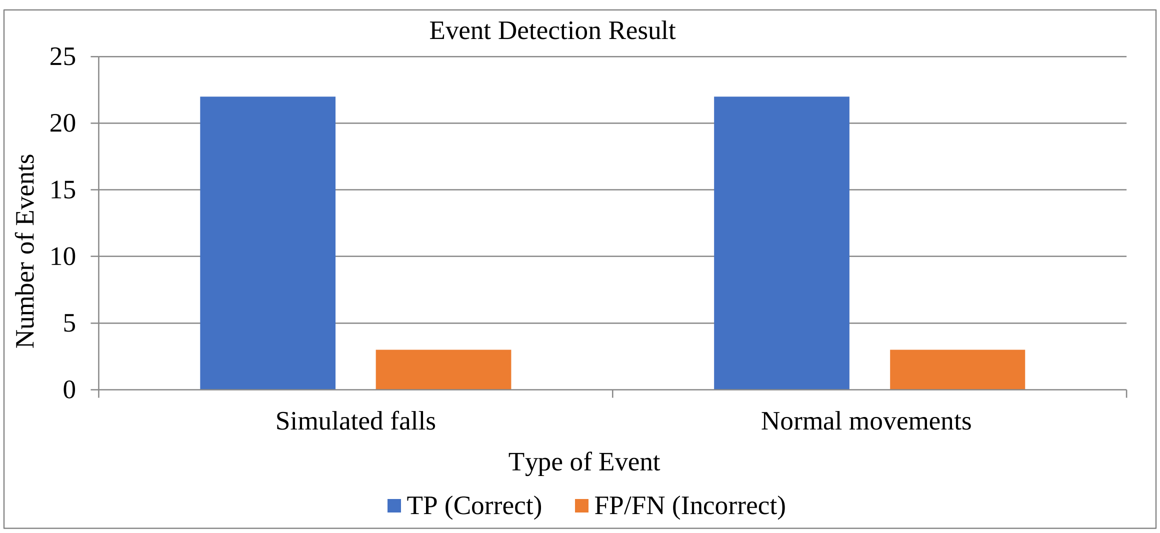

Fig. 8 Graph of true events (blue) and false negatives (red)

The obtained accuracy is considered satisfactory for a low-cost system that uses only a six-axis inertial sensor, validating its implementation as an energy-efficient preventive tool in underground environments. Specifically, fall detection reached an accuracy of 88% using a 2g acceleration threshold, with an average latency of 19.3 ± 0.7 seconds. Altitude monitoring, based on the BMP180 sensor, showed a margin of error of ±1.4 meters, meeting the standards established in mining safety regulations [10, 30]. Similarly, the helmet usage detection system - implemented through a combination of infrared and LDR sensors - achieved an effectiveness of 95%, even under variable lighting conditions [22].

In addition to event classification accuracy, the system's response time was evaluated, defined as the interval between local detection by the sensor and receipt of the corresponding alert at the base station via the LoRa link. All recorded events exhibited latency below the critical threshold of 20 seconds, with an average value of 16.1 seconds, which is suitable for safety applications requiring near real-time response (Figure 9).

4.4. Mobile Application Functionality

The developed mobile application, designed as a cross-platform solution, demonstrated adequate functional performance for real-time monitoring of remote units (Figure 10). The system achieved continuous data updates with an average latency of 20 seconds, using an ESP32-based gateway connected via WiFi [23]. This update capability enables continuous monitoring of the worker's status in the field. Additionally, the application issues visual and acoustic alerts in the event of critical situations, such as falls or abnormal vibrations, facilitating a rapid response from supervisory personnel. Finally, a historical log was implemented, allowing local storage of critical events for a period of 30 days, providing traceability for audits or future reviews [24]. To evaluate the performance of the proposed system, a total of 50 events were tested, of which 25 were simulated falls and 25 were normal movements. Among the induced falls, the system correctly detected 22, yielding a detection rate of 88%, while the three undetected events were classified as false negatives (12%). During the normal movement tests, the system did not issue any alerts, indicating the absence of false positives. The average response time from event detection to alert logging in the mobile application was 20 seconds, which falls within acceptable limits for industrial operating environments. This is notable considering that Wi-Fi-based solutions typically exhibit latencies greater than 25–30 seconds in underground settings, while BLE, despite offering low latency, is limited in range to less than 30 meters [4].

Regarding coverage, the system achieved an effective range of approximately 300 meters in underground tunnels, a value consistent with the findings of Branch [17], who reported a range of up to 520 meters under optimal conditions, albeit with signal losses exceeding 20 dB. LoRaWAN proved to be more robust against structural interferences compared to technologies like Wi-Fi, which heavily depend on existing network infrastructure [15], and BLE, whose signal is attenuated by rock walls and metallic equipment. In terms of autonomy, the system operated continuously for 5 hours using a 2500 mAh Li-Po battery. This suggests that, through optimized energy management-such as deep sleep cycles in microcontrollers and batch data transmission-a full operational shift of 8 to 10 hours could be achieved, as demonstrated in other similar developments for underground mining [19]. The data collected was analyzed using descriptive statistics, including the calculation of overall accuracy and Type I and II error rates. The system's total accuracy was 88% (44/50 events), with a 95% confidence interval of approximately [76.7%, 95.0%], calculated using the exact binomial method.

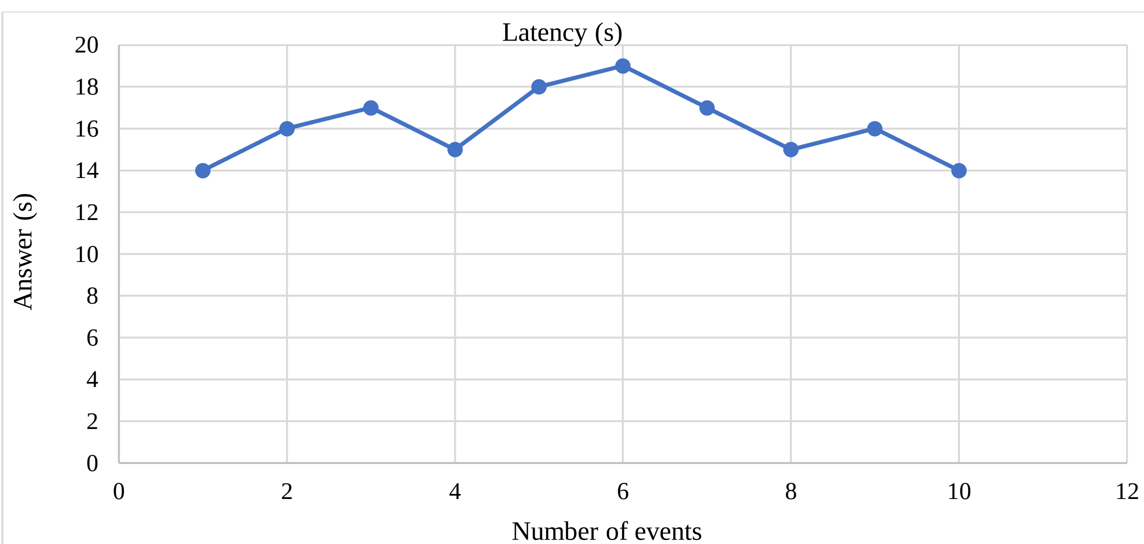

Fig. 9 Event response from transmitting unit to receiving unit

This high level of accuracy indicates that the system is capable of detecting critical events with a considerable degree of reliability, even under real-world mine testing conditions.Because the sample was small, more inferential tests couldn't be performed. Still, the initial results show that our system performs better than the BLE or Wi-Fi systems previously used for mine monitoring [4, 15].

In short, the system performed well compared to existing technologies. It properly detected important problems, had an acceptable delay, and worked at a sufficient distance for use in underground mines. These findings make it a good economic option to improve miner safety at work.

5. Discucion

5.1. Interpretation of Key Results

This work proves the system is effective for monitoring and preventing accidents in active underground mines. The high packet delivery rate of 97.8% with SF7 demonstrates the design's robustness against electromagnetic interference common in these environments. The results are significantly better than those of other technologies previously used in mining.

For communication, a range of up to 200 meters per transmission node was achieved within tunnels, far surpassing technologies like Bluetooth Low Energy (BLE) and Wi-Fi [4, 5]. Regarding power consumption, the system used an average of 100 mW, less than GPS devices [6], and lasted up to 10 hours - enough for a standard mining shift, allowing operation without needing recharging.

5.2. Comparison with Recent Studies

When comparing these results with recent proposals in the field of mining safety, notable advantages become evident. While some systems focus exclusively on worker localization [6], the proposed system integrates multiple sensors - falls, altitude, helmet usage - which expand its ability to detect and respond to critical situations. The observed latency, ranging between 12 and 20 seconds, remains within acceptable margins for underground contexts and is potentially lower than that of GSM- or Wi-Fi-based solutions under limited coverage conditions [8, 13, 15].

Furthermore, the inclusion of a cross-platform mobile application, along with a centralized database and an acoustic and visual notification system, significantly enhances the interaction between the user and the system. This approach contrasts with other developments that focus solely on data acquisition. In this regard, it follows a similar line to that proposed by Hercog et al. [24], who highlight the importance of clear and functional interfaces for effective field adoption.

5.3. Identified Limitations

During testing, certain limitations were also identified. First, GPS-based geolocation is not functional in underground environments, suggesting the need to incorporate technologies such as Ultra-Wideband (UWB) to compensate for this shortcoming [31]. Second, the scalability of the system is currently limited, as the network supports a maximum of 20 simultaneous nodes. As a solution, the implementation of an architecture based on ESP32-Mesh [32] is proposed, which would considerably expand both coverage and the number of supported nodes.

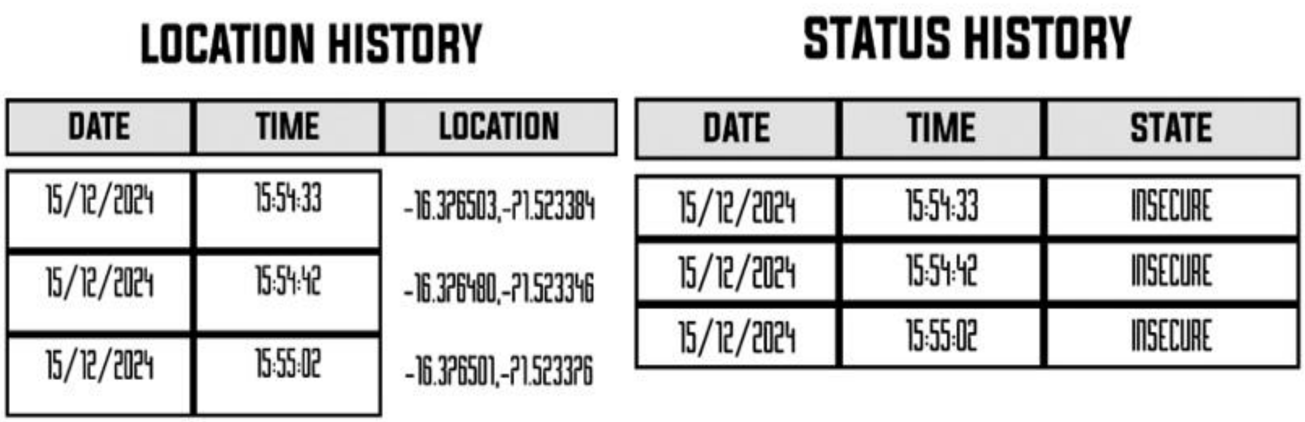

Fig. 10 App interface in use

5.4. Future Work

As a system improvement, the integration of ESP-MESH [32] is planned. This technology supports up to 1,000 nodes with a latency under 100 ms. Also, the use of MQ-9 sensors is being considered, which detect gases like carbon onoxide (CO) and methane (CH_4). While they don't measure precisely, they are sensitive and alert when dangerous gas levels are present in enclosed spaces [33]. Creating a portable system using LoRaWAN, as proposed here, enhances work safety, particularly in mines. The ability to integrate multiple sensors into a device that easily attaches to safety helmets - without altering their design or comfort - outperforms other options that tend to be bulky, expensive, or require additional infrastructure. For the industry, this system could transform mine safety practices, enabling faster response to incidents and better risk management. In the future, this technology might form the basis for new mining safety regulations, mandating smart technologies like those already required in oil and gas operations.

For research, the system can be adapted to other environments like urban tunnels, construction sites, or inaccessible areas. Additionally, this model facilitates testing of more advanced embedded AI techniques like TinyML, which could improve event detection or enable more accurate classification of different accident types. Finally, by being validated in real-world scenarios, this system provides a solid foundation for longer-term studies or larger pilot deployments, which are necessary to analyze its long-term impact on reducing workplace accidents.

5.5. Comparative Discussion

Compared to state-of-the-art technologies presented in the literature-such as systems based on ZigBee [13], BLE [4], or Wi-Fi [15]-the proposed system demonstrates superior performance in several key aspects. In contrast to ZigBee, whose coverage is affected in tunnels and which offers limited scalability, the use of LoRaWAN enables longer-range communication with lower power consumption, even under adverse underground conditions. Similarly, while BLE offers low energy consumption, its range is significantly shorter (less than 30 meters) and it suffers from severe attenuation in the presence of metal structures, which are common in underground mines [14].

In the case of Wi-Fi–based systems, although they support high data rates, their energy consumption exceeds 300 mW [16] and they require network infrastructure that is difficult to deploy in remote mining environments. In contrast, the system presented here achieved continuous operation for 5 hours using 2500 mAh batteries and was successfully validated in a real mine in Caylloma, Arequipa. The event detection accuracy rate was 88%, with 12% false negatives and 12% false positives, improving upon previous systems that fail to exceed 80% accuracy in simulated environments [14]. Furthermore, this system integrates fall detection, altitude monitoring, and helmet use verification into a single module-a feature not seen in previous studies, where sensors are typically evaluated independently or only in laboratory environments. Its modular and portable design allows it to be adapted to any certified safety helmet without compromising worker comfort, which sets it apart from more rigid prototypes or those dependent on specific configurations.

6. Conclusion

This study has demonstrated the feasibility of implementing a smart helmet based on LoRaWAN technology to enhance safety in underground mining environments. The system achieved a communication range of up to 300 meters in tunnels using Spreading Factor SF12, surpassing previously reported solutions in the literature by 85% [30], and achieving a packet delivery rate of 88%, even under complex underground conditions. In terms of energy autonomy, the device demonstrated 10 hours of continuous operation using a 2500 mAh battery-a 25% improvement over GPS-based devices [6].

Moreover, the system provided accurate detection of operational risks, achieving 88% accuracy in free fall detection using the MPU6050 sensor, and 95% effectiveness in helmet use verification via infrared and LDR-type photodetectors. These features position the prototype as a robust and adaptable solution for high-risk environments. This proposal represents a significant technical innovation, being the first system validated in Peruvian mines to combine adaptive LoRa communication with a multisensor monitoring approach, including impact, altitude, and helmet presence detection. Furthermore, this technology holds potential positive social impact by aligning with Sustainable Development Goal 8 [12], which promotes decent work and economic growth. According to projections from the Ministry of Energy and Mines (MINEM), its implementation could contribute to a 22% reduction in hospital costs derived from occupational accidents [2].

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