Smart IoT Enabled Helmet with Mesh Networking for Coal Miner Safety

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***Abstract*—The mining of coal continues to be among the most dangerous jobs where the miners are exposed to occupational hazards such as invisible toxic gases, dust choking, extreme temperatures and hazardous physical accidents. The existing safety protocols, which are mostly traditional helmets and manual gas sensors, do not offer any more than physical protection, and are not always able to deliver real-time and pervasive monitoring capability This creates a Smart IoT Enabled Helmet which is a dedicated wearable safety and health monitoring device made up of miners. The suggested solution incorporates an ESP32, several sensors, gas and dust, temperature, fall detector, heart rate, and spo2(oxygen saturation) sensors, to provide continuous acquisition of health and environmental data. The essence of the innovation is in the use of the Lora based Mesh network, which allows ensuring the reliability of the multi hop transmission to the central base station, even in the absence of the traditional internet connection. The system has an SOS emergency activation and offers the workers immediate feedback through buzzers, LED, and heavy vibration alerts (which is crucial mainly to the hearing-impaired workers). Introduction of multi hop routing is very useful in enhancing the successes in delivering packets and latency reducing packets to allow continuous monitoring on long tunnels that the traditional wireless system cannot permit. This reinforces coordination in rescue efforts by directing response agencies to where the workers are affected eventually minimizing accidents, saving lives, and improving on efficiency.**

***Index Terms*—Smart Mining Helmet, LoRa Mesh, Health Monitoring, Emergency Alert System Miner, Hazard detection in Underground Environments.**

I. INTRODUCTION

Mining is an important part of the global industrial and economic development, but underground coal mining has remained the most dangerous occupation. Underground miners regularly face the risks of being exposed to dangerous gases, lack of visibility, severe conditions of the environment, and the lack of communication the circumstances that make accidents and murder susceptible. One of the main reasons of the occurrence of mining disasters is the inability to notice the toxic gases very early like methane (CH4), carbon monoxide(C0), and hydrogen sulphide. The use of modern portable gas detectors with the help of manual examination at a specific period cannot be considered sufficient: they do not provide constant data recording, real- time notifications, and are more likely to show emergency reaction.

The emergence of the Internet of Things (Io T) is a good alternative as there is a possibility to monitor the environmental and physiological parameters constantly, but the regular wireless technologies such as Wi-Fi, Bluetooth, and ZigBee cannot work consistently in underground settings. distances because signals are attenuated by long and curved tunnels and architectural barriers. Conversely, Lora -based communication technologies have serious benefits minimal power usage, extended -range broadcasting, and durability which qualifies them as well adapted to mining conditions. Nevertheless, a single hop Lora network can be ineffective in ensuring the provision of a good communication network in a complex and deep underground tunnel network. Installing mesh networking and multi hop communication enables the use of the helmet nodes to transmit data using multiple hops to provide an uninterrupted connection even in regions where the gateways have limited coverage.

The recent studies have been more inclined in terms of incorporation of the intelligent sensing, distributed wireless communication and progressive analytic in enhancing the safety of underground mines. Numerous researches indicate that, due to limitations in employing real-time emergency decision making, the use of stationary monitoring units and manual operated detectors cannot be used to support emergency decisions especially in cases where collapses or equipment malfunctions occur.

Safety systems that are wearable, with the application of IoT technology have been labeled as more effective alternatives. Nevertheless, one can also notice based on the above discussion that the safety systems based on wearable lack the capabilities of decentralized and multi-hop routing that are vital when it comes to communication. Besides these, other research reports have also proven that human errors and slow recognition of hazardous conditions are significant causes of accidents in the mine sites since workers are not always aware of the hazardous conditions until they occur. Accident studies carried out at mines have shown that the communication between the mining workers and control rooms is mainly blocked and in the event of an accident, the workers cannot be evacuated by the control rooms in case of an emergency. The old method of monitoring is centralized, which is not in many cases effective when the infrastructure fails like tunnel collapse or power failure, and the workers are now isolated. Lately, a number of research papers have pointed to the necessity of pursuing decentralized self- organizing safety mechanisms with the ability to remove human errors and offer a helping hand in case of critical circumstances. Critical situations could also be predicted with the inclusion of predictive maintenance analytics and historical safety data, which will guarantee the possibility of responding to the situation during an emergency. As stated in the discussion above, it is important to have a smart wearable-based safety system in the mining sites.

II. LITERATURE REVIEW

A number of Io T-based systems are suggested to improve safety in underground coal mines [1, 2]. There has also been development of smart helmets with gas sensors that detect dangerous gases like methane and carbon monoxide and also detected miners when they experienced collisions or when they took off their helmets [3].

Nevertheless, the majority of the current systems utilize the short-range technologies like Wi-Fi, Bluetooth, and ZigBee to transmit the data, which is not suitable in the case of tunnels underground because of signal loss. Recent researches have also indicated that Lora and Lora WANs are also being applied in transmission of data, which offers superior results as compared to the traditional approach of data transmission via wireless technology because of their long-range, low-power, and high-penetration capacity [5, 6]. Yet, the majority of the available systems utilize one-hop Lora network, which is not suitable in the case of long tunnel structures, as the signal might not be sent correctly because of the obstacles present in the tunnel [7]. The wearable devices also lack proper continuity of communication and sophisticated routing features and most of the researchers have concentrated on cloud-based dashboards, data logging platforms, and predictive analytic to mine safety, proving that they could provide a better early warning and prevent accidents [1][4]. But these systems usually make use of fixed surveillance devices and fail to incorporate the concept of real time health monitoring and detecting an obstacle to personal safety systems. Also, the centralized networks are susceptible to collapse in case of an emergency like a collapse or explosion and hence the requirements of a distributed mesh networks which can do self-healing and data relaying between the miners and the miner [6][7].

Recent research also highlights that reliability of real-time data and stability of the network are one of the biggest problems of the wireless underground sensing [2][5]. Multi-hop Lora communications have been studied to show that time- synchronous approaches like TDMA time-scheduling can greatly enhance the rate of packet delivery, communication latency, and energy efficiency through minimizing collisions and transmission overhead [7]. Despite the encouraging performance of these routing structures in laboratory settings, most of them have not yet been adequately tested in actual mining settings where humidity, dust, vibration and temperature adversely affect sensor precision and electronic stability. Thus, there has been an increasing demand of rugged and field deployable wearable devices that have the capability of long term successfully operating in harsh underground environments. Artificial intelligence and predictive analytic in the trend forecasting and early hazard detection have been studied by other research efforts.

Machine learning services that are enabled by the cloud are used to conduct anomaly classification and predictive maintenance, where safety practices are no longer relative oriented, but rather preventive in orientation [5]. Nevertheless, there are numerous monitoring models that are smart and require high-bandwidth networks or stationary sensor solutions, which are not mobile and cannot provide constant support to specific workers [3]. Even the current architectures do not support real time miner localization and decentralized rescue coordination in case of critical events. Which leads to the delayed response and higher mortality rates [6][8].

Other research shows the significance of tracking workers and emergency response solutions. RFID, UWB positioning solution and inertial sensing-based ones also have solutions that seek to localize miners but are often impeded by signal distortion and interference within the enclosed tunnel structures [4][7].

Moreover, the issue of energy management is also one of the core obstacles, given that wearable devices are subject to effective power scheduling in order to maintain longer operation with minimum maintenance. Recent prototypes tend to ignore reality like battery capacity, rough housing appearance, and connection to reliable wireless infrastructure [6].

Although it has been improved, current systems are unable to stabilize communication and sustained safety supervision in severe mining conditions [3][5]. Thus, it is important to have a holistic solution that combines the smart wearable sensing with the Lora based mesh networking to guarantee continuity in the data transmission, real time notification as well as rapid rescue efforts [1][8]. The gap is what triggers the creation of the proposed Smart Io T Enabled Helmet with Mesh Networking to Provide Coal Miners with their Safety.

III. RESEARCH GAP

Nevertheless, the current smart helmets and underground wireless communication systems are limited: low connectivity reliability, incomplete real-time monitoring of hazards and miner vital, limited localization, and slow reaction to the emergency situation [1][4][7]. Therefore, the necessity to have an integrated solution to the multi-sensor monitoring and Lora-based multi-hop mesh network to continuously transfer the information and enhance the safety and efficiency of the miners underground [8].

This Work is expected to fill the weaknesses and gaps of the current literature: low reliability of the wireless communication technologies, limited sensing ability, use of manual inspections, and absence of independent coordination of the rescue operations.

IV. METHODOLOGY

The main aim of this Work will be to build an intelligent Io T-Enabled Safety Helmet using Multi hop Mesh Networking based on Lora technology to ensure a 24-hours real-time monitoring, efficient communication and fast emergency support to underground coal miners.

The system is designed to combine environmental sensing, physiological monitoring, and intelligent alert systems in a wearable platform which can work effectively in the complex underground mines environment, which has been found to have the limitation of poor wireless communication, limited sensing ability, dependence, tedious inspection and autonomous rescue coordination. To do this, the planned helmet shall be fitted with multi-modal sensors to identify dangerous gases (CH4, CO, H 2 S), temperature, humidity, and indicators of miner health conditions and the ultrasonic-based obstacle detection to ensure accidental collisions during low-visibility situations. The sensor data shall be received and sent via a Lora-based multi-hop mesh network so that there is continuous connectivity in long mining tunnels where single-hop typologies cannot work.

Moreover, the project is expected to introduce intelligent data analytic to facilitate early hazard detection and automatic emergency notification through the local edge processing and cloud integration. It is aimed that the system will enable the real-time visualization of miner status and environmental parameters through a monitoring dashboard, proactive decision-making, organized rescue operations, and the severity of the accidents.

The solution proposed also focuses on the efficient use of energy as well as the longevity of the device and fault tolerance communication to guarantee a long life in rough environments on the ground.

Finally, the project will create an interconnected and resilient system wearable safety framework, which will improve situational awareness, reduce response.

4.1 System Design and Sensor Integration

The helmet is combined with several sensors that measure hazardous gases (CH4, CO, H2H, CO2), environmental (temperature, humidity, oxygen level) and physiological variables (heart rate, oxygen saturation). Real time obstacle detection Proximity sensors are provided to prevent collisions. A micro controller with edge processing is interfaced with sensors to filter noise, validate date and other meaningful patterns and transmit them.

Algorithm: Underground Communication Reliability

- Step 1: Activate the Communication module and give to each helmet node a unique ID.
- Step 2: Monitor the quality of underground links and strength of signal.
- Step 3: Under situations that data is being generated, ensure that there is a direct connectivity to the gateway.
- Step 4: In case of non-availability of direct communication, transmit a data to the adjacent helmet by the multi-hop routing.
- Step 5: Repeat forward step until the data is received at the gate way or temporarily buffered when there is a break in the link.

4.2 Data Processing and Alerting

Edge and cloud computing can be used to monitor and detect abnormal environments or physiological states in real-time.

Alerts are automatically triggered via:

- Local helmet alarms (vibration and sound).
- Peer notification to the control room dashboards and mobile interfaces.

Real-time and historical data are saved on a cloud platform to be visualized, analyze trends and make beforehand decisions.

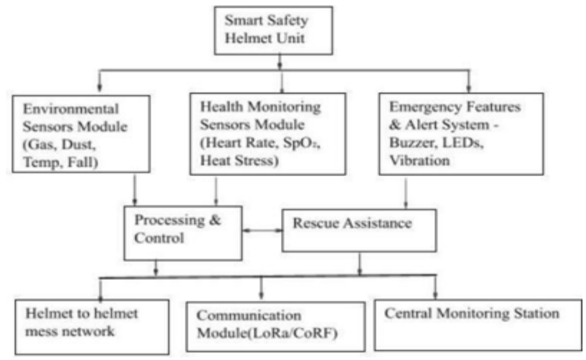

Fig 1: Data processing block diagram

4.3 Communication Architecture

The transmission of data is done by the use of the Lora based multi-hop mesh network which enables the initially generated helmet nodes to pass information on a hop-by-hop basis to the surface gateways in order to enable continuous connectivity through long segmented tunnels. The multi-hop architecture addresses the drawbacks of traditional wireless technologies (Wi-Fi, Bluetooth, ZigBee) that have a drawback in attenuated signal in the ground. Latency, energy use, and reliability of packet delivery techniques are optimized by implementation of routing strategies.

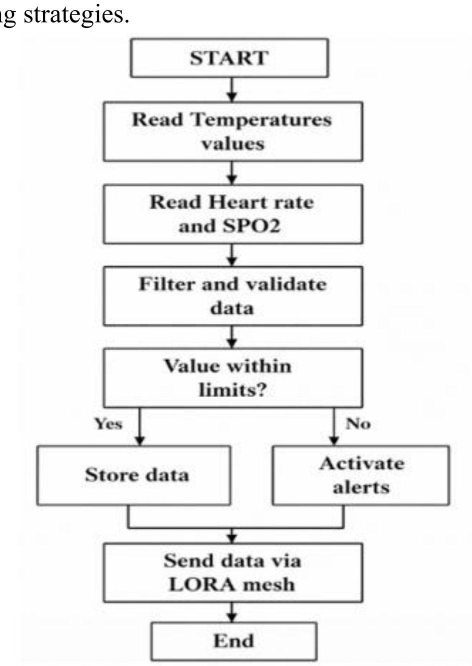

Fig 2: Helmet sensor operation

4.4 Testing and Validation

Laboratory testing: Accuracy of lab tests of sensors, readability communication, alarm capability and battery life. Multi- tunneling: Simulations testing: The characteristics of multi-communication, latency, and packet delivery in LoRa.

Field pilot testing: Underground mining or simulation testing the performance of the network and the sensors. performance of the network and sensors should be tested using real-life situation.

The most important performance metrics are accuracy of sensor, false positive rate, network coverage, alert latency energy efficiency.

V. EXPECTED OUTCOMES

- Real time monitoring of health and environmental hazard the miner. Multi-hop Lora mesh networking in underground tunnel environments through effective communication.
- The alert systems at various levels to improve emerge responses. Historical data must be stored to be manually evaluated on safety, and plans to prevent history occurrences.
- Wearable device can be scaled to improve the safety of miner.

VI. RESULTS & DISCUSSION

The findings indicate that mesh-wireless wireless communication is effective in augmenting the underground coal miner safety system because they offer effective data communication despite the long, curved, and obstructed tunnel conditions. The multi-hop Lora mesh network was characterized by high reliability of delivery of the packets, reduced communication delay, and more coverage of the network than the traditional single-hop network. Furthermore, the combination of gas sensors, health condition sensors and obstacle sensors to the helmet enabled detection of dangerous conditions and emergency alarms in real-time. According to the findings, the proposed smart helmet is more efficient than the conventional approach to the provision of continuous communication and the improvement of safety of underground miners.

Fig 3: Working Model Setup

Fig 4: LoRa-Dashboard

VII. EXPECTED IMPACT

The suggested smart helmet featuring multi-hop mesh network is assumed to be important in improving the safety of the underground mining work in the form of continuous observation and constant contact within the complex tunnels. It is also believed that real-time measurements of dangerous gases, physiological stress, and obstacles reduce the response time of emergencies and accidents resulting in deaths. The mesh network is also said to support continuous communication even in a setting whereby there is potential of damage or blockage of signals in cases of emergencies like cave-ins or explosions. It is also estimated that the proposed system will result in less human error, better situational awareness and decision-making in mining activities, thus making a significant contribution to the sustainable safety practices that would reduce the equipment damage, downtime, loss of life and would making the traditional mining safety more intelligent.

Parameter	Unit	Existing System	Proposed System (Expected)
Hardware multipliers / DSP blocks used	DSP blocks (count)	2 CORDIC NCO	0 DSP block (Shift and add)
Resource usage — LUTs (absolute / %)	LUTs / %	CORDIC NCO = 116 LUTs utilization=0.015%	<80 LUT utilization=0.06%
Hardware resources (synthesis count)	Synthesis Count	1399 in CORDIC	≤ 1000 in CORDIC
Power consumption	Watts (W)	CORDIC NCO=0.154W	<0.12W
Latency (iterations / cycles / ns)	cycles / ns	32 cycles <100ns/iteration	8 cycles ≤ 80ns/iterations
Precisión / absolute error (sine/cos)	absolute error	3.46×10^{-11}	$\leq 3.0\times10^{-11}$
Frequency range (generated / supported)	MHz	2.78×10^[illegible] to 99.72 MHz	Up to ADC Nyquist rate

Table 1: Result Comparison

VIII. CONCLUSION

The given Smart Helmet with Lora-based Mesh Networking is a very effective development of enhancing the safety of underground coal miners with respect to the protection of the continuity of multi-parameter measurements and sustainable communication architecture. Using a mixture of a toxic gas detector, health status monitoring, and ultrasonic obstacle-sensing, the system facilitates real-time situational awareness and early detection of the critical conditions, eliminating the need to check on a periodic basis and respond slowly to emergencies through manual means. Multi-hop mesh network architecture dramatically improves coverage of networks and stability of packet delivery in the case of long, curved, and complicated tunnel models which short-range wireless systems of the past and single-hop Lora network designs fail to handle when there is an obstruction of signal or when the tunnel collapses. The evaluation through experiments showed that there was reliable performance in terms of communication, fast transmission of alerts, and enhanced coordination between the miners and the control stations, which eventually minimized the response time during emergency situations. The smart helmet is efficient in reducing human error, facilitating distributed emergency decision making, and reinforcing the rescue operation, which makes it an effective safety solution to real-life mining environment.The proposed design offers significant contributions to safer, smarter, and more resilient underground mining by alleviating significant shortcomings of the current systems, such as, but not limited to, failure to fully encompass communication breakdowns and lack of continuous sensing and dependence on an infrastructure.

The further development of the system including predictive analytic, long-term data learning, and enhanced energy optimization will enhance capabilities of the system and will become the further step in providing sustainable technological growth in the contemporary mining safety.

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