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Opportunities and Challenges in Health Sensing for Extreme Industrial Environment: Perspectives From Underground Mines

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ABSTRACT Occupational health and safety hazards in the extreme work environment of underground mines remained a serious concern for both mine management and regulatory agency. Miners are often employed to perform different mining activities across the mine and are always exposed to health risks such as lung cancer. With the technology advancements, it is now possible to keep track of mine individuals and their health parameters. The current practice of health analysis is periodic in nature and is highly dependent on voluntary participation. Wearable health sensing system is an alternative solution to overcome these challenges and is able to provide insights on miners' health conditions. Timely analysis of physiological parameters of the miners is immensely helpful to minimize the injuries and can also provide preventive measures for potential health hazards. In this paper, we propose a wireless health monitoring system, especially for underground mines. The contributions of this paper are twofold. First, it presents and discusses our proposed system architecture and solution followed by challenges of such system in the context of underground mines. Second, as a preliminary analysis, detailed discussion on the wireless link behavior for reliable data transmission and communication are presented. We performed real-world experimental measurements in an operational underground coal mine considering several deployment settings in straight, near face and curved mine galleries. The communication metrics (e.g., received signal strength and packet reception rate) are extensively evaluated.

INDEX TERMS Health sensing, activity monitoring, underground mines, occupational health hazards, communication, data analytics, wearables in mines, artificial intelligence, miners.

I. INTRODUCTION

Mining industry being the key role player in the economic growth of a nation poses several challenges to carry out production activities. In general, there are two types of mines globally: open pit and underground mines. Though the technology advancements in open pit mines have been witnessed over the past decade, underground mines are still struggling to update its work area with latest technology inventions, e.g., reliable wireless communication infrastructures, remote operation of mine vehicles and quick rescue of trapped miners [1].

Underground mines are extensive labyrinths spanning over several kilometers and have narrower workspace (e.g., a few in meters) interconnecting different working zones. In a particular shift of operation, several miners are involved in different mining operation tasks including drilling, roof support maintenance task, transportation of extracted ores, inspections of different mine working areas, and blasting. Moreover, the underground mines have been considered as high stress work environments due to their unique features such as high humidity, temperature, hazardous gas concentration, dust, noise, and poor visibility. These challenges make the underground environment extreme for working compared to normal industry environments [2].

The safety and health of miners are the top priority in the mining industry. Miners' physical health and mental health

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are significantly affected by the unique and challenging mining environments. According to a recent report, 5,190 people died in a single year in the USA as a result of fatal injuries, and almost 2.8 million workers suffered from non-fatal injuries. It is also emphasized in the report that the workers in many cases (more than 800,000) had to take an off from work with an average of eight working days per year [3]. The facts and figures of occupational health and safety hazards indicate the scale of the problem in different industrial work environments. In the context of the underground mines, working in hazardous environments is a part of miners life and their safety and health remained a serious concern for the mine management.

In literature, several data collection and health related programs are funded to improve health and safety for underground miners across United States (US) [4]. However, the nature of data collection method is generally periodic and limited to geographic distribution. Though there are different safety and health guidelines followed in underground mines including comprehensive periodic training on health, safety and emergency preparedness, several injuries and other accidents still happen at the workplace. Considerable research efforts are demanded to minimize safety and health risks. These efforts will not only improve the quality of life of miners, but also enhance the productivity of operations as an injury/accident hampers the production activities as well.

In the past, many researchers have used IEEE 802.15.4 for health monitoring tasks. Recently Koren and Šimunić [5] discussed the ZigBee based body area network for health monitoring in the smart home application category. However, the study is limited to the simulation environment. Schalk Wilhelm and Reza [6] carried out a survey on context-aware sensing using wearable devices. The study touched some discussion about the use of such technology in underground mines and possible issues in deployment. However, the study lacks to propose any networking architecture and insights from either wireless signal characteristic in underground mines or overall system functionality. Motivated from the problem scale of miners' health, Adjiski *et al.* [7] in their recent work discussed the role of wearable technology for the mining environment. A theoretical prototype embedded with sensors is proposed which can be further integrated to personal protective equipment (PPE) including clothing, hats, and glasses. Nevertheless, the study is only limited to the discussion of the functionality of sensors, and does not discuss challenges of wearable technology in the mining workplace and any theoretical/experimental results.

Motivated from this pressing need of the technology advancements and well-being of the miners in underground mines, we will focus on the feasibility of integrated health sensing and prediction of future health hazards among miners. In addition, we also aim to exploit the sensed health data in continuous location tracking of underground miners.

Therefore, our approach not only addresses the health sensing of miners working underground, but is also capable to estimate the location of miners in a real-time fashion. The main motivation of such a promising approach is to reduce the installation and maintenance cost of independent localization and tracking solution for the mining industry while offering other future benefits to the mine management.

Contributions: Motivated from the exciting offers of wearable health sensing system and its scope in underground mines, our major contributions in this paper are summarized as follows:

- We proposed a wireless health and activity monitoring architecture particularly for underground mines.
- Based on the health monitoring solution, we further exploit this in zone based location tracking of miners working underground.
- Different associated challenges for wearable health sensing system in the context of underground mines are discussed in detail.
- Building upon the above proposed solution, detailed preliminary experimental results of wireless communication link behavior are presented. The measurements are performed in real-time operational underground coal mines. These experimental results will help to identify the access point deployment locations and future communication protocol development.

The rest of the paper is organized as follows. In Section II, we briefly present the state-of-the-art in health sensing considering industrial environments. We further discuss the problem statement of occupational health and safety hazards of mine personnel, followed by the solution approach in Section III. We then discuss in detail the associated challenges of such solution in Section IV. Considering one of the major challenges of such a system in underground mines, a preliminary analysis is presented in Section V. A future research direction on health sensing is also discussed in Section VI. The concluding remarks are presented in Section VII.

II. RELATED WORK

Smart computing techniques such as wearable devices at workplaces which could be utilized to monitor the physiological parameters and safety of the individual are recently introduced by the research community and industry management. Such technology is a representative of advancements in sensor and computing paradigm and has been popularly utilized in personal health monitoring and activity tracking. Moreover, recent research efforts are made to perform studies related to wearables at workplace and industry environment. The main motivation for such technology update at workplace is to avoid the occupational health risks and improve production.

Milenkovic *et al.* [8] performed a comprehensive study on wireless sensor networks based personal health monitoring. Different associated issues and implementation of wireless sensor networks for health monitoring are discussed considering on-chip signal propagation, power management, and time synchronization among nodes in the network.

Hamdan *et al.* [9] in their work focused on the mitigation of the interference and its impact on IEEE 802.15.4 health sensors due to other devices operating in the same frequency range i.e. 2.4 GHz. Furthermore, they considered different algorithms to maximize the network throughput of wireless health sensors and energy efficiency. Chandra *et al.* [10] also carried out a study on wireless cardiovascular monitoring and proposed biomedical sensor nodes. They further analyzed the proposed system in a floor area considering packet reception rate and network latency. It is reported that the proposed system outperforms the present wireless sensor networks based solution for cardiovascular monitoring.

Alam *et al.* [11] focused on the platform design of an advanced wearable system for personal supervision and maintenance tasks at workplace. They further discussed about the integration of such personal wireless wearable system with the existing infrastructure to improve the maintenance task and safety. However, the work was limited to the conceptual system architecture and hardware design.

To understand the association of occupational lifting and day to day activity on workers of supermarkets and its impact on the low-back pain (LBP) intensity, Andersen *et al.* [12] recently performed a detailed study. The method of experiment includes the response from the workers over three consecutive weeks and data base maintained by the company. It is reported that the LBP intensity is more in the morning after work compared to the non-working day. Nevertheless, it is mentioned that to understand the future consequences of this pain intensity on the workers, more data have to be collected and analyzed properly. A detailed systematic review on the association of long working hours and health can also be found in [13].

In another effort by the researchers Baka and Uzunoglu [14], a wearable device is proposed to save the workers from the step voltage hazards, a common occupational health hazard for the electricians. Further, it is discussed that such system can be utilized in any field where the step voltage hazard is common and frequent. Chu *et al.* [15] performed experimental studies to find the scope of wearable robots in shipbuilding environment for the workers. The main motivation of such study is to reduce the work load and help the workers to lift heavy weight objects from one place to other. Several shipbuilding environments are considered for the analysis such as bumpy, steep and narrow staircase, and longitudinal stiffner. For each environment, utilization of such techniques have been also discussed.

Kritzler *et al.* [16] discussed the use of personal protective equipment at the workplace and how such technology can improve work safety and improved productivity goals in the industrial environment. Furthermore, the proposed device solution is evaluated through domain experts and interview conducted with the workers, while the deployment and testing of such a solution in real-environment remained as future work.

Though recent research directions of the wearable health sensing and monitoring in industrial environment discusses promising benefits to both workers and management [17]–[20], detailed analysis of such infrastructure such as in depth performance analysis, real-time data analytics, novel algorithm designs, data privacy and security, prediction of health hazards, and future integration of such solution at *large scale* is still in progression phase. Moreover, most of the prior work is either limited to a wireless body area network (WBAN), point-to-point solutions, or in the context of a smart home. Considering the scope of such a system in working environments of underground mines, research efforts are needed to develop a unique solution considering mining features.

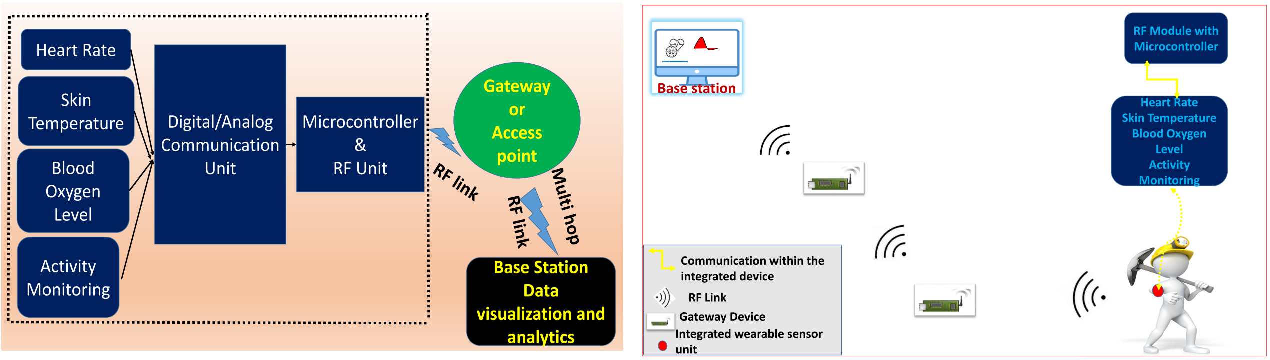
In this paper, we propose a solution to monitor the health condition of miners which could be also used to predict the future health and safety hazards for miners. Though the main objective of the wearable health device is to monitor miners' health condition, we also aim to exploit the health data of the miners working underground to predict and estimate their location as well. In the following sections, we discuss our proposed solution and findings.

III. PROBLEM STATEMENT AND PROPOSED SOLUTION

Independent surveys and training activities have been performed by different organizations across the world to understand the occupational health disease in mining industries. However, exact statistics and reasons for diseases (e.g., coal workers' pneumoconiosis and cancer) are difficult to estimate and follow up. The main reason to this gap is due to the fact that these diseases develop over time and are highly dependent on factors such as exposure to the coal mine dust and working location of the miners. In addition, it is also possible that the miners, when diagnosed with cancer or pneumoconiosis may have left the mining occupation. Hence this makes it difficult to understand the actual behavior of the disease. According to a report, 6000 coal miners die every year as an occupational health disease in China only, and it is estimated that 600,000 miners suffer from lung cancer and diseases [21]. Also, it is discussed in the report that such diseases remain a concern for the U.S. based miners as well. In fact, it was highlighted that the rate of coal workers' pneumoconiosis is increasing in the U.S. mines.

While medical treatment efforts have been made and are going on to cure lung disease of miners, a preventive approach to reduce health risks is equally important. One promising approach is to timely sense miners' health conditions and factors leading to such life threatening diseases. A timely and daily based health monitoring is significant to improve the quality of life of miners. Moreover, due to the advancements in wearable health sensing technology, it is now feasible to estimate the roots causing adverse health conditions.

Though the National Institute for Occupational Safety and Health (NIOSH) in the U.S. and mine management engage miners through health related surveys and programs, the participation is totally voluntary. Hence, such training and survey may not help to understand the health and safety issues among miners at large-scale across the mines. To address



(a) Block diagram of integrated system

(b) Health monitoring architecture

FIGURE 1. Integrated health monitoring system deployed in underground mines.

this challenge, a wearable health sensing infrastructure could be significantly useful for both the mine management and regulatory body to adopt the preventive measures for the miners in a timely fashion.

From a mine management perspective, if the miners in a particular shift feel uncomfortable due to the extreme work environment such as high humidity/temperature/dust, and take an off from work for several hours, this will negatively affect mining production. Considering the untimely detection of health hazards, it is possible that several hours may be converted to days or months. To these serious issues, a preventive health monitoring infrastructure is significantly useful for the management to achieve the objectives of a healthy working environment and improved productivity per shift of operations. In addition, the wireless health monitoring infrastructure deployed underground can also be beneficial to formulate the different relationship between working areas and type of work assigned and their roles on health conditions of miners using advanced data analytics algorithms.

SOLUTION APPROACH

In this subsection, we present and discuss our proposed solution to monitor the health condition of miners which can be also used to keep track of miners' location.

1) HEALTH MONITORING OF MINERS WORKING UNDERGROUND

To achieve this, we aim to customize an integrated wearable device equipped with different sensors to record biomarkers such as skin temperature, blood oxygen level, heart rate, and fall detection. The motivation of customized design approach of the health sensors is to provide a wearable unit to the miners without any discomfort to their normal routine operations and share the data among other miners and to the gateway node/base station. Therefore, this system is immensely helpful to improve the unforeseen circumstances to avoid any mishaps at workplace. We for our health monitoring purpose have used pulse sensor to sense the heart rate, particularly Maxim's MAX30101. It is an integrated sensor module capable of pulse oximetry and heart rate monitoring and consists of internal LEDs, photodetectors, optical elements, and low-noise electronics with a feature of ambient light rejection. Detailed features and other specifications can be seen in reference [22]. For temperature and humidity measurements in underground mine workings, HTU21D by TE connectivity is used [23]. A block diagram of the integrated wearable unit is shown in Fig. 1(a).

Different sensors will sense the physiological parameters of the miners and then communicate this to the in-built microcomputer unit. Then the health data are sent over a wireless communication module in-built within the integrated wireless wearable device. The sensed data are eventually expected to transmit to the command centre or central base station for data analysis and visualization on a human machine interface. Since the wireless communication channel underground is different than those of terrestrial wireless communication network, the sensed data have to relay via multiple gateways or access points (AP) over a multi-hop wireless communication topology, which is referred to as routing. The proposed health monitoring architecture follows ZigBee protocol [24] for data transmission from AP to the base station. However, in the near future, we would also like to examine the feasibility of LoRa technology [25] for such system architecture. The proposed sensing system is illustrated in Fig. 1(b).

Once the data are sent at the base station, the sensed data could be utilized to monitor the health condition of miners on a daily basis as well as to keep the health history of individual miners. Hence, the proposed system addresses the problem of periodic and manual data collection of health parameters among miners, a process which is tedious and unreliable to provide timely medical assistance to the miner. At the base station, we intend to use different intelligent algorithms to establish the relationship of health data with the miners activity, the impact of work type and location. The main motivation of this analysis is to identify and group different factors which may cause a health concern among the miners. Based on the data analytics, it is expected to formulate healthy guidelines for the miners working in different underground mine locations. Hence, the mine management can efficiently

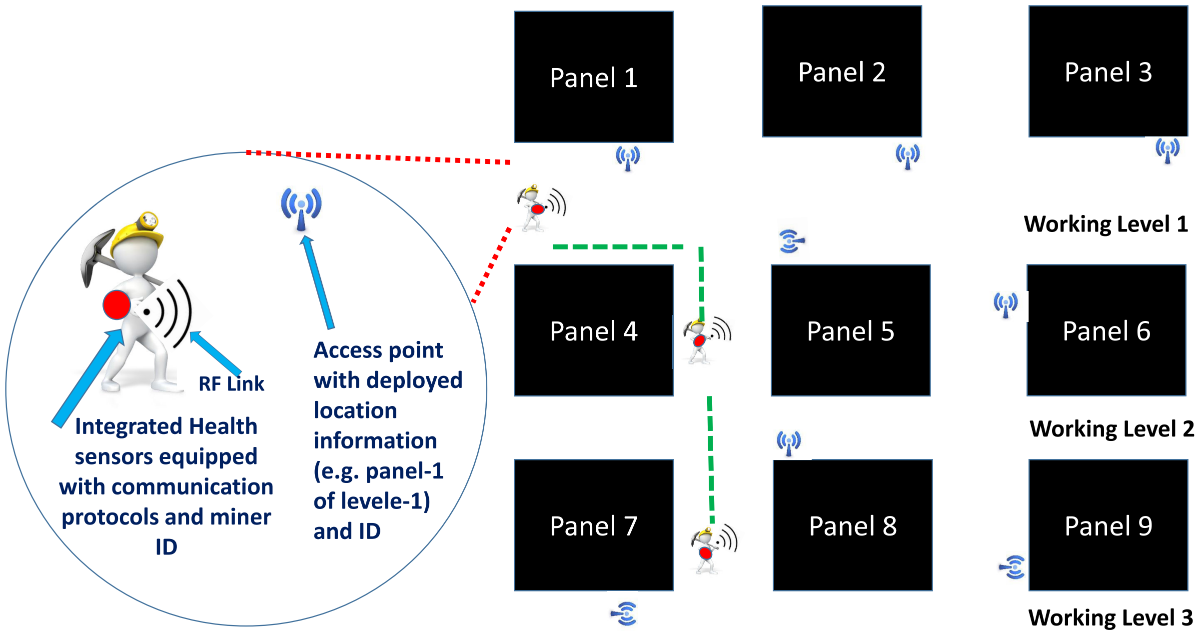


FIGURE 2. A conceptual view of localization of miners based on the health data.

utilize the human resource and may categorize the potential health risks area within the work locations to take preventive measures.

2) LOCALIZATION BASED ON THE SENSED HEALTH DATA

Underground mines are always prone to accidents such as roof fall, gas explosion, mine fire, sudden undulation, etc. Hence, the miners working underground are always exposed to risks. In case of any mine accident, the miners may get trapped underground. To provide a timely rescue and recovery operation, it is essential to know the information as priori about the miners' location or the last communication point to the base station. Such information is crucial to the mine management and rescuer team. Therefore, continuous localization of miners working underground remained a significant concern for the mining industry and among researchers. As discussed in the above sub-section, we intend to exploit sensed health data for our localization task. The proposed solution will be helpful to keep track of miners' working location throughout the underground mine. Therefore, in case of any emergency (such as roof fall/gas explosion) the data received at the base station could be utilized to provide the location estimate of the miners.

The continuous tracking of miners' position will be conducted based on the health data over the wireless link to the base station on the ground. To achieve this particular task, every wearable health sensor module is assigned with a unique Miner ID that is associated with a miner and worn by the individual miner. A corresponding database for each miner is maintained at a server/base station. Therefore, we know as a priori that which miner has which wearable tag so the person can be identified and his/her physiological and location information can be retrieved when required. Based on this assumption, a zone based location tracking approach is adopted here.

Since the wireless communication in underground mine galleries is unreliable in performance, hence the communication range is restricted. We address this problem considering multi hop technology to route the wearable data to the base station located at the ground. Therefore, APs or gateway devices are used for this purpose. The proposed system follows the ZigBee protocol which supports the wireless mesh networking. In case of any node failure (i.e., AP fails due to power failure, any malfunction or physical damage), then the neighboring node opts for alternative routes available for data transmission. Such analysis on the unavailability of any AP or damage of AP in wireless mesh networks has been actively researched and contributed by the research community in both normal and underground mines propagation environment. Few interesting analysis and discussions on the same can be seen in the state-of-the-art works by different researchers [2], [26]–[28].

It may also be noted here that there are different mine working zones in an underground mine. Therefore, each AP in the wireless communication network is assigned with a unique ID and its corresponding deployment location is also recorded at the central server/base station. This approach helps to identify the serving zones by each AP deployed in the underground mine gallery. For a better understanding, a conceptual view of such tracking in room and pillar also known as bord and pillar mining method is shown in Fig. 2.

Here three working levels have been shown with different working panels. Consider each AP in Fig. 2 serves as a working panel of the mining area. Once the miner equipped

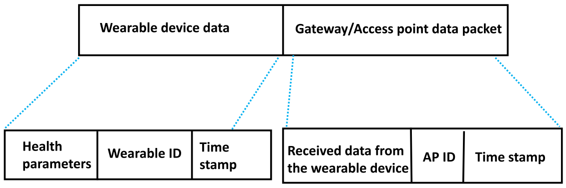


FIGURE 3. Data packet format.

with wearable device comes under the communication zone of AP, then the wearable unit first transmits its sensed health data to the AP. As a second step, the AP appends a data packet including Node ID and timestamp at the node along with the received data packet from the individual wearable device and forwards it to the other AP over a wireless link. The same procedure is followed till the sensed health data are received at the base station on the ground. At the base station, the associated Miner ID, all Node IDs and timestamp in the path will be extracted besides the biomarker information. A sample of data packet format is shown in Fig. 3. Based on this architecture, we are able to continuously track the miners' locations in the zone level. The same method is applied to multiple miners as well, hence the proposed system will provide a near zone tracking information for all miners at all the time. This proposed architecture is cost effective, since it does not require additional infrastructures for location tracking resulting in reduced maintenance cost to the mine management.

IV. CHALLENGES IN HEALTH SENSING IN MINES

A. RELIABLE WIRELESS COMMUNICATION

One of the key challenges for the successful adoption of wireless health monitoring system in the underground mine environment is reliable wireless communication and networking. In literature, several theoretical and limited experimental studies have been performed to understand wireless propagation characteristics for different applications including mine environment monitoring, remote asset tracking, RFID based monitoring, and two-way wireless communication [29]–[33]. However, research efforts are still needed to provide a reliable wireless communication infrastructure in underground mines considering the dynamic mine operations and scalability of such networks. This extreme and inferior performance of the wireless communication link is mainly characterized by unique features of underground propagation environment including long range tilt of the ore body, mine wall roughness, random support systems, noise from the mining equipment, miner movements, and complex mine infrastructure. The majority of the existing studies are mostly performed either in simulation environments or tunnels of rail/road transportation. Very limited detailed experimental studies have been performed in different underground mines [1], [31], [34]. Hence, considering the real-time propagation characteristics of wireless signal in the mining environment, more systematic experimental measurements are required to bridge the gap of theoretical vs. experimental understanding. In this regard recently, Zhou *et al.* [35] performed a detailed study to understand the radio signal behavior for wireless communication in tunnels and underground mines. Several experimental measurements performed in tunnels and experimental mines have been used to develop the understanding of wireless signal behavior in such confined spaces. The work reported is significant as it covers several aspects such as antenna polarizations, different frequency ranges, channel modeling approach, and analysis from measurement campaigns considering Tx-Rx along the tunnel centre. Since the wireless health monitoring system may engage APs deployment on other locations also such as on side walls, it is equally important to consider this use case. In addition, the proposed solution aims to explore low-powered sensors for both sensing and data transmission. Hence, we in this work have tried to develop experimental understandings of wireless link behavior for low-powered sensor architecture. Moreover, such detailed experimental studies considering different underground mine propagation environment will be helpful to develop new communication protocols.

B. ENERGY CONSTRAINTS AND DEVICE PORTABILITY

The nature of mining operations is continue in fashion and generally three shifts of eight hours are practiced. Considering the large scale deployment of such wearable device at workplace, it is implicit that the devices worn by the miners should have sufficient amount of energy to last till a working shift. Typically, wireless health monitoring architecture deployed in underground mines goes through three major energy consumption phases: a) sensing of the physiological parameters, b) processing of data within the wearable device and c) transmitting data packet over the wireless link to the AP. Each step will consume energy. Hence, how to keep the wearable devices charged till eight hour shift would require research efforts for such technology adoption in this work environment.

One possible solution in this regard may be that mine management should maintain a wearable charging place, so that after each particular shift, the wearable can be plugged in to the charging point until its fully charged and ready to hand over the mining personnel for use. Apart from this, energy harvesting to power up the wearable device would be an alternative solution. However, such a solution would require significant efforts to carry out the feasibility study of harvesting energy from the ambient mine environment. In addition to the energy harvesting technique, energy efficient communications (e.g., demand based data transmission over frequent data transmission) would be another approach to minimize energy consumption at wearable devices. Therefore, it is interesting to pursue research considering different reliability of data and energy efficient communication mechanisms, especially for wearable devices in such extreme work environments.

In general, every miner carries different accessories while going for a mining shift including cap lamp, helmet, jacket, mining shoes, and noise-cancellation headphones. In view of already adopted accessories by the miners for work operations, a wearable device design should be handy in nature and may not compromise with the comfort of miners. Moreover, the wearable design should not affect the normal routine operations of the miners involved in mining activities. Considering such requirements, it would be necessary to identify the mounting positions of the wearable solution, so that it maintains the overall data reliability and integrity and could also be adopted as a daily routine accessory by the miners. Hence, how the mounting position affects the physiological parameters of the miners should be studied in detail. Considering wireless communication limitations in underground, research efforts would also be required to understand the miners' body movement on the health data and miners as an obstruction for reliable data transmission and communication ranges.

C. SCALABILITY FOR FUTURE INTEGRATION

The advantage of having a wearable health monitoring solution in workplace of mines is to track the individual among other workers. For instance, the wearable unit capable of sensing the activity may be significantly useful if an individual miner suddenly goes inactive or undergoes a sudden elevation on acceleration data, indicating a possible fall at workplace. Such detection is crucial in case of miners who are involved in blasting operations in mine gallery, so that every individual miner among all could be tracked and identified after the blasting operation, a daily routine mining activity. Information about the location of miners is very significant to send any help and support to the victims at workplace who face any kind of injury and are unable to communicate with other peers.

Underground mines employ several miners in a particular shift of mining operation. The number of miners involved in mining activity at a certain working level inside underground mine gallery may change depending on the production requirement or maintenance tasks. In such a scenario, the wireless health monitoring architecture should support the new users and additional devices without compromising reliability and robust performance. In addition to this, due to the dynamic nature of mining operations, it is expected that the mining area keeps on advancing over time to extract the minerals. Considering this dynamic operation requirement, it is obvious that the wireless health monitoring solution should also cover the newly developed working areas. In such circumstances, adding new APs and wearables to the network should maintain the reliability and mine wide communication coverage.

D. DATA PRIVACY AND SECURITY

Mining industry employs a large number of mine personnel to achieve its different objectives such as production per year. To this high number of mine personnel using wearable health monitoring technology, data privacy and its security is a serious concern for both the mine management and mine individuals. Hence, such technology adoption in underground mining industry should follow the compliance with the regulatory body for worker data privacy and security. Occupational health hazards and potential future health risks are always high among miners and there may be several miners diagnosed with minor to life threatening diseases such as lung cancer. It is obvious that sharing such medical findings is one's personal choice and the proposed system should maintain such privacy.

Authorized access to both wearable sensor unit and the central base station would be one approach to ensure data privacy and security. The mine management must be abide by data confidentiality and should follow the government regulations such as general data protection regulations (GDPR) policy. They should not use miners' personal health data for their productivity related tasks and benefits. The mine management should be well aware about the present use and potential future access to miners' health data for any analysis and results. It is also essential for the mine management to first understand the gaps in miners' health and safety requirement and then identify that how using the wearable technology can improve the workplace safety and well-being of the miners.

E. DATA ANALYTICS

Wearable device and context aware health sensing in the mining environment is a promising solution addressing the pressing need of the miners well-being update and future safety hazards. The scope of such technology advancements in workplace has several interesting benefits to the mine management including improved productivity per shift of operation. Since the scale of health monitoring solution in mining industry is large (considering the total workers), it is expected that the amount of data generated would be significantly huge. On one hand, it is expected that the health monitoring data will be collected on daily basis to avoid any potential future health risks among miners, therefore the data size is huge. While on the other hand, it is also necessary to develop understandings on, how to utilize the collected health data of miners for meaningful interpretation.

Use of intelligent machine learning algorithms and advanced analytics is increasingly popular in health domain sectors. A comprehensive review on deep learning algorithms for health monitoring applications is recently reported by Faust *et al.* [36]. Different machine learning algorithms have been used specifically in identifying and analysing different physiological signals such as Electrocardiogram (ECG) [37], [38], Electrooculography (EOG) [39], [40], Electroencephalography (EEG) [41], [42], Electromyogram (EMG) [43], [44] for classification and predictions results. More specifically, convolutional neural network (CNN) and other versions of its derivative such as region based CNN i.e. R-CNN, recurrent neural network (RNN) and deep neural network (DNN) have been used for the studies in identifying and prediction of health hazards.

The medical features and kind of activity monitoring cover mostly urban population. It is also learned from the state-of-the-art work in such domain that the medical information and features extracted from the personal health monitoring systems are limited to the daily lifestyles of the user. Also, the data analysis framework on such consideration is quite mature and still several research is going on. In contrast to the daily routine operation of a person in a normal day/office environment, the scenario and factors which may affect the underground miners' health are not very well studied. Very little is known about the factors such as work culture among miners, types of role assigned in a particular shift, exposure to the different gaseous environment, mine dust, etc., and its impact on miners' health. Considering such a unique work environment of the mines, a detailed and serious effort would be required to design a data analytics framework including the medical features and pattern of physiological health parameters of the miners. In this regard, several questions arise as follows.

- How the exposure to the coal dust/mine dust may affect the heart rate?
- Miners involved in normal routine operation vs. special roles such as blasting, drilling operation, miners involved in operating highly mechanized machines, etc.
- Does the shift of operation affect the health condition of miners?
- Impact of work locations such as miners working near face vs. miners working in the passageway.

Apart from the above mentioned questions, there might be plenty of factors which should be analyzed and considered while maintaining a database and performing the correlation analysis of the present health data of the miners and predicting the future health risks and hazards. One approach to address this challenge would be to design a data analytics framework considering several factors, especially from the mining work environment and the occupation. Intelligent machine learning and big data techniques could be very useful to perform health data analytics solution for such an extreme work environment.

V. PRELIMINARY ANALYSIS

Wireless signal characteristics in confined spaces of underground mine galleries are different than those of terrestrial wireless communication environment. In contrast to the normal terrestrial environment, underground mine wireless channel characteristics are mainly influenced by surface wall roughness, available complex infrastructures (such as transmission lines, cable pipes, belt-conveyor, mining equipment, rail tracks), tunnel geometry (long range tilt of ore body), support systems, choice of signal frequency, curved mine galleries, antenna deployment positions and movement of miners. In this context, few good reviews and survey articles highlighting the challenges of wireless communication links have been reported by the researchers. In [45], researchers have discussed the effect of tunnel geometry and additional losses due to the miners' movement and noise induced from the mining machinery. Hrovat *et al.* [46] and Forooshani *et al.* [29] also discussed the different challenges and wireless link behavior in underground mine tunnels with a focus on channel modeling approach for this application category.

FIGURE 4. A photograph of mine gallery of underground coal mine.

In this section, we present our preliminary work, which focuses on the experimental investigation of wireless communication and signal characteristics in underground mine galleries. The main motivation to understand wireless communications in such an extreme environment is due to the unreliable communication performance of wireless devices. Specifically, we perform experimental studies to answer the following questions:

- Where should we mount the AP to provide a reliable communication link and routing the data packets of sensed health data? Node at the tunnel centre (such as miners with wearable device) vs. on side wall (AP)?
- How the wireless signal propagation behaves in normal straight gallery vs. in curved mine zones vs. near face environment (mining extraction area)?

Moreover, these studies will help to estimate the number of APs required to provide a reliable mine wide communication coverage. With these considerations, the following subsections detail the study area and experimental results carried out in an operational underground coal mine.

A. STUDY AREA

Several measurements at different work levels in an operational underground coal mine situated in India are carried out. The mine gallery dimension is 4 meters in width and 3 meters in height. The coal seam is occurring at a depth of 25 meters to 110 meters from the surface having a top thickness of 3-5 meters whereas the bottom seam thickness ranges in between 1.5-2.5 meters. The studied mine uses Room and Pillar, also known as Bord and Pillar mining method to extract the coal seam. Several complex infrastructures such as rail tracks, transmission cables, sub-station, roof support system and water pipes, etc. are part of the working area where the measurements are performed. Fig. 4 shows a mine roadway having different mine infrastructure.

B. EXPERIMENTAL METHODOLOGY

To perform the experimental measurements in mine galleries, a total of 3 TelosB sensor motes operating at 2.4 GHz signal frequency were used. To store the collected data, a laptop was used which was further useful for post-processing of collected data. Out of three sensor nodes, one node was used as the master node attached to the laptop and was responsible for passing the commands to other sensor node working as the transmitter (Tx). The third node was used as the receiver (Rx) in the underground mine working space.

For all measurements, we kept the Tx static and relocated the Rx node from one point to the other along the incremental axial distance of the mine tunnel. We used a fixed incremental distance strategy of 3 meters for every measurement. Tripods were used to mount the sensor nodes above the mine floor. We considered different mine zones such as: i) straight mine gallery which is used for different mine workings access, transportation purposes, and material handling; ii) near mine extraction area is also known as face, most of the miners working place and active zone of mine workings; and iii) in a curved gallery consisted both line of sight (LoS) and no line of sight (NLoS) scenario and is irregular in mine dimension at some place.

We also considered three different deployment settings of Tx-Rx combinations considering: a) Tx-Rx both at tunnel centre, b) Tx at tunnel centre and Rx on the side wall, and c) Tx-Rx both on the side walls of the mine tunnel. For each deployment settings and propagation environment, a total of 10 measurements for each distance were performed by transmitting 200 data packets of size 140 bytes from the Tx to Rx. The TelosB nodes were programmed using TinyOs and nesC. The transmission power of Tx was $0dBm$ for all use cases and deployment settings. Also, a $2dBi$ antenna gain with vertical polarization was used for both Tx and Rx.

C. EXPERIMENTAL RESULTS AND ANALYSIS

In this subsection, the link behavior analysis and characterization have been categorized considering average received signal strength (RSSI) and packet reception rate (PRR) for all the measurements.

We performed detailed experimental studies in an operational underground coal mine. For all propagation environment and deployment settings, the walls of the tunnel were dry. It is worth to discuss here that the dielectric property of the material varies from type of mines such as coal vs. uranium/gold. Though the dielectric properties of the coal that is dry coal vs. coal with moisture content or side wall with some water seepage are different, but its overall effect on the wireless signal attenuation is almost negligible [47]. The same observations considering the dielectric properties of coal on the wireless signal characteristics are reported by Sun and Akyildiz in [48]. However, the detailed observations were limited to mathematical modeling and its validation with the measurements performed in the transportation tunnel. Hence, based on the findings reported in prior works, it is learned that wireless signal attenuation in underground mine tunnels is mainly influenced by the tunnel geometry [45] and mine infrastructures as an obstruction [31], [47] than the dielectric property of coal. Nevertheless, how precisely the wireless signal attenuates in underground mines with dry coal vs. coal with moisture content in real-time is an open research problem and needs careful experimental realization considering different signal frequencies for wireless communication.

1) RECEIVED SIGNAL STRENGTH INDICATOR (RSSI)

RSSI is typically used as a measure of power of the signal in the receiver antenna. A higher RSSI value indicates a stronger signal. The power of the received signal decays with distance and is inversely proportional to the separation distances between the Tx and Rx [49]. Hence, RSSI is defined as the ratio of the received power P_{Rx} at Rx to the reference power P_{Ref} and is typically considered as 1 mW (0 dBm). Therefore, RSSI can be expressed as [50]:

$$RSSI = 10.log\frac{P_{Rx}}{P_{Ref}} \tag{1}$$

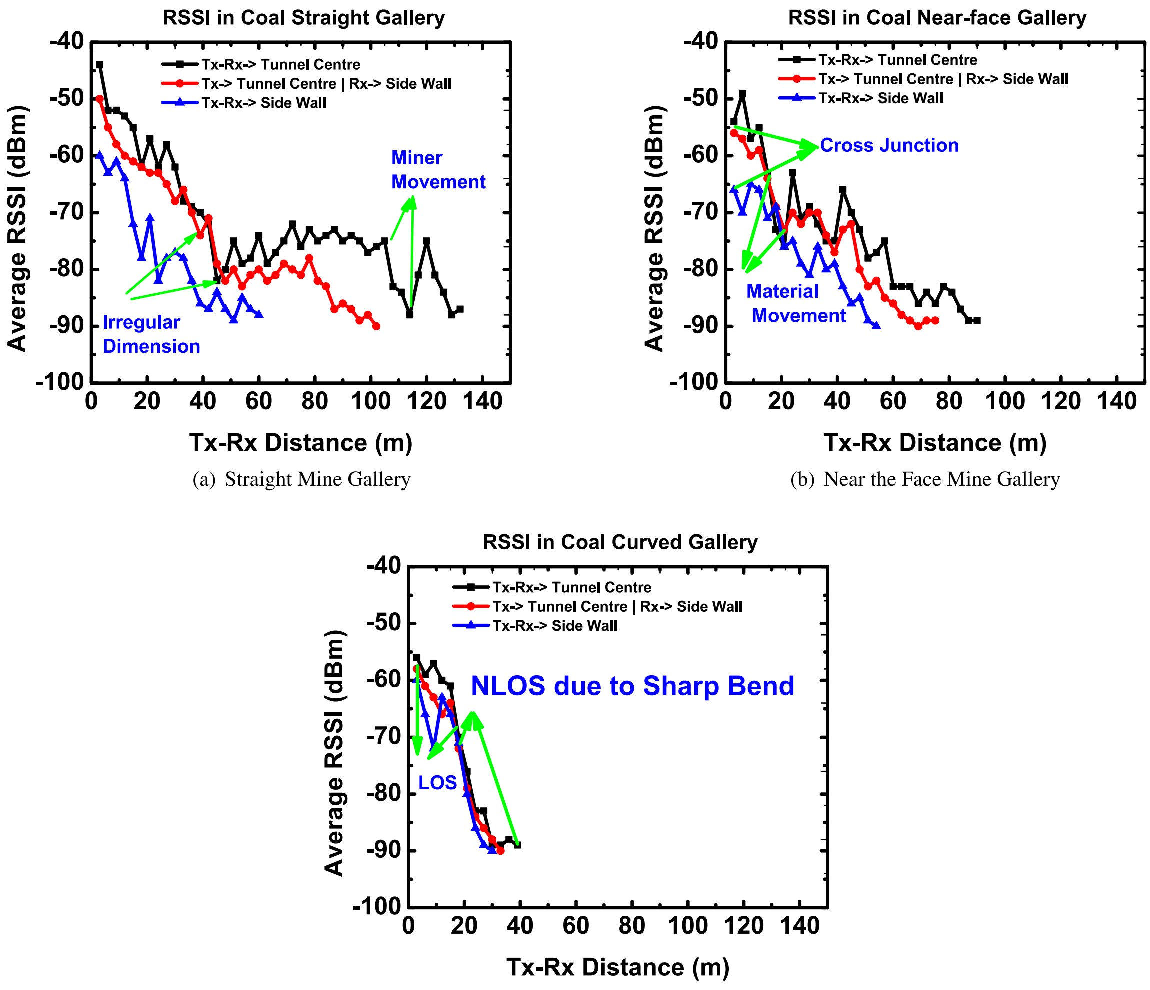
where P_{Rx} can be defined as:

$$P_{Rx} = P_{Tx}.G_{Tx}.G_{Rx}\left(\frac{\lambda}{4\pi d}\right)^2, \tag{2}$$

where P_{Tx} is the transmission power, G_{Tx} and G_{Rx} are the antenna gains for Tx and Rx respectively, λ is the wavelength of the signal frequency and d is the separation distance between the Tx and Rx. These equations do not take into considerations the unique features of underground workings, e.g., side wall roughness and tilt of the ore body. Since the underground mine workings are quite different than the normal propagation environment, we refer the readers to some comprehensive articles in this particular topic where researchers have discussed in detail about the mathematical modeling of communication networks in underground mines [29], [47], [51], [52]. We do not provide such insights here as this topic is beyond the objective of this research work. For all measurement scenarios, different deployment strategies of sensor nodes (Tx-Rx) have been adopted with an aim to identify other propagational factors which affect the link behavior significantly such as sharp bends, irregularities in the mine gallery dimensions, support systems and dynamic change in the propagation environment, etc.

Measurements are carried out in underground coal mine workings, and the deployment assumptions are the same as of discussed in the above sub-section. For all the measurement scenarios, the graphs of average RSSI as a function of distance are plotted and can be seen in Figs. 5(a), 5(b) and 5(c) for straight, near face and curved gallery respectively.

It is observed that within the same underground mine galleries, the propagation characteristics and signal attenuation varies significantly. While the straight mine gallery has the highest communication ranges between Tx-Rx, near face propagation environment is the second followed by the curved mine zones. It is crucial to observe that the curved mine settings have the worst communication ranges compared with the other two deployment environments. This could be due to the variations in mine gallery dimensions and irregularities. While the straight mine gallery



(a) Straight Mine Gallery

(b) Near the Face Mine Gallery

(c) Curved Mine Gallery

FIGURE 5. **Underground coal mine: Average RSSI vs. Tx-Rx distance.**

had the dimensions of 4 meters in width and 3 meters in height, it was 2.5 meters in height only with random support systems in case of near face measurement settings. However, the curved mine settings had the same dimensions as of the straight mine gallery. Nevertheless, LoS and NLoS both consisted in case of curved mine measurements. Hence, it is understood from the experimental results that mine gallery dimension and a LoS propagation path have a strong impact on the wireless signal characteristics and link behavior.

It is also observed that the miner movement in between the measurements caused for additional signal loss at the Rx and can be seen in the graph 5(a). The Tx-Rx both on the side wall of the mine experienced severe signal loss and high attenuation. The reason for high signal attenuation for side wall measurements for all three deployment settings may be exhibited from the wall roughness and disorientation of ore chunks over the space. The side wall roughness may have caused for destructive phase polarization, hence a reduced communication range is unpreserved in all measurement scenarios. Such an observation of impact of the side wall roughness is also discussed and reported by the researchers in their work carried out in tunnel environment [53]–[55]. Also, for the near face measurements, additional noise added by the running belt conveyor (used for transportation of extracted coal) working in the other passage and opposite to the Tx placement (20 meters apart and left of the Tx) may also have affected the signal propagation compared to the straight mine gallery (empty) of underground coal mine.

From the experimental observations, it is analyzed that the change in gallery dimension due to cross-junction causes additional signal attenuation and can be seen in the Fig. 5(b) compared to the straight mine gallery (Fig. 5(a)). In case of the curved gallery of underground coal mine, the WSN link goes under severe signal attenuation, hence is limited to a maximum communication ranges of 39 meters, 33 meters and 30 meters only for Tx-Rx at tunnel centre, Tx at tunnel centre and Rx on side wall and Tx-Rx both on side walls respectively. This is mainly because of two reasons: 1) the curved gallery consisted both LoS and NLoS and 2) the change in mine gallery dimension due to the sharp bend of 70°.

A LoS link between the Tx-Rx was observed for first 15 meters along the axial distance of the mine workings, whereas after 15 meters the measurements followed a NLoS scenario for the communication link between Tx and Rx. Moreover, a wider opening around the sharp bend caused for change in gallery dimension, hence resulted in destructive interference. This interference further leads to significant signal attenuation at the Rx. Also, the beginning of the curve is a cross-junction with random stitching for a roof support system which could have caused for additional signal loss due to the reflection/refraction phenomena and resulted in inferior link performance.

Based on the experimental measurement analysis and findings, it is understood that the Tx-Rx at tunnel centre has the highest communication ranges over the Tx at tunnel centre and Rx on the side wall and Tx-Rx both on the side walls for all propagation environment. However, considering the health monitoring application, it is expected that the AP will be deployed on the side walls. It may be noted here that AP, in this case, is static not mobile so other deployment consideration and channel characteristics will be different. Therefore, AP deployed on the side walls will function reliably in the normal routine scenario. But considering the roof collapse situation, hence causing the physical damage of AP; it is obvious that in such circumstance the AP will not behave reliably. To tackle this emergency scenario, research contribution would be needed to understand how an AP will behave in case of roof collapse in underground mine gallery. One possible approach to this problem may be to perform experimental studies considering different signal frequency such as ISM, Sub-GHz bands where sensors are partially/fully buried in pebbles/ore chunks. This will help to model the wireless communication link in case of there is a roof collapse scenario. In addition, the AP should be also deployed in the ruggedized and shockproof casing so that a roof collapse may cause minimum physical damage to the AP.

2) PACKET RECEPTION RATE (PRR)

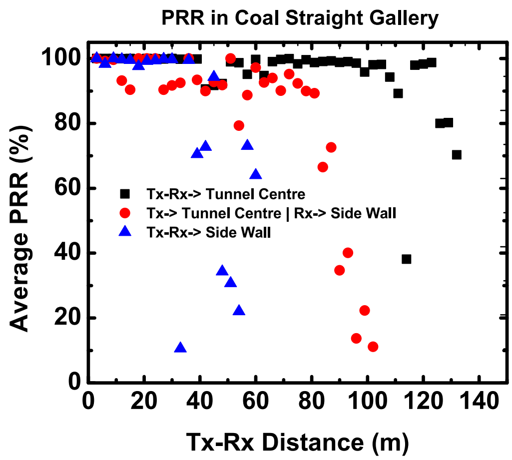
PRR is used as a benchmark performance metric to design a reliable and robust wireless communication protocol. It is calculated as the ratio of a total number of packets received (n) at the Rx to the total number of packets transmitted (m), i.e., $\frac{n}{m}$. To design a reliable wireless health monitoring systems for underground mines, it is vital to understand the performance behavior of packet reception rate over Tx-Rx distance, so that such metric could be efficiently utilized while designing routing and other communication protocols especially for underground mine workings.

As discussed in Section V-B, 200 data packets of 140 bytes were transmitted for each Tx-Rx position, and the experiment was repeated 10 times for all measurement considerations. The corresponding values of the total packets received by the Rx of each transmission were then recorded. Based on the measurements, an average of the PRR of each distance between Tx-Rx for all propagation environment of an underground coal mine, i.e., straight, near the face and curved gallery area, were taken for the analysis. For a better understanding of PRR behavior, three kinds of classifications have been assumed: (1) good link- the link with more than 90% PRR; (2) moderate link- link between Tx-Rx with PRR in the range of 80% to 89% and (3) disconnected link- link with PRR value less than 80%.

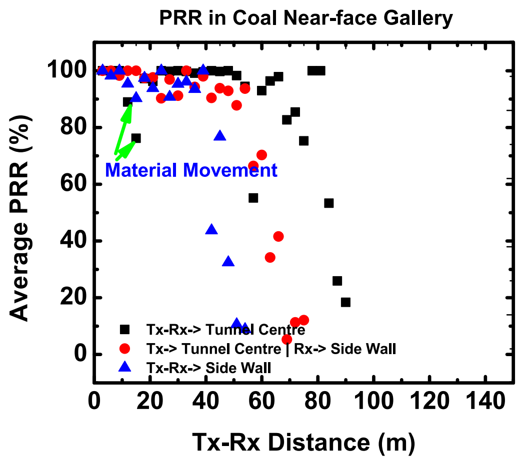
The graphs of average PRR of all measurement scenarios are plotted and can be seen in Fig. 6. From the graph of straight mine gallery of the coal mine (6(a)) having Tx-Rx placed at the tunnel centre, it can be analyzed that the PRR for up to 100 meters is more than 92 %. However, after 100 meters, there is no uniform behavior of PRR with respect to the distance between the Tx-Rx. Unlike the Tx-Rx at tunnel centre (i.e., straight mine gallery), the PRR for the rest sensor deployments does not have consistency and varies with distances. Therefore, an accurate behavior of PRR with respect to distance is hard to understand as after some specific distances the PRR decreases drastically, which can be seen by comparing the results for different Tx-Rx deployment assumptions of underground coal mine workings.

It is also observed from the graphs that irregularities in mine workings and sharp bends significantly affected the PRR. The change in mine gallery shape, i.e., *straight mine gallery to curved gallery* caused for both unreliable PRR and reduced RSSI. The curved gallery of coal mine workings consisted of both LoS and NLoS. There was a 70^o curve in case of measurements performed in the curved gallery. The PRR of the curved gallery having NLoS for all three deployments varied from lowest 5.2 % to maximum 87.2% and can be seen from the distance after 15 meters onward till the Rx stopped receiving packets from the Tx. Such PRR could also be utilized in the protocol design targeting delay tolerant applications such as ventilation on demand, air flow and pressure monitoring, two-way text messages, and periodic monitoring such as mine equipment and trucks.

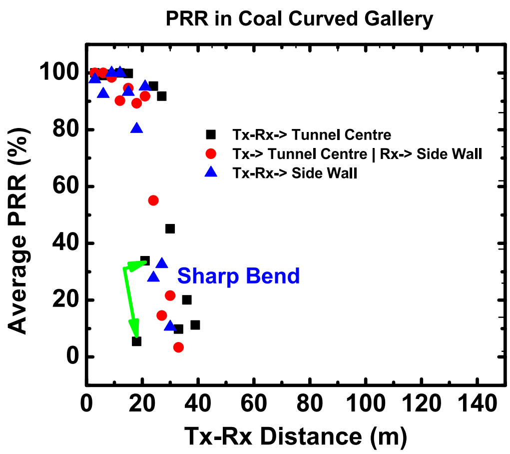
Movement of miners in between the measurements also affected the PRR. However, since the movements were temporary (material handling purpose), it did not cause any drastic change in the PRR. The PRR for such measurements was recorded as 88.95 % and 76.15 % for the distance of 12 meters and 15 meters, which can be seen in Fig. 6(b). From the experimental observations of PRR behavior with respect to the distance between Tx-Rx, it is found that there is no strong correlation of PRR with distances and it is majorly affected by the mine tunnel shape, sudden change in the mine gallery dimensions, placement of sensor nodes such as cross-junction and additional noise from the mining machinery. Hence, PRR is highly dependent on the RSSI rather on distance between Tx-Rx. Such findings are also reported by different researchers in many application categories such as indoor localization [56], factory automation [49], tunnel-like environment [57] etc.



(a) PRR in Straight Mine Gallery



(b) PRR in Near the Face Mine Gallery



(c) PRR in Curved Mine Gallery

FIGURE 6. Underground coal mines: average PRR vs. Tx-Rx distance.

VI. FUTURE RESEARCH DIRECTIONS

In this section, we will shed lights on future research directions of health monitoring for mining environments.

Wearable devices in workplace have been used for decades to assist with the hazards notifications and protection. The rise of digital wearable systems such as smart watch monitoring heart rate, smart glasses, augmented reality headsets have opened the scope for research on such industrial wearable system applicability in the extreme work environment such as underground mines. At present, the health and safety analysis in the mining industry is highly dependent on the participation of miners and their willingness to share the details. Such practices are making it a tough task to estimate the possible reason for different occupational diseases among miners. Using the wearable technology for health monitoring of miners and further data analytics would be a great tool to understand the flow of health hazards among miners involved in different mining roles. Based on the health statistics over time, it may be significantly useful to share the preventive measures from future health risks. However, such future prediction and analysis need advanced data analytics algorithms exploiting the different mines data and its role on miners' health. One approach to this challenge may be to collect the previously published health-related data of underground miners from NIOSH and Mine Safety and Health Administration (MSHA) and apply different machine learning techniques on such data sets considering parameters like mine employment history, type of work assigned, time of stay near the face, use of the respiratory system, etc.

While in this work we mainly focused on the wireless health monitoring and localization solution, it is worth to mention that the wearable device may have additional sensors (e.g., dust and gas sensors) to monitor the mine environment continuously and report it back to the server. Nevertheless, such implementation needs a careful customized design approach, so that it will be easy to use. Also, based on the location of the miners working underground the evacuation or nearest escape route could also be sent on the device by the mine management in case of any mine emergency such as fire, gas explosion, etc.

On the one hand, the wearable device for health sensing in the underground mine environment offers promising benefits for the well-being of the miners. On the other hand, the intrinsic safe operation of such a system will be a concern for the mines. It may be noted that any kind of electronic device to be used/deployed in underground mine workings should be approved by the competent agencies such as MSHA. If the device is not approved by the agency, then deploying such a solution would be an issue for the mining industry. Therefore, research efforts are needed in this direction to design an intrinsically safe wearable health sensing device for mines. In addition to this, mine management may conduct a survey on workers willingness to adopt such a wearable system while working underground. A training or awareness program will also be beneficial for the uptake of such technology at the workplace.

VII. CONCLUSION

Occupational health and safety hazards among underground miners remained a serious concern for the mine management. On the one hand, the mining industry contributes to the economic growth of the nation, while on the other hand, the well-being of the miners and their health have been overlooked. Wireless health monitoring system is a reliable and promising solution for the wellness of miners. In this work, we first proposed a wireless health monitoring system for underground mines to improve the health analysis of the miners and then discussed the advantages of such a system in tracking the location of miners as well. A detailed description and several associated challenges of such systems in the context of the underground mines are also presented. As a final contribution, we also provided experimental insights into wireless communication and signal propagation characteristics as a case study in this research direction. The detailed experimental findings could be utilized to design the communication and data transmission protocol for implementing a wireless health monitoring system. In future, prototyping of the proposed solution, tests in underground mines and detailed analysis are planned. We believe that the discussions and findings reported in this work will be inspiring to the community to advance the adoption of wearable solutions in mining industry.

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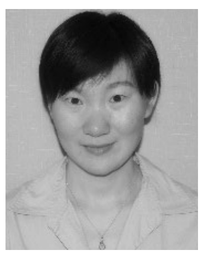

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