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A WSN for Monitoring and Event Reporting in Underground Mine Environments

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***Abstract*—Every year, mining industry sees huge losses in terms of human lives and valuable infrastructure due to accidents and disasters. Besides other measures, effective monitoring and control can greatly reduce the risks of such incidents. Wireless sensor networks (WSNs) are increasingly being used for such applications. This paper proposes a WSN-based system, which is capable of detecting and identifying events of interest (with 90% success rate) and localization of miners (2–4 m) and roof falls (10–12 m). A comprehensive integrated system covering a range of aspects from radio frequency propagation, communication protocol with latency, and energy–efficiency tradeoff and autonomous event detection is presented. The results show a lower path loss for 433 MHz operating frequency compared to 868 MHz. Moreover, a novel energy-efficient hybrid communication protocol using both periodic and aperiodic modes of communication while adhering to low latency requirement for emergency situations is proposed and implemented. Finally, for intelligent processing of gathered data, a spatio-temporal and attribute-correlated event detection mechanism suitable for the highly unreliable mine environment is described.**

***Index Terms*—Communication protocol, event identification, outlier detection, radio frequency (RF) modeling, system design, underground mines, wireless sensor networks (WSNs).**

I. Introduction

ALTHOUGH technological advancements and stricter regulations have helped in controlling the accident rate in underground mines, still hundreds of people lose their lives and huge financial losses are incurred to mining industry each year from mining disasters. In the classification of mine accidents issued by Mine Safety and Health Administration of the U.S. Department of Labor, the major causes apart from faulty equipment, structure failure, and personal negligence are explosions, roof falls, fires, and accumulation of gases [1]. In a report published by Centers for Disease Control and Prevention, a total of 11 606 underground coal workers died in 513 disasters in the USA from 1900 to 2006, with most disasters resulting from explosion or fire [2].

Proper ventilation and regular inspection of hazardous gases, or in other words environmental monitoring and control, is emphasized to avoid accidents in underground mines. However, monitoring of such harsh environment is not an easy task and even if human negligence is completely avoided, dynamic nature of the environment calls for an automated, intelligent, and reliable monitoring system.

Typical underground mine consists of stretches of kilometres long tunnels with excavation branches spreading out like a tree. This means the monitoring system should be scalable, easily deployable, and have low-maintenance cost (i.e., longer life) to increase coverage as the mine grows. The tunnels normally have very rough terrains, i.e., a very harsh environment for radio frequency (RF) communications. The communication scheme in such environment must be robust to blockages and redundant to node failures.

The mine environments are typically quite dynamic; attributes may change instantly calling for immediate evacuation in a rare case of event contrary to a normal condition lasting for weeks and months. Therefore, the solution must be responsive in case of events and energy efficient during normal operating conditions. In addition, there may be cases of events that are confined to a part of the mine and do not pose a threat to people working in other areas. Therefore, the solution must have a central server capable of inferring the global picture in conjunction with a distributed system required for energy-constrained sensing network.

In case of accidents, localization of events and miners is of key importance. Activity monitoring of miners can also provide useful information at times. The most important thing is the seamless integration of all the subsystems into a complete monitoring system. This paper presents a unique and comprehensive monitoring and control system for harsh environments. It is based on an application-specific communication protocol, utilizing known network topology to design energy-efficient routing and collision-avoidance (CA) mechanism. RF modeling is used for optimum node placement and reliable connectivity. The system has integrated an intelligent anomaly detection mechanism that not only has the capability to detect and identify events in real time but also has the memory to cater for the spatio-temporal dynamics of the environment. The solution is distributed (takes care of the spatial dynamics) where individual nodes have the capability to detect local events but also carry out periodic reporting so that the central server has the global picture. In addition, localization of miners and events and roof falls, etc., has been integrated in the system. Following are the key contributions of this paper.

1) Empirical investigation of key RF performance indicators for different operating frequencies of 433 and 868 MHz in underground mine environment.

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TABLE I
SUMMARY OF SUPPORTED FEATURES FOR EXISTING IMPLEMENTATIONS

Previous works	Standard sensors and reporting	Miner monitoring	Intelligent outlier/event detection	Event localization	Event forecasting	Emergency priority transmission	Roof Fall detection	Distributed processing
[11]	✓		Partial					
[13]	✓	Partial						
[4]	✓	Partial		Partial			✓	
[9]	✓	Partial						
[10]	✓			Partial		✓		
[14]	✓		Partial					Partial
Proposed system	✓	✓	✓	✓	✓	✓	✓	✓

2) Implementation of an application-specific, energy-efficient, scalable, reconfigurable, and reliable communication protocol.
3) Implementation of an intelligent outlier and event detection and identification algorithm that takes into account spatio-temporal and attribute correlations.
4) With key infrastructure in place, lightweight miner localization and miner activity monitoring (standing, active or lying down) algorithms suitable for underground mine environment have been implemented.

II. MOTIVATION

To cater for challenging environments such as underground mines, wireless sensor networks (WSNs) are increasingly being used in a range of similar applications such as underwater sensing [3], structural health monitoring [4], and event reporting applications [5] as they are scalable and can be easily deployed and maintained. They are also more resilient to failure in case of accidents such as fire, roof falls, and tunnel disruptions as compared to wired networks that are prone to damage and breakage [6]. However, effective monitoring of underground mines even using WSNs is intrinsically difficult to achieve because of several design challenges such as unfavorable, time-varying and frequency-selective channel environment, difficult terrain for installation and maintenance of nodes, etc.

A review of challenges associated with harsh environment communication that hinder applicability of ordinary communication protocols has been presented in [6] along with ongoing practices of mine monitoring and their problems. The authors propose the use of WSNs based on an empirical study in an actual mine. Detailed analysis of communication systems for underground mines has also been presented in [7]. Authors conclude that of all the considered communication means, wireless communication can offer solutions to some of the fundamental challenges in the underground mines.

Previous works on various domains of WSNs in underground mines have been presented ranging from hole (caused by roof falls) detection and robust query handling [4], to audio and video transmission to the central station [8], and application and data management on the gateway [9], etc., For the underlying network, the authors have proposed various solutions such as ZigBee [10], a heterogeneous model utilizing both wired access via controller air network bus for base station (BS) and RF for mobile users [11], using both wired (optical fiber) and wireless (IEEE 802.15.4/ZigBee) [12] and a hybrid system utilizing both Wi-Fi (IEEE 802.11.x) and ZigBee [13]. Furthermore, the authors have also proposed the need for intelligent event detection algorithms [5].

However, the literature lacks a complete and comprehensive system-level treatment of monitoring and control of harsh and dynamic underground mine environments. This paper targets optimum solutions for individual aspects, studies their mutual dependencies, and builds on it to design and evaluate an integrated system. One of the key uniqueness of this paper is that throughout the design process understanding of application domain is leveraged to gain performance enhancements in an energy and cost-constrained environment.

III. LITERATURE REVIEW

The literature review has been categorized into two categories: the first one summarizes the features and the second one summarizes the underlying methodology and scheme for control and monitoring system incorporated by existing works.

A. *Comparison of Features*

Key existing works are compared in Table I for features that are essential for a widely effective mine monitoring. They all support a basic monitoring and event reporting system; however, they lack an integrated perspective considering range of features and constraints posed by each. For example, some designs propose fixed nodes solution, which cannot support miner localization. Some works present a centralized approach where a server initiates query and nodes reply with instantaneous values of the requested parameter. This approach can be energy efficient but does not consider temporal correlation and is not suitable for ever changing mine environment. For intelligent decision making, algorithms need to be integrated at the core hardware and protocol level to be effective at the global level.

B. *Prior Art on Methodology*

A comprehensive review of existing approaches for mine monitoring has been presented in [15]. For the base protocol, most works have relied on ZigBee for its ease of deployment, low data rate (250 kb/s), substantial range and most importantly low power consumption when compared to other technologies such as Wi-Fi, bluetooth and ultrawideband communication [12], [16]. However, this paper targets an even lower data rate and lower frequency protocol, DASH-7. Due to the simple direct energy-bandwidth relationship; lower data rate projects better energy efficiency and lower frequency promises higher range.

Also, ZigBee is a general purpose protocol. Although nodes can be configured to some extent, the nodes are randomly deployed and the network is formed and operates dynamically. This means that it does not benefit from known characteristics such as signal attenuation, network topology, and

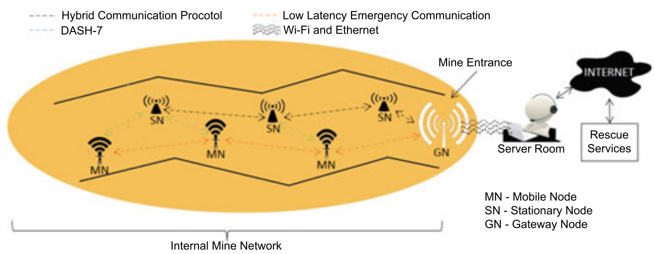

Fig. 1. Overall system architecture.

routing. Connection is established using carrier sense mechanism which increases delays, uncertainty, and power usage [10]. Nodes are set to specific roles such as cluster heads and sensor nodes, which reduce flexibility [10]. Even dynamic routing between randomly distributed nodes in a big network can be complex and energy-consuming and may lead to areas with redundant or weak coverages (specially without signal attenuation consideration). An application-specific approach can benefit from known facts and answer all these challenges.

The review in [15] also points out that some works have focused on simulations while not giving enough consideration to power requirements for long term operations [4] and did not present experimental results [17]. Finally, although existing works emphasize reliability, not a lot has been researched on run time intelligent decision making capability for reliable event detection. Authors in [14] and [5] emphasize the need for data collaboration between nodes and intelligent processing for efficient decision making but their scope is limited to energy saving and gas concentration detection, respectively. Unlike previous works targeting a single aspect of system, this paper takes an integrated approach, improving separate subsystems and taking advantage of dependability of various subsystems.

IV. System Model

The overall system architecture is shown in Fig. 1. The system consists of three types of devices: mobile node (MN), stationary node (SN), and gateway node (GN). Each type of device runs its specific firmware and communicate, via set communication protocol. Hardware design as well as power requirements also vary for each type of device as described in subsequent sections.

A. Mobile Nodes

MNs are carried by the miners. The nodes are capable of monitoring miner activity, sense parameters critical for miner's survival inside the mine (e.g. temperature, humidity, and oxygen levels) and convey information to the nearest SN. Miners can also send distress signal(s) to the gateway as well as run miner localization algorithm. MNs are charged by Li-Po batteries (2200 mAh, $62 \times 50 \times 5$ mm^3) and are designed with a view that they can be recharged easily, just like cell phones, every few days. This fact allows for less stringent power constraints and flexibility when communicating with SNs. MNs use DASH-7 protocol for communication, which is further explained in Section V-C. Dimensions of an MN are 2.5×2.75 in^2 and it weighs about 220 g with battery contributing a large chunk of the weight (150 g).

B. Stationary Nodes

SNs are deployed throughout the mine at an appropriate distance from each other. SNs sense different parameters critical to structural integrity of the mine (e.g. roof fall, temperature, humidity, and concentration of toxic gases such as carbon monoxide (CO)). Based on readings of different attributes, SNs run local event detection and identification algorithm. This distributed processing is one of the key features of the proposed system. This means that in case a node or certain number of nodes are disconnected from server, they can still use the gathered data (of that particular region) for localized event detection and localized alarm generation. Finally, SN is responsible for data aggregation and routing to GNs. Each SN acts as a cluster head and forward the received data to the GN. SNs communicate with MNs using DASH-7 (see Section V-C) and with other SNs using customized protocol (see Section V-C1). SNs are powered with low-cost maintenance free-sealed lead-acid batteries. They, unlike MNs, cannot be monitored on daily basis for wear and tear and have a higher probability to come under tremendous stress after a roof fall. Hence, Li-Po batteries are avoided for fixed nodes since they can explode if mistreated. The system was tested with 10 Ah batteries ($151 \times 51 \times 100$ mm^3) for SNs.

C. Gateway Node and BS

GN collects data from SNs in its vicinity using custom designed protocol (see Section V-C1) and sends it to the server/BS via Ethernet or Wi-Fi. At BS, data received from GN can be visually analyzed. BS is also responsible for declaring a global event. Proposed system also supports down-link communication from the BS to one or multiple SNs.

V. System Design

The usual practice for monitoring in WSNs is to have an event triggered design, i.e., communication between the sensor nodes (SNs and MNs) and the sink node (GN) is required only if an anomaly occurs or the server initiates a query. Although this approach saves energy, but has a danger of missing trends. For this reason in the proposed system design, in addition to an event triggered reporting, attributes readings are also periodically reported to the GN, where event detection and identification algorithm (explained later in Section V-D) continuously looks for global anomalies. Next, individual features of system design necessary to overcome the shortcomings of previous systems (summarized in Section I) are presented and a full feature monitoring system is provided.

A. Feature I: Economical Hardware Design

The test bed has been fully custom designed for low power and economical solution. An ultralow-power system-on-chip with integrated RF transceiver core, from CC430 range of Texas Instruments [18], has been used in the developed nodes. As for gas sensing, metal-oxide semiconductor based sensors have been used for methane (5 V/100 mA) and carbon monoxide (5 V/75 mA) sensing. A low cost and ultralow-power MEMS based accelerometer (2.5 V/11 μA) has been used for roof fall detection and miners' activity monitoring. For the sake of comparison, experiments have also been carried out using commercial hardware board (both are shown in the Fig. 2, including a picture of MN with packaging).

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(a) (b) (c)

Fig. 2. Nodes hardware. (a) Mobile node. (b) Custom hardware node. (c) Commercial hardware node.

TABLE II
DASH-7 MODE 2 KEY SPECIFICATIONS

Specification	Value
Frequency band	433.05–434.79 MHz
Channel size	216 kHz, 432 kHz, 648 kHz
Channels	8
Modulation	GFSK $\pm$50KHz
Encoding options	PN9, FEC
Symbol rate	Normal: 55.6 kbaud, Turbo: 200 kbaud
Data rate	Min: 27.8 kb/s, Max: 200 kb/s
Access methods	CSMA, Reserved slots
Addressing	Unicast, broadcast, multicast
Maximum packet size	255 B

B. Feature II: Reliable RF Propagation Through Mine Environment

Prior work acknowledges the need for the assessment of link quality in harsh environments such as factories, etc., before moving on to the network design of system [19]. Specially for mines, structure is abrupt with supporting pillars (concrete, wood, or metal), rough walls and variable tunnel widths and therefore these environments experience adverse and dynamic channel conditions [20]. This leads to communication link distortion, high packet error rate (PER), intermittent connectivity and extended delay. Some of these issues can be resolved via effective communication protocol but more importantly, all these depend on the choice of operating frequency and RF modeling of channel.

For low-power wireless technologies, 2.4 GHz and 868 and 915 MHz bands are being widely used in various monitoring applications. However, they suffer from higher attenuation in underground environments and/or have global acceptance issues limiting their suitability for targeted application. Recently, 433 MHz ISM band has gained momentum as an alternative. Lower frequencies have better propagation characteristics and inherently use cost-effective and low-power electronics. Antenna size can be an issue at such low frequencies; however, good quality rubber ducky antennas are available. One can find higher gains with larger dimensions (20.7 cm/6 dBi, 8.5 cm/3 dBi are a couple examples); this paper uses a 4.5-cm antenna with gain 2.5 dBi for all measurements. In the results section, RF performance comparison is provided between 433 and 868 MHz to select the most suitable frequency for underground mine communication.

C. Feature III: Application-Specific Communication Scheme Design for Energy Efficiency and Resilience

The choice of communication protocol is very important for optimum performance when using WSNs for any application. Key aspects that differ based on different applications are communication range, power consumption, scalability, hardware constraints (cost and size), complexity of implementation, etc., These features are controlled by standard defined features such as transmission rate, connection requirements, packet size, error detection, data and addressing formats, communication overhead and routing, etc.

In existing works, ZigBee [12] and Wi-Fi [13] have been widely proposed communication protocols for WSNs but both operate at higher frequency bands. However, this paper chooses to adopt DASH-7, which has been more recently developed by Developers' Alliance for Standards Harmonization of ISO 18000-7 and operates at 433 MHz. It is an extension of ISO 18000-7 standard and does the same work as ZigBee does to IEEE 802.15.4. A summary of key DASH-7 physical layer features (mode 2) is given in Table II.

DASH-7 works on the BLAST (Bursty, Light-data, ASynchronous, Transitive) scheme. The design requirements of targeted application are similar to the ones provided by BLAST architecture, i.e., low data rate, event triggered (and thus bursty) traffic. The application requires variable rate transmission for periodic and event reporting in line with asynchronous transmission mode of DASH-7. Finally, reconfigurable nature of proposed solution is helped by transitive nature of DASH-7 architecture. To the best of our knowledge, DASH-7 has not been previously adopted for WSNs in any high-stress environment. For the first time, this paper investigates and profiles realtime performance of DASH-7 mode 2 protocol and compares against ZigBee for underground mine monitoring. However, in the implementation phase, few application-specific enhancements have been made in network and MAC layer protocol.

1) Custom-Designed MAC Layer for Periodic and Aperiodic Communication: After selecting the base communication protocol (DASH-7), the work seems to enhance the performance by employing application-specific modifications. This is in contrast to the widely adopted use of self-configuring networks, which rely on intelligent networking algorithms to form clusters and routing paths to BS [3]. Instead, the philosophy of this paper is to propose a communication protocol driven by known specific topology of tunnels and show its advantages for low power periodic communication, scalability and communication with MNs. Furthermore, this paper seems to leverage certain factors to enhance the battery life of SNs.

In the proposed approach, time-division multiplexing allows reserved time slots each for MN–SN and SN–SN communication. For the MN–SN communication link, DASH-7 mode 2 communication protocol has been implemented as such. This paper uses a single channel at turbo symbol rate of 200 kbaud. As SNs act as cluster-heads/coordinators as well, a standard command–response scheme suits SN–MN communication. SNs use a broadcast addressing when communicating with MNs whereas MNs respond via unicast. Multiple MNs communicate with SNs using carrier sense multiple access with CA (CSMA/CA) scheme as defined in DASH-7. CSMA/CA uses an unslotted scheme that uses carrier sensing, by measuring signal strength in the medium, before transmitting. If the channel

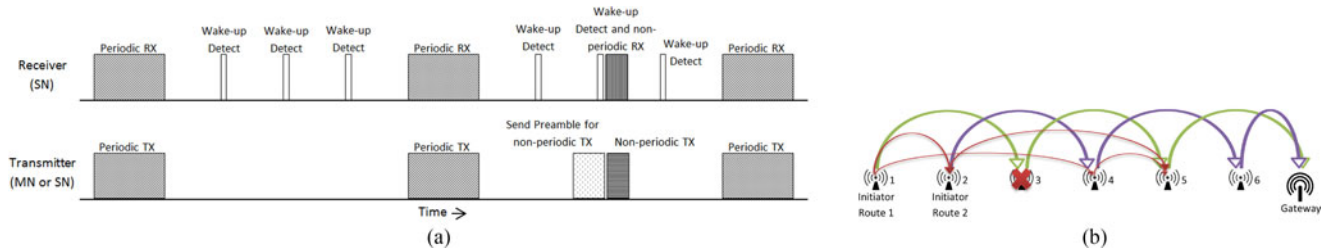

Fig. 3. Hybrid communication protocol. (a) Timing diagram of hybrid protocol. (b) Routing scheme.

is available, the node transmits its entire data, else it waits for a fixed or random period of time and tries again. This paper uses random increase geometric division model for flow control in which the CSMA process starts after a random delay and the slot duration decreases with increasing number of tries.

Since MNs are relatively easily rechargeable, they are kept awake all the times with low-power listening (LPL) [21]. This is an unconventional design decision but it can help in a few ways. First, it makes MNs always available for communication using the command–response method. The SN sends a beacon when it is free to accept new data and MNs, in response, transmit data packet instantly with current measurements of key attributes; thus, power saving for SN on behalf of MN power. Such a mechanism can be described as receiver initiated asynchronous communication and is considered very energy efficient [22].

Second, MNs can also directly communicate with other MNs. Being awake all the times means any distress signal from a miner can instantly be conveyed to other miners to alert them for necessary action. They can also be used for low latency routing in case an SN is not available either because of failure, out of range or being in sleep mode (as explained below).

For the SN–SN communication link, a unique approach has been proposed on top of DASH-7 to answer their more strict battery constraints. For this purpose, a hybrid scheme utilizing both periodic and aperiodic modes of communication is implemented. Periodic communication protocols with active and sleep cycles are more energy efficient but at the expense of latency, whereas aperiodic communication protocols allow nodes to stay alive more often and thus reduce latency at the expense of battery usage [23]. The proposed scheme avoids battery usage in idle mode by implementing a periodic communication protocol in conjunction with adaptive duty cycling to send the nodes to sleep mode when they are not communicating. By being adaptive, it means that slot lengths can be varied as per run time traffic flow using the known location of SNs and updated number of MNs beyond any particular SN.

Moreover, proposed solution makes use of a modified channel access mechanism to minimize the wastage of power in channel sensing with CSMA. The implemented approach makes use of a timer; all nodes wait for data to arrive from previous node and then forward them to the next. If the timer expires and a node does not receive data from previous nodes, it will forward its own data. In order to avoid collision, nodes secure channel via RTS-CTS (request to send-clear to send). This mechanism greatly reduces scheduling overhead associated with CSMA and is also more reliable as it alleviates the problem of hidden nodes. In case a node does not receive CTS from the next forward link node, it tries to communicate with other nodes in its range, as explained in the next section. Having failed to communicate in set time limit forces node to run a local event detection event only and discard data for that cycle. Furthermore, to avoid long delay in emergency situations with multiple nodes in the sleep mode, an out of order communication is allowed in DASH-7; all SNs wake-up with LPL at small intervals (much smaller than sensor data transmission period) to overhear if any MN or SN is trying to communicate with it.

The concept has been elaborated in Fig. 3(a). Here, during normal transmission, a transmitter (MN or SN) can send data to receiver (SN) at fixed synchronized cycles. The receiver also wakes up at shorter intervals to detect any nonperiodic communication. Now, if the TX needs to send nonperiodic data, it will send a preamble first and will keep sending it until the RX acknowledges. On the receiving side, when during short wake-ups, RX detects a request, it sends acknowledgement and stays alive for communication as required.

Active synchronization needs to be developed among nodes for custom protocol. The GN initiates the synchronization packet and the packet then travels down to the end of tunnel in multiple hops. Each receiving node increments the hop count to cater for delay. Synchronization is done periodically because of clock drift.

2) Linear Routing for Mine Structure: In our local scenario, 10–12 m length of mine is affected on average with a roof fall or a collapse, and hence is a reasonable internode distance. For redundancy against single-node failure, the proposed protocol is designed such that each SN can communicate with at least two forward-linked SNs and hence a transmission power for a range of 25 m is required by default, evaluated through RF measurements. In case of disaster causing blockages or more number of nodes failing, a range of 80 m can be attained at maximum, using high-power transmission in the custom built modes.

The proposed routing scheme uses a linear topology and implements two routes to transfer data to sink. When the network is configured, a node which is i hops away from GN establishes link with a node which is $i - 2$ hops away and so on. This scheme has several advantages; it is energy efficient at system level, achieves low latency, and allows data aggregation at intermediate nodes. In case of a link failure, a node in one route can partially route through its adjacent node in other route.

The concept is further elaborated in Fig. 3(b). In normal operation, the two initiators (1 and 2) will start transmission and try to connect to alternate nodes all the way to GN via route 1 and route 2, respectively. Now considering the scenario depicted in figure, if, for example node 3 goes down, route 1 will be effected. It will then try two options, 1-2-5 or 1-4-5, whichever works, to reattain the path to GN. It can take a few cycles for the network to reconfigure. Similarly, if node 3 goes alive again, it

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sends beacons to surrounding nodes and the network reattains its original position.

D. Feature IV : Intelligent Outlier/Event Detection and Identification

As mentioned previously, SNs run distributed event detection algorithms for localized decisions while a global event detection is run at BS. The heart of event detection and identification problem is outlier detection. Outlier detection algorithms identify anomalies in newly arrived measurement. As these anomalies may also be caused by sensor faults and/or noise in the measurement, a local event is temporally correlated and only detected upon a series of Q consecutive outliers. Event can either be atomic (in single attribute), composite (in multiple attributes), local (detected at single node), or global (detected at multiple nodes). An efficient event detection technique is able to detect all the above-mentioned types of events. Event identification is about identifying the contributions of the individual attributes in a detected event and is thus essential for composite event detection. First, the mechanism with which outliers are declared in the proposed system is briefly explained and then event identification is discussed in detail.

1) Outlier Detection in Environment Parameters: An outlier is an observation that differs significantly from normal set of values [24]. Out of various outlier detection schemes, clustering-based outlier detection schemes are most appropriate for implementation in harsh dynamic environments such as underground mines [24] because of their computational simplicity, high detection rates (DRs), and low false positive rates (FPRs). Clustering algorithms such as hyper-ellipsoidal clustering [25] are able to incorporate multiple attributes and can be deployed in unsupervised environments (as they do not need any training dataset for detecting outliers).

To reject the anomalous readings, hyper-ellipsoidal clustering model for outlier detection is used. Let $X_k = \{x_1, x_2, \ldots, x_k\}$ be the first k samples of data collected at a node where each sample x_i is a $d \times 1$ vector in $\Re^d$, where d is the number of attributes. Hyper-ellipsoidal outlier detection clusters the normal data points and the points lying outside the clusters are declared as outlier. The boundary of the cluster (a hyper ellipsoid in this case) is related to a distance metric which typically is a function of mean $m_{X,k}$ and covariance S_k of the incoming data X_k. One example of the distance metric is *Mahalanobis* distance D_i [26] for which the cluster can be characterized by the following equation:

$$e_k(m_X, S_k^{-1}, t) = \left\{ x_i \epsilon \Re^d \mid \underbrace{\sqrt{(x_i - m_{X,k})^T S_k{}^{-1} (x_i - m_{X,k})}}_{D_i = \text{Mahalanobis distance of } x_i} \leq t \right\} \quad (1)$$

where e_k is the set of normal data points whose Mahalanobis distance $D_i < t$ and t is the *effective* radius of the hyper ellipsoid. The choice of t depends on the distribution of the normal data points. The data samples x_i which are not enclosed in the hyper-ellipsoidal boundary, i.e., have a Mahalanobis distance greater than t are identified as outliers.

The mean $m_{X,k}$ can be incrementally calculated using (2). This exponential moving average technique uses λ as a *forgetting factor* that adds tracking capability in the algorithm making it feasible for implementation in harsh unsupervised dynamic environments [27]. The suggested value of λ is between 0.99 and 0.999 [27]. The covariance inverse S_k^{-1} can then incrementally be updated by using (3).

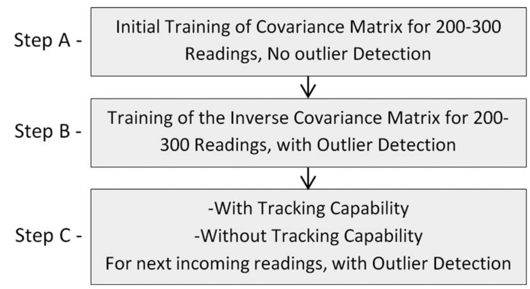


Fig. 4. Outlier detection steps for robust implementation.

$$m_{k+1,\lambda} = \lambda m_{k,\lambda} + (1-\lambda) x_{k+1} \quad (2)$$

$$S_{k+1}^{-1} = \frac{k S_k^{-1}}{\lambda(k-1)} \times \left[I - \frac{(x_{k+1} - m_{k\lambda})(x_{k+1} - m_{k\lambda})^T S_k^{-1}}{\frac{(k-1)}{\lambda} + (x_{k+1} - m_{k\lambda})^T S_k^{-1} (x_{k+1} - m_{k\lambda})} \right]. \quad (3)$$

The incremental update of covariance inverse S^{-1} matrix helps to alleviate the problem of computing the inverse of the covariance matrix S_k again and again. For implementation in hardware, the above mentioned algorithm in two forms as shown by Fig. 4 is implemented. The initial 200–300 readings are used to train normal readings. Thereafter, for the next 300 readings, covariance is also computed to verify if the incoming measurement is an outlier or not. Thereafter, the means and covariance matrix are incrementally updated using (2) and (3). Note that for datasets without a trend $\lambda = 1$ is used. For trendy dataset, $\lambda = 0.9999$ has been chosen for implementation. In order to avoid issues due to large values of k in (3), k is fixed at $k = 3000$ once first 3000 readings are processed. For the initial readings, the value of k can be approximated by the expression $\frac{3}{1-\lambda}$ [27].

2) Event Identification: The technique for event identification is essentially derived from the inherent hyper-ellipsoid outlier detection technique [28]. When an event is detected, the cumulative Mahalanobis distance D_m derived from the outlier detection scheme is stored and then for each attribute, following steps are performed for approximating the contribution ratio of that attribute in the detected event.

1) The contribution of each attribute is left out from the mean m and covariance inverse matrix S^{-1} successively by removing the corresponding rows and columns.
2) Mahalanobis distance is calculated again using the information related to remaining attributes in the m and S^{-1} matrices.
3) The newly calculated Mahalanobis distance is subtracted from the commutative Mahalanobis distance D_m.
4) The result of step 2 is then divided by the commutative Mahalanobis distance D_m to get the required contribution ratio of the attribute which was left out in m and S^{-1} (step 1).

3) Event Reporting and Global Event Detection at BS: A simple and light-weight event report packet (ERP) format has been specified for event reporting to BS. The ERP format facilitates in global event identification and tracking. Following is a description of the individual fields in the proposed packet format.

Event Flag: A *1 b* specifying whether an event has happened or not.

Node ID: The node identification number. It uses $\log_2(N_n)$ bits, where N_n is the number of nodes in the network.

Attributes: This field specifies the attributes contributing towards a detected event. This field will occupy d bits, i.e., where d is the maximum number of attributes being monitored.

Spatial Confidence Level: This field is only updated by the SN when it receives multiple ERP from adjacent nodes. This field will have $\log_2 N_n$ bits.

Identification Percentages (IPs): 7d bits are used to describe IPs of the individual attributes contributing towards a detected event.

Event Intensities: 32d bits are used to represent floating point values of the event intensities derived at the nodes reporting the events.

Location Estimates: The localization algorithm running in MNs and loaded geographical position in SNs will be used to update this field using 64 bits for x and y coordinates.

Event Tag: $\log_2(N_s)$ bits, where N_s are the number of SNs, are used to differentiate between multiple event reports from multiple SNs.

So, the total number of bits in ERP packet will be $d + 7d + \log_2 N_n + 32d + 64 + 1$ for MNs and $d + 7d + \log_2 N_s + 2 \times \log_2 N_n + 32d + 64 + 1$ for SNs.

The proposed ERP is suitable for implementation on energy-constrained wireless sensor nodes and can effectively communicate all the information to both the adjacent nodes and the BS. Along with event identification, BS can also define severity of a global event by implementing spatial correlation and weighing all nodes in the locality. This helps decide the actions needed; miners can be alarmed or evacuated as necessary. The BS can also estimate the approximate location of the event as well.

E. Feature V : Miner Localization and Activity Monitoring

In case of an accident, the proposed solution runs miner localization algorithm to estimate the position of miners. Most localization algorithms already available in the literature are either propagation based [29] and require computation of mathematical models on received signal properties, or use fingerprinting, (such as based on *k*-Nearest Neighbor [30] etc.) by calibrating the environment and employ exhaustive queries on databases built during training [31]. Both approaches can estimate real-time location more accurately but at the cost of increased memory and CPU usage both of which are limited in energy-constraint MNs. Even more complex approaches are available based on the basic two to address application-specific challenges and enhance precision [32], [33]. However, in this paper, a tradeoff is made between accuracy and computational complexity and uses a very simple approach to estimate location with reasonable accuracy.

The proposed approach makes use of the fact that the RSS values depend logarithmically on the distance from the source for line-of-sight case. For non-line-of-sight case, there variation is captured in the logNormal RV. Obstacles and environment variations will affect the case but it is assumed here that on average dynamic variations usually average out over time. Although more complex environmental factors can be catered for, but they will lead to more complex loss models. The following approach is then used to achieve appropriate weighted average of the anchor node positions according to the respective RSS values of their beacon signals

$$P_m = \frac{\sum_{i=1}^{N} P_i W_i}{\sum_{i=1}^{N} W_i} \tag{4}$$

where P_is are the position vectors communicated in beacons sent by the surrounding anchor nodes participating in localization and $W_i = 10^{\frac{\mathrm{RSS}_i}{10}}$ is the assigned weight to the position of that anchor node based on the RSS value, N is number of participating anchor nodes and P_m is the final position estimate of the miner (pseudo code given in the Appendix). The proposed scheme has been experimentally tested in the underground environment with low cross sections. The achieved accuracy is dependent on distance between the nodes and number of beacons a node is able to receive. Typically in the mine environment with a 10 m internode separation, it offers an accuracy of 2–4 m.

Finally, a simple yet very useful miner's activity monitoring algorithm has been implemented. It uses a low-power 3-axis MEMS accelerometer in the MN. The accelerometer reports on miner state (moving/stationary, lying/standing) as well as detects sudden miner fall. Intelligent processing of this information is used to generate emergency help signal.

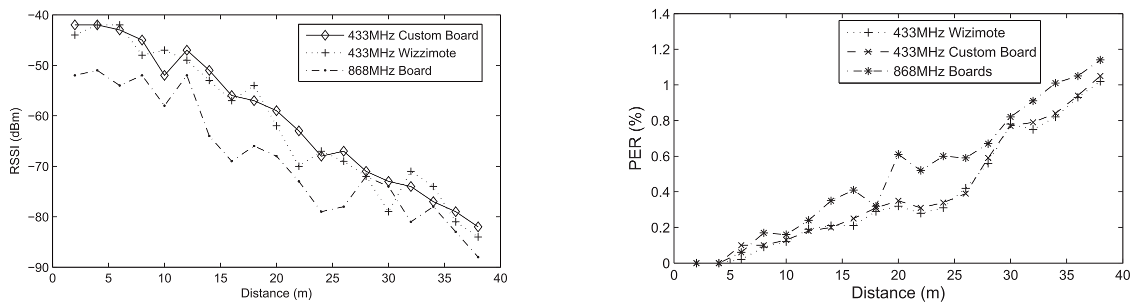
VI. Performance Evaluation and Analysis

A. RF Link Performance

The mine used for measurement campaign is a tunnel mine of dimension 2×2 m^2. The mine structure contains iron rods (at 1 m distance) to support the structure while wooden planks are placed on the top. The nodes are attached to the roof top at the center. The experiment compares link performance with different operating frequencies. Fig. 5(a) and (b) shows performance results for RSS and PER, respectively, with operating frequencies of 433 and 868 MHz. As expected, a lower operating frequency performs significantly better in mine environment. 433 MHz based commercial and custom boards showed 11.5% and 12.8% stronger RSS than 868 MHz based system, respectively. This led to a 20.16% and 23.51% lesser PER for commercial and custom boards, respectively.

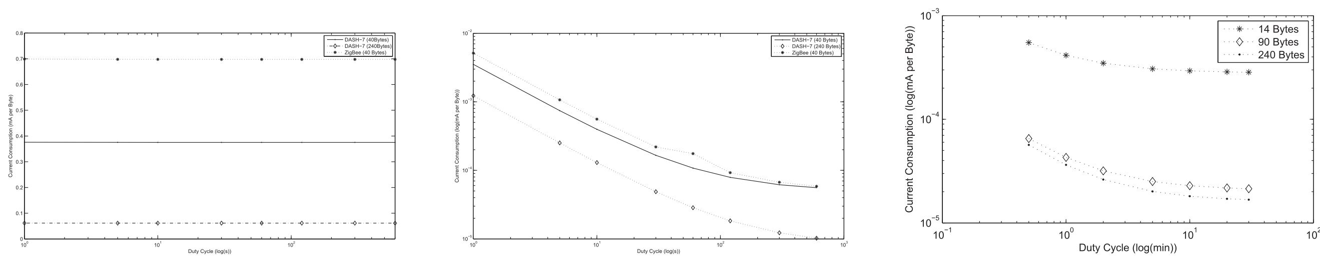
B. Energy Efficiency

In order to compare the energy efficiency of ZigBee and DASH-7, custom built nodes for DASH-7 have been used. A single frequency channel with a transmit power $P_{t_x} = 0$ dBm has been used. The symbol rate used for DASH-7 is 55.6 kHz at a data rate of 200 kb/s along with other standard options. For this section, results were carried out in an anechoic chamber with nodes placed closed to each other. This was to rule out RF performance differences of ZigBee and DASH-7. The power consumption is estimated using values of current consumption (mA) in each mode (RX, TX, Sleep, Idle, etc.) and the time (ms) for which node stays in each mode [34]. For DASH-7 empirical values have been used while for ZigBee, experimental power readings for Texas Instrument's development kit, CC2530ZNP have been used [35]. The average current consumption is



(a) (b)

Fig. 5. RF performance results. (a) Measured RSSI at various distances for 433 and 868 MHz ($P_{tx} = 0$ dBm). (b) Measured PER at various distances for 433 and 868 MHz ($P_{tx} = 0$ dBm).



(a) (b) (c)

Fig. 6. Energy consumption analysis for DASH-7, ZigBee, and hybrid protocol. (a) DASH-7 vs ZigBee: Comparison of current consumptions in MN with a transmit power of $P_{tx} = 0$ dBm. (b) DASH-7 vs ZigBee: Comparison of current consumptions in SN with a transmit power of $P_{tx} = 0$ dBm. (c) Current consumption of hybrid protocol for SN–SN communication for various packet sizes sent at different duty cycles with a transmit power of $P_{tx} = 0$ dBm.

computed using the following equation:

$$I_{\text{avg}} = \sum_{i=0}^{n}\left(\frac{T_c}{T_i} \times I_c\right) + \left(1 - \sum_{i=0}^{n}\left(\frac{T_c}{T_i}\right)\right) \times I_s \qquad (5)$$

where I_c and I_s are current consumptions in communication and sleep mode respectively, T_c is the time for which the node remains in the communication mode and T_i is the total time over which the average is being measured. A comparison of ZigBee and DASH-7 protocols is shown in Fig. 6(a) and (b) for the designed MNs and SNs respectively. It can be seen that that for SN, DASH-7 is an order of magnitude better than ZigBee whereas for MN DASH-7 is upto 30% more energy efficient as compared to ZigBee for a packet size of 40 B. The graphs also show that for MN, the current consumption per byte (mA/B) reduces significantly with an increase in the data packet size for a given duty cycle. This is because of the fact that the MNs are always ON when idle, as per design choice, and consume almost same amount of current in TX, RX, and idle wake-on-RX modes. Because of the same reason, the current consumption is almost constant with an increase of duty cycle for a given data packet size.

The SN on the other hand wakes up periodically, transmits and receives from the MNs, and goes back to sleep. It can be observed that for a given data packet size, the current consumption decreases with an increase of duty cycles, because of larger sleep time intervals. This proves the effectiveness of sleep scheduling.

1) Hybrid Communication Protocol: The hybrid communication protocol allows to trade energy efficiency for latency by varying t_p and t_o, where t_p is the time interval between two periodic transmissions and t_o is the LPL period [see Fig. 3(a)]. In the experiments, $t_o = 5$ s has been used as a reasonable number. Fig. 6(c) shows the current consumption for SN–SN communication with hybrid protocol using different values of duty cycles (t_p) and data packet sizes. The numbers are slightly higher than ordinary SN communication due to LPL listening. Based on the experimental results with the proposed hybrid approach for a fixed packet size of 40 B, latency can be improved by 60 times at an expense of 70% increase in energy.

TABLE III
ENERGY USAGE BY NETWORK FOR VARIOUS SAMPLING PERIODS

SN no.	Energy usage (mWh) in 30 days for various time periods		
	5 min	10 min	20 min
1	51.8	40.6	34.9
10	86.1	60.1	47.1
25	124.3	84.8	65.1
50	177.3	117.9	117.9

Next, these readings are extrapolated to measure the effect of sampling rate and larger communication for nodes deeper in a larger network on battery timing of SNs. Estimated battery usage is reported for 30 days period for various sampling frequencies in a way that it can be used to estimate device stand by time for any capacity battery (see Table III). It is to be noted here that frequency of events or aperiodic reporting has negligible effect on standby time of nodes. This is due to the fact that frequency of events is normally very low and insignificant against frequency of periodic reporting.

TABLE IV
LATENCY OF COMMUNICATION FOR NODES WITH DIFFERENT DEPTH IN THE NETWORK

SN no.	Total time from first node to current node w/o guard band	Total time from first node to current node with guard band
1	2.9 ms	2.9 ms
10	108.49 ms	508.49 ms
25	497.75 ms	1497.75 ms
50	1536.59 ms	3536.59 ms
GN	1560.61 ms	3580.61 ms

TABLE V
COMMUNICATION PROTOCOL ENERGY PROFILING FOR COMPLETE SYSTEM

S. no.	Device type	R_x (bytes)	T_x (bytes)	Power (mW)	Current/byte (mA/B)
1.	MN1	20	11520	1536	0.3939
2.	MN2	20	11580	1642	0.3939
3.	Hop0-SN1	16040	27560	10.105	4.54×10^{-5}
4.	Hop1-SN2	34200	45760	13.142	4.84×10^{-5}
5.	Hop2-SN3	45480	57040	13.423	3.93×10^{-5}
6.	Hop3-SN4	56920	68440	13.792	3.33×10^{-5}

C. System Operation and Performance

1) Response Time: The time it takes for essential data to be delivered to BS from different parts of the mine is important. Although the actions required to counter disasters are at macro-human level and the underlying network operates at much higher speeds, a study of best and worst case latency for response times is presented here. Now, as two different modes of communication are simultaneously in place, latencies for both cases need to be calculated separately.

For the sake of study, assume a network of 100 SNs and 20 MNs. Furthermore, let us assume that all the MNs are within the farthest 20 SNs' range. Now each MN sends its data to nearest SN. For SNs, only the first node in the network transmits its own data (excluding data received from MNs in its vicinity) to next node in the network. The next node receives the packet, appends its own data and sends the new packet to the next node and so on. Furthermore, the network uses two routes. Hence, at the end of the assumed network, the node next to GN transmits data for 50 SNs and 10 MNs. This means that unlike some networks, where delay is simply a multiple of number of hops [36], in proposed architecture, the latency does not vary linearly as each hop node takes different transmit and receive time for variable data sizes.

First, the time required to send fewer bytes was measured up to the maximum packet size, i.e., 255 B. For example a SN takes 0.77 ms to receive data from a single MN while it takes about 2.99 ms to send one SN and one MN data to next SN. The rest is extrapolated for a large network with larger data sizes. Table IV gives the latency for various number of hops. In addition to the time spent in actual transmission, each node has 20 ms guard band for RTS–CTS with forward node and 20 ms waiting time to receive data from previous node. The guard band is important to counter the challenging channel conditions but constitutes a major portion of latency.

Next, for aperiodic communication, the same packet is communicated all through the network. The latency depends on the distance of nodes from the GN and the LPL frequency being used. Due to asynchronous nature of LPL cycles, it can vary for each instance and best and worst case latencies can be very different. For the considered network and five attributes, packet size will constitute 34 B for an event generated on MN and 36 B for one generated on SN. Now for the best case, it can be assumed that each forward node wakes up exactly at the time the previous node wants to communicate with it. In that case it will take about 687 ms for an event generated on the farthest MN to reach GN and about 693 ms for an event generated on farthest SN to reach GN.

For the worst case, it can be assumed that each forward node has just passed wake up cycle when previous node tries to communicate and goes alive again after time t_o, where t_o is the LPL period. In that case, $t_o \times N_s$ will be the added latency because of LPL which for 50 nodes and $t_o = 5$ s becomes 250 s. Adding transmission time to it, MN event will take about 250.687 s and SN event will take about 250.693 ms to reach GN. The actual latency at each generated event will be somewhere between the worst and best case scenarios.

D. Energy Results

Next, empirical results for validation and power measurement campaign carried out in underground mine environment with four SNs (at a distance of 10 m to each other) and two MNs being operated for 24 h are presented in Table V. Besides normal periodic transmissions, two distress signals were also generated at random times by MN2 and a local event was also generated once on two consecutive SNs. Overall communication success rate was 97.3%. Also, reliable mine communication comes at a cost; about 48% more energy consumption than an indoor (lab) environment.

It can be seen that the MNs consume relatively higher power, as they never go into sleep mode. On average, for a 2200 mAh battery pack, a MN can give its full functionality for 32 h. However, it is designed such that if the battery is less than 25%, it only switches on periodically to send its location or be used to send distress signal, leading to a full functionality for about 24 h and then limited for an extended five days. The battery life estimate for SNs is somewhat more complex. SNs are, however, more energy efficient and depending on sensing, sampling and transmission rate, they can operate up to six months without charging. The sampling rate is configurable via BS.

E. Event Detection and Identification

The results for outlier detection are shown in Fig. 7(a). It can be observed that the implemented scheme successfully detects the abnormal changes in the sensed data (outlier shown in red). Fig. 7(b) presents results of proposed event detection and identification algorithm with percentage contribution of each attribute towards the event for the same dataset.

The results show an accurate detection of outlier and event detection. The algorithm was tested under various scenarios and showed 100% success rate. The contribution of each attribute towards event detection can be trained to better suit the mine environment. After system's deployment in actual mine, measured values of attributes during events can be evaluated to better improve efficiency of event forecast.

VII. TEST CASES

This section presents functional testing results for the proposed system being validated on a case by case basic for each of

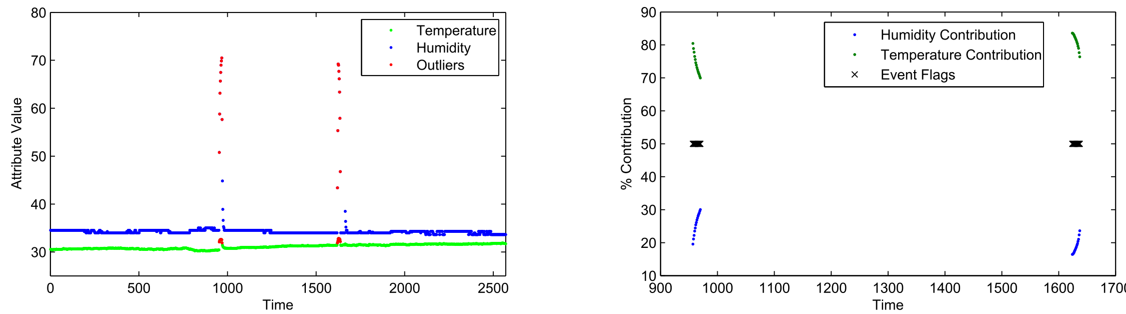


Fig. 7. Outlier and event detection simulations. (a) Node 1 dataset with outlier detection algorithm applied. (b) Event detection and identification results for node 1.

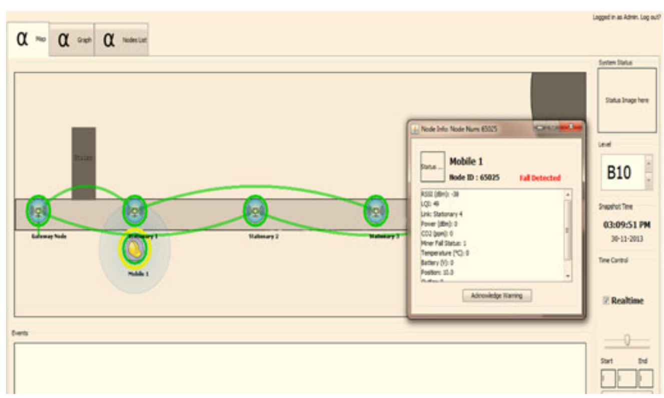


Fig. 8. Application dashboard on BS.

the feature in real-world deployment settings to ensure unparalleled safety of miner community. Fig. 8 shows a snapshot of the developed application dashboard for real-time testing. The events were artificially generated for the tests mentioned below.

Case 1: Parameter Anomaly Detection

Scenario: Artificially varied attribute values for temperature, humidity, and CO on individual nodes in standalone scenario while outlier detection algorithm was running locally. The system was first trained using initial 200 values (see Section V-D).

Results: PASSED. The system detected and reported outliers with 100% success within less than 1 s for all the limited tests performed in underground mine. For simulation based results conducted on more extensive dataset, the algorithm showed a DR of 97% and a FPR of 0.01% in an earlier work of authors [37].

Case 2: Local and Global Event Detection and Identification

Scenario: Multiple outliers were created on multiple nodes for temperature, humidity and CO values.

Results: PASSED. The system detected and reported events with 100% success within less than 10 s for the limited tests performed in underground mines. The simulation based results using extensive set of data show a DR of 98.52% and 90% and FPR of 0.34% and 0.1% for simulated and real data respectively [38].

Case 3: Roof Fall Detection

Scenario: Nodes alive in the network were dropped from a reasonable height (at least 1 m). This algorithm runs locally and was tested on individual nodes. The algorithm measures acceleration and the initial altitude does not matter.

Results: PASSED. The system detected and reported roof falls with 100% success within less than 1 s.

Case 4: Node Failure, Rerouting and Reconfigurability

Scenario: A network of four SNs connected in proposed linear topology was created. SN 4, the final SN before GN for one of the routes, and SN 2, the initiator SN for the same route, were in turn and then both at the same time switched OFF when the network was operating normally i.e., when two routes were operating via 1-3-GN and 2-4-GN. The powered off SNs were turned on again after a while.

Results: PASSED. The system detected and reported dead SNs (2, 4, or both) with 100% success within less than two periods. Adjacent SNs were able to re-route data within 3 periods via alive SN 3. After SN 2 and 4 were switched on again, the network reconfigured to original configuration within one period.

Case 5: Downward Communication

Scenario: Using the same 4 SN and 1 GN system, alarm signals were sent to different nodes, both individual nodes at a time and multiple nodes simultaneously, using the GUI.

Results: PASSED. Alarm signal was transmitted to the specific node(s) with 100% success within 1 s.

Case 6: Distress Signal/ Miner Fall

Scenario: The test was conducted with two MNs, four SNs, and one GN and the network was allowed to detect all the nodes and configure accordingly. Distress signal was generated using a push button on MN while miners carrying MNs were made to suddenly fall/lie horizontal to generate miner fall signal. The miners were made to change their location while being in network range.

Results: PASSED. Distress signals were transmitted with 100% success within 10 s. Miner fall showed a success rate of 83% (failed samples were because of less than required acceleration from manual falls).

The extensive testing in the real world environment has validated the suitability of proposed system towards safety of mines and miners.

VIII. System Limitations and Future Work

One limiting factor of current system design can be scalability when deploying in large area. The current addressing scheme allows for 255 mobile and SNs each. The other constraint is the on-chip memory for data buffering, which at present allows for a total maximum of 100 nodes. Now both can be modified (more bits for addressing and more off-chip memory) to improve scalability at the cost of increased delay. The system will also need to be retuned. Another option to enhance scalability is to place multiple gateways in a distributed monitoring scheme. Multiple shafts are usually available inside the mine, which can be utilized for distributed gateway's access to the surface dashboard. Further, some mines have multiple levels and allow for monitoring in hierarchical clusters. Finally, some mines have distributed excavation sections. These can be seen as different chambers/clusters, which can be monitored with a consolidation mechanism (e.g. a worker monitoring a dedicated BS placed in a nonworking area for a few chambers/clusters) [39].

At the moment, the maximum attainable range by SN is 80 m, which means that up to six adjacent stationary node failures can be tackled. However, huge accidents causing large number of node failures can affect the safety of the system. Multiple gateways would partially solve the problem as it would allow the rest of the network to operate normally and only the affected region remains offline.

Another feature that can be added to the system is vibration pattern analysis. Vibration in a mine can be caused by various reasons such as drilling, earthquake, blasting, rock displacement, etc. The vibration pattern of each of these can be fed into the system and can be correlated with vibrations at run time to deal with them accordingly.

IX. Conclusion

The mining industry suffers frequent loss of lives. WSNs based monitoring of environment can help to save human lives and costly infrastructure. In this paper, the system level aspects of a control and monitoring system for mining industry have been empirically investigated. This paper has addressed three design considerations for WSN being used for underground mine environments. They include RF propagation modeling, energy-efficient communication protocol and a local and global event detection mechanism. Comparison of ZigBee and DASH-7 shows that DASH-7 operating at lower frequency is significantly more energy efficient as compared to ZigBee. Building on that and based on the empirical measurements in underground mines, a hybrid communication protocol which trades latency for energy efficiency is proposed and implemented, which is particularly useful for applications requiring periodic reporting to sink node. Furthermore, an attribute and spatio-temporal correlated event detection algorithm to generate reliable disaster detection using sensing data from all over the mine has been devised.

To summarize its effectiveness, this paper reports on integrated system working, both functional and technical performance, in a real world underground mine environment. A comprehensive set of artificially created events, such as node failures, roof falls, gases concentration, etc., that the previous statistics have shown to be the major causes of accidents in underground mines, have been tested and validated proposed system's response and robustness. The system successfully detected and identified the events in all tested cases providing a comprehensive control and monitoring mechanism and tracked location of miners and events required for rescue operations.

Appendix
Miner Localization Algorithm

1: initialize P_m /*Mobile node position*/
2: **Wait for beacons from more than 2 anchor nodes**
3: initialize $\mathbf{I}$ /*Node IDs $(1 \times N)$ vector*/
4: initialize $\mathbf{P}$ /*Node positions $(2 \times N)$ vector in beacons*/
5: initialize **RSS** /*Received Signal Strength $(1 \times N)$ vector*/
6: initialize $\mathbf{W}$ /*$(1 \times N)$ Weight vector*/
7: **for all** $i \in I$ **do**
8: $\quad W_i = 10^{\frac{RSS_i}{10}}$ /*Updating weight of each position*/
9: **end for**
10: $P_m = \frac{\sum_{i=1}^{N} P_i W_i}{\sum_{i=1}^{N} W_i}$ /*Estimating mobile node position*/
11: **go to line** 2

References

[1] H. Safety, Mine and Administration, Accident/illness Investigations Procedures (ph11-i-1) (Maha Handbook Series), U.S. Dept. Labor, Washington, DC, USA, pp. 55–58, 2011.

[2] K. Kowalski-Trakofler *et al.*, "Underground coal mining disasters and fatalities, United States, 1900–2006," *Morbidity Mortality Weekly Rep.*, vol. 57, no. 51, pp. 1379–1383, 2009.

[3] J. Shen *et al.*, "A novel routing protocol providing good transmission reliability in underwater sensor networks," *J. Internet Technol.*, vol. 16, no. 1, pp. 171–178, 2015.

[4] M. Li and Y. Liu, "Underground coal mine monitoring with wireless sensor networks," *ACM Trans. Sensor Netw.*, vol. 5, no. 2, 2009, Art. no. 10.

[5] I. O. Osunmakinde, "Towards safety from toxic gases in underground mines using wireless sensor networks and ambient intelligence," *Int. J. Distrib. Sensor Netw.*, vol. 2013, 2013, Art. no. 159273.

[6] P. Misra, S. Kanhere, D. Ostry, and S. Jha, "Safety assurance and rescue communication systems in high-stress environments: A mining case study," *IEEE Commun. Mag.*, vol. 48, no. 4, pp. 66–73, Apr. 2010.

[7] S. Yarkan, S. Guzelgoz, H. Arslan, and R. R. Murphy, "Underground mine communications: A survey," *IEEE Commun. Surveys Tuts.*, vol. 11, no. 3, pp. 125–142, Jul.–Sep. 2009.

[8] N. Pogkas, G. E. Karastergios, C. P. Antonopoulos, S. Koubias, and G. Papadopoulos, "Architecture design and implementation of an ad-hoc network for disaster relief operations," *IEEE Trans. Ind. Informat.*, vol. 3, no. 1, pp. 63–72, Feb. 2007.

[9] C. Bo *et al.*, "Web of things-based remote monitoring system for coal mine safety using wireless sensor network," *Int. J. Distrib. Sensor Netw.*, vol. 2014, 2014, Art. no. 323127.

[10] Y. Zhang *et al.*, "An integrated environment monitoring system for underground coal mines wireless sensor network subsystem with multi-parameter monitoring," *Sensors*, vol. 14, no. 7, pp. 13149–13170, 2014.

[11] X. Niu *et al.*, "The design and evaluation of a wireless sensor network for mine safety monitoring," in *Proc. IEEE Global Telecommun. Conf.*, 2007, pp. 1291–1295.

[12] W. Yang and Y. Huang, "Wireless sensor network based coal mine wireless and integrated security monitoring information system," in *Proc. IEEE Int. Conf. Netw.*, 2007, pp. 13.

[13] P. Tao and L. Xiaoyang, "Hybrid wireless communication system using ZigBee and wifi technology in the coalmine tunnels," in *Proc. Int. Conf. Meas. Technol. Mechatronics Autom.*, 2011, vol. 2, pp. 340–343.

[14] Y. Huang *et al.*, "Study of multi-agent-based coal mine environmental monitoring system," *Ecological Indicators*, vol. 51, pp. 79–86, 2015.

[15] Y. S. Dohare *et al.*, "Wireless communication and environment monitoring in underground coal mines—Review," *IETE Tech. Rev.*, vol. 32, no. 2, pp. 140–150, 2015.

[16] M. A. Moridi *et al.*, "An investigation of underground monitoring and communication system based on radio waves attenuation using ZigBee," *Tunnelling Underground Space Technol.*, vol. 43, pp. 362–369, 2014.

[17] W. B. Heinzelman, A. P. Chandrakasan, and H. Balakrishnan, “An application-specific protocol architecture for wireless microsensor networks,” *IEEE Trans. Wireless Commun.*, vol. 1, no. 4, pp. 660–670, Oct. 2002.

[18] *Cc430f5137 msp430 soc with RF core*. Texas Instruments Inc., Dallas, TX, USA, 2013.

[19] L. Tang, K.-C. Wang, Y. Huang, and F. Gu, “Channel characterization and link quality assessment of IEEE 802.15.4-compliant radio for factory environments,” *IEEE Trans. Ind. Informat.*, vol. 3, no. 2, pp. 99–110, May 2007.

[20] A. Forooshani, S. Bashir, D. G. Michelson, and S. Noghanian, “A survey of wireless communications and propagation modeling in underground mines,” *IEEE Commun. Surveys Tuts.*, vol. 15, no. 4, pp. 1524–1545, Oct.–Dec. 2013.

[21] J. Polastre *et al.*, “Versatile low power media access for wireless sensor networks,” in *Proc. Int. Conf. Embedded Netw. Sensor Syst.*, 2004, pp. 95–107.

[22] X. Fafoutis *et al.*, “Receiver-initiated medium access control protocols for wireless sensor networks,” *Comput. Netw.*, vol. 76, pp. 55–74, 2015.

[23] G. Anastasi, M. Conti, and M. Di Francesco, “Extending the lifetime of wireless sensor networks through adaptive sleep,” *IEEE Trans. Ind. Informat.*, vol. 5, no. 3, pp. 351–365, Aug. 2009.

[24] N. Shahid *et al.*, “Characteristics and classification of outlier detection techniques for wireless sensor networks in harsh environments: A survey,” *Artif. Intell. Rev.*, vol. 43, pp. 193–228, 2012.

[25] S. Rajasegarar *et al.*, “Elliptical anomalies in wireless sensor networks,” *ACM Trans. Sensor Netw.*, vol. 6, no. 1, 2009, Art. no. 7.

[26] M. Moshtaghi *et al.*, “Anomaly detection by clustering ellipsoids in wireless sensor networks,” in *Proc. Int. Conf. Intell. Sens., Sens. Netw. Inf. Process.*, 2009, pp. 331–336.

[27] M. Moshtaghi *et al.*, “Incremental elliptical boundary estimation for anomaly detection in wireless sensor networks,” in *Proc. IEEE 11th Intl. Conf. Data Mining*, 2011, pp. 467–476.

[28] N. Shahid, S. B. Ali, K. Ali, M. A. Lodhi, O. B. Usman, and I. H. Naqvi, “Joint event detection & identification: A clustering based approach for wireless sensor networks,” in *Proc. IEEE Wireless Commun. Netw. Conf.*, Shanghai, China, 2013, pp. 2333–2338.

[29] R.-H. Jan and Y. R. Lee, “An indoor geolocation system for wireless lans,” in *Proc. Int. Conf. Parallel Process. Workshops*, 2003, pp. 29–34.

[30] S. Khodayari *et al.*, “A RSS-based fingerprinting method for positioning based on historical data,” in *Proc. Int. Symp. Perform. Eval. Comput. Telecommun. Syst.*, 2010, pp. 306–310.

[31] X. Jiang *et al.*, “Feature adaptive online sequential extreme learning machine for lifelong indoor localization,” *Neural Comput. Appl.*, vol. 27, no. 1, pp. 215–225, 2016.

[32] Z. Chen, S. Wang, Y. Chen, Z. Zhao, and M. Lin, “InferLoc: Calibration free based location inference for temporal and spatial fine-granularity magnitude,” in *Proc. IEEE 15th Int. Conf. Comput. Sci. Eng.*, 2012, pp. 453–460.

[33] Z. Chen, S. Wang, Y. Chen, Z. Zhao, and M. Lin, “Combing multiple linear regression and manifold regularization for indoor positioning from unique radio signal,” in *Proc. Joint Conf. Pervasive Comput.*, 2009, pp. 611–614.

[34] S. Jain and M. Braathen, “Measuring the power consumption on cc2530znp using cc2530 znp mini kit,” Texas Instruments Inc., Dallas, TX, USA, Tech. Rep. An108, 2011.

[35] Texas Instruments Incorporated. Dallas, TX, USA, 2010. [Online]. Available: http://www.ti.com/lit/ug/swru268a/swru268a.pdf

[36] S. Xie and Y. Wang, “Construction of tree network with limited delivery latency in homogeneous wireless sensor networks,” *Wireless Pers. Commun.*, vol. 78, no. 1, pp. 231–246, 2014.

[37] K. Ali and I. H. Naqvi, “Evetrack: An event localization and tracking scheme for WSNS in dynamic environments,” in *Proc. IEEE Wireless Commun. Netw. Conf.*, 2016, pp. 1–6.

[38] N. Shahid S. B. Ali, K. Ali, M. A. Lodhi, O. B. Usman, and I. H. Naqvi, “Joint event detection & identification: A clustering based approach for wireless sensor networks,” in *Proc. IEEE Wireless Commun. Netw. Conf.*, 2013, pp. 2333–2338.

[39] M. Nasim *et al.*, “An energy efficient cooperative hierarchical MIMO clustering scheme for wireless sensor networks,” *Sensors*, vol. 12, no. 1, pp. 92–114, 2011.

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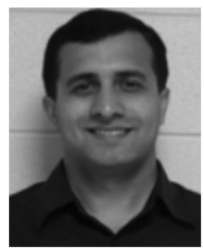

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