WIRELESS COMMUNICATION SYSTEM DESIGN FOR UNDERGROUND MINE

A thesis submitted in partial fulfilment of the

requirements for the degree of

B.Tech. & M.Tech. DUAL DEGREE

in

MINING ENGINEERING

by

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Certificate

This is to certify that the thesis entitled "**WIRELESS COMMUNICATION SYSTEM DESIGN FOR UNDERGROUND MINE**" submitted to the National Institute of Technology, Rourkela by **Ashutosh Patri**, **Roll Number 710MN1164,** for the award of the **B.Tech. & M.Tech. Dual Degree** in Mining Engineering is a record of bona fide research work carried out by him under my supervision and guidance. The results presented in this thesis has not been, to the best of my knowledge, submitted to any other University or Institute for the award of any degree or diploma. The thesis, in my opinion, has reached the standards fulfilling the requirement for the award of the B.Tech. and M.Tech. Dual Degree of Technology in accordance with regulations of the Institute.

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Abstract

Deployment of Wireless Sensor Networks (WSN) and wireless communication system has become indispensable for better real-time data acquisition from the ground monitoring devices, gas sensors, and equipment used in the underground mines as well as to locate the miners. The conventional methods i.e. use of wire for communication is found inefficient and ineffective at the time of mine hazards such as roof falls, fire hazard etc. Before the implementation of any wireless system, the variable path loss indices for different workplace should be determined. This helps in better signal reception and localization of sensor nodes. This also enhances the way of tracking the miner carrying the wireless device. An attempt has been made for the determination of parameter of a suitable radio propagation model. It includes the results of an experiment carried out in GDK-10A incline, SCCL, India. The path loss indices at different areas along with other essential parameters for accurate localization have been determined using XBee module and ZigBee protocol at 2.4 GHz frequency.

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INTRODUCTION

1 Introduction

Communication is the activity related to the transmission of signals for the sake of information exchange. In underground mines, communication is the crying need both from safety and productivity point of view [1, 2]. Keeping pace with the business market and lifestyle of the miners, which demand more reliable communication methods, more and more researches have been made for improving the technology from the beginning of 20th century. Underground communication methods are lagging behind the surface level communication which is now crowned with 4G technology. The less improved communication inside underground mine is not only due to lack of interest in this area but also for the unfavourable and hazardous environment. Communication is mainly comprised of transmission of data from the sender to receiver which may be in groups or from a miner to another miner, in which transmission deals with the amount and speed of the data through the transmitting medium. This seems very simple as a huge amount of data can be sent at a very high data rate through cables or optical fibres in which noise can be easily eliminated without using any special techniques. But the real facts say wired communication is worthless at the time of need (i.e. at the time of exposure to fire, roof fall, power or battery failure, and at the time explosion). This encourages wireless communication in underground mines.

1.1 Objectives

The main aim of the project is as follows:

1. To design a wireless communication system and that should be reliable, efficient, safe, portable, and cheap.
2. Testing of the designed system in a real underground mine scenario.

1.2 Methodology

To achieve the above said objectives, the following methodology was adopted.

1. **Literature review:** The collection of all the past works done by various academicians/researchers/scientists both national and international.
2. **System design:** A low-cost wireless system was designed.
3. **Experimentation:** The efficiency of the designed system was tested in an underground coal mine.
4. **Analysis:** Data analysis of the experimented data was done to achieve accurate localization.

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LITERATURE SURVEY

2 Literature Survey

2.1 Types of communication system for underground mine

Conventional systems or the wired system is comprised of magneto phones, paging phones, voice-powered phones etc. Magneto phones are the oldest crank ringer phones of the 20th century operated by DC batteries and AC signals [3]. Paging phones are partly line wired phone for voice communication with no tracking capability [4]. When high voltage trolley line is used as signal path only for voice communication then it is called as the trolley carrier phones system. Hoist rope system is nearly same as trolley carrier phones except that the hoist radio signal is inductively coupled to hoist rope through the use of capacitor as coupling device with the trolley carrier phones.

Through The Earth (TTE) system is a well-known system providing alarming, tracking and messaging with the help of loop antennas on surface of mine which transmit low-frequency signal to receivers, integrated into cap lamps [5]. Whereas, wireless network system deals with Wi-Fi (IEEE 802.11), Bluetooth (IEEE 802.15) and Wi-Max technologies. Ultra Wide Band (UWB) system is another radio system for short-range communication with very low power at a very high data rate [6-10].

RFID System is comprised of radio frequency identifier tags, RFID readers, routers and a host station. RFID tags are very small chips which store a specified amount of data in its circuitry. RFID tags are of two types, active and passive; in underground mine active tags should be used as the signal range is nearly 100 metre for active tags whereas for passive tag’s the range is practically 6-8 metres. In each level of the underground mine, routers are placed for a specified region and these routers act as intermediate for host station and RFID tags. Routers give the information about the tags which are in its coverage region and the RFID Reader reads the tag information and sends it to the host station. By this way miners position can be located and monitored by tracking and monitoring software. Attendance of miners can also be taken by this method and in the event of an undesirable situation the miners can be saved from the trapped zone [11, 12].

ZigBee is new wireless technology guided by IEEE 802.15.4 Personal Area Network standard. It is primarily designed for the wide-ranging controlling applications and to replace the existing non-standard technologies. It currently operates in the 868MHz band at a data rate of 20Kbps in Europe, 914MHz band at 40kbps in USA, and the 2.4GHz ISM bands Worldwide at a maximum data rate of 250kbps. The sensor nodes in the underground section will send the collected data to the wireless network and then to the host or database for further analysis.

For TTE communication radio wave attenuation creates the main problem. Attenuation is dependent on the frequency of radio wave, earth conductivity, transmission power, antenna type and noise over the surface and in the underground [13-15]. To decrease the attenuation, low or very low-frequency radio waves should be used. According to MSHA rules more power can’t be transmitted through the earth due to the risky conditions and noxious gases present in the mine environment. In such conditions, helical ferrite antennas are very much helpful for a long range duplex voice communication and text messaging at very low power transmission. These low-cost antennas are also small in size which can be mounted or wound around the pipes or pillars present in the underground mine. It also enables the communication in case of roof fall.

Multi-hop Protocol technology is developed to provide long-range wireless communication inside the mine (through the air) by using portable relay nodes. These nodes carry the data in packet form and this is a half-duplex communication method. By implementing this method, instructions can be given to the rescue robots with a certainty of guaranteed data transmission [16].

Voice over Sensor Network in underground mine works for the data communication between the sensors and the host station [17]. But nowadays wireless sensor network is developed to use the wireless network for real-time voice streaming in a TDMA based bi-directional communication. Audio signals are compressed and then modulated in the carrier radio wave as the wireless network works for low-frequency bandwidth.

2.2 **Development of communication system**

Since the US Bureau of Mines performed experiments to detect radio signals from their experimental mine in Bruceton, Pennsylvania, a lot of research has been done in the area of communication in underground mines [18].

Use of leaky feeder technique was first introduced using simple open-braided coaxial or a twin-lead cable connected to one or more standard VHF base stations [19]. From 1970 to 1980 communication technology for underground mines emerged. In this decade, radio waves in the tunnels of coal mines were also studied theoretically, mainly focusing towards the rate of loss of signal strength along a tunnel and around a corner.

Implementation of ultra-high-frequency (UHF) radio communication and closed circuit television (CCTV) system was done in the Black River Mine near Butler, Kentucky [20]. Use of passive reflector to increase the quality and distance travelled by radio wave was also successfully implemented in this mine.

Techniques were developed to measure the electromagnetic noise in and above the mine due to mine machinery used in Itman No-3 mine and McEloroy mine, West Virginia. Leaky feeder radio system using the signal booster for powerful amplification was improved in many underground mines.

Utilising the EM waves in the frequency range of 630 to 3030 Hz (in the voice frequency range) research was done for detection of trapped miner inside a coal mine with the help of regression analyses and probability calculations. In 1980, U.S. Department of the Interior, Bureau of mines, conducted a data analysis in eleven coal mines for the radio wave propagation at 50 KHz to 5000 KHz frequency [21-23]. In 1980-90 low and medium frequency radio system was developed by Dr. Stolarczyk, which provides both TTE and inside the underground communication utilising two robust signal transmission mode which were Seam Transmission mode (medium frequency-300 to 23000Khz) and Conductor Transmission Line mode (low frequency-30 to 300Khz) [24].

From the mid of 1990's a new deployable and adaptive Mobile Ad Hoc Network (DAMAN) protocol by Sarnoff corporation, Washington, has been enabling the formation of self-organizing, self-routing and self-maintaining communication networks. This supports continuous data communication between many highly mobile users, ideal for underground rescue operations [25]. Tele Mag wireless system (United States) is a two-way (duplex) system both for voice and data communication operating at a frequency range of 4 KHz which was first demonstrated in august of 2000 at NIOSH Lake Lynn Laboratory Mine [26].

A system composed of beacon contained in a miner's cap lamp and handheld location receiver for trapped miner's beacon was tested at Tirol mine up to a detection accuracy of 50 cm.

In the Val d'Or mine, Canada, experiments gave fruitful results regarding mesh wireless local area network (WLAN) using WAP (Wireless Access Point) protocol [27]. Since 2007 Rajant and Mine Site Technologies (MST) offers digitally based communication systems for mines. Rajant offers a variety of Bread Crumb units and configurations to meet specific portable mesh-networking needs. Bread Crumbs are MSHA approved, and classified as intrinsically safe (IS).

In 2008 Western Australian gold mine's management system installed VDV Leaky feeder technology (advanced very high-frequency leaky feeder). In 2009 installation of the BlastPED as the mine's remote and centralised blasting system took place.

SIAMnet Communication system uses the cable modem and coaxial cable for voice and data communications in underground mines. It is a cost-effective alternative to fibre optic and leaky feeder technologies for voice and data communication in undergrounds mine. One coaxial cable supports up to 32 simultaneous voice transmissions, three 1.5 Mbps mobile data sub-networks each supporting up to 64 UG vehicles, and 12 DOCSIS 1.1 cable modem channels for total of 360 Mbps downstream and 120 Mbps upstream. Modem and 802.11 access point draw power through the coaxial cable. By the help of this system hard wired or wireless VoIP telephones may be used underground as well as at the surface. Vehicles can be monitored wherever there is coverage in the area where the vehicle is situated. Engine condition can be checked and instructions can be sent to the operator for quick actions.

SIAMnet provides Voice and Mobile Data Communication with High-Speed Data rate along with Wireless Applications and Video Communication [28].

In the South African mining industry, most of the mines implement Radiaflex cable for communication purpose. The first installation of 1/2-inch RLK Radiaflex cable was successfully implemented in the South Deep gold mine by the beginning of 21st century. Originally it was designed to provide immediate and near-future 3G cellular confined coverage requirements. The Radiaflex cables in the mine are used for multi-level UHF-based voice, video and data communications.

In Europe from the year of 2007, Mine Radio Systems Inc. offers the following Integrated Safety and Communication Solutions.

- Leaky Feeder based communications
- Voice, Video and Data
- Personnel, Vehicle and Asset Monitoring and Control
- Collision Avoidance
- Ethernet over Leaky Feeder
- Trapped Miner search and location
- Equipment remote control and monitoring.

The personal emergency device (PED) communication system is one way TTE system operating at the frequency range of 1 KHz for digital text messaging first demonstrated in United States in 1990. The first successful evacuation of miners attributed to PED technology occurred during the Willow creek Mine fire in Helper, Utah, on November 25, 1998. It is a portable device which utilises Ultra Low Frequency (ULF) range for mine-wide text messaging

There have been several folds of advancements in the mining industry in last three decades. The primary focus has always been on the improvements of heavy machinery, support systems, and safety equipment. But in the last few years the focus has shifted to the development of communication systems both for safety and communication purpose. In this context, Wireless Sensor Network (WSN) [29, 30] having an upper hand over the wired systems in terms of their efficiency, speed and applicability in an emergency conditions has come on the top of the list [31]. The present scenario of mining industry gives an impetus to achieve a reliable wireless system in the harsh underground mine environment [11]. Some of the recent works are also oriented towards the radio propagation model and wireless communication.

An experimental result has also shown that the signal propagation models for an indoor environment is similar to underground mine scenario at 900 MHz [32]. This indicates that the wireless motes used in the indoor environment can also be used in mines with some modifications. Underground mine can be considered as a hybrid case of regular and harsh environment. The above experiment also revealed most of the critical parameters of wireless channel propagation in underground mines are similar to indoor environment [33].

Some experimental studies have also been carried out in underground mine at 900 MHz to evaluate the additional losses due to the curvature of the passageway and presence of common coal mining equipment in the underground coal mine [34]. Based on this, the waveguide propagation model for mining scenario has been also modified. Zhang et al. experimented at two different scenarios i.e. passageway and mining zone of longwall coal mine. The model uses both free space propagation model and a modified waveguide propagation model to represent the mining scenario appropriately. This involved the hybrid tunnel propagation model to describe the propagation characteristics.

In [35] some commercial and licence free simulation tools have also been developed for path loss calculation and propagation modelling. In this model, the simulations are done by varying the frequency with a standard tunnel dimension & shape and material properties. The effects of the barrier are also considered for algorithm design and simulation. The simulation results are compared with a real practical scenario and it proved that the path loss is mostly dependent on the tunnel dimension and the signal frequency.

Qi et al. briefly reviewed the WSN localization algorithms for various application and compatible devices. The study suggests that the algorithms should be developed taking routing protocol, energy-constraint, and dynamic nature of surrounding into consideration [36]. But in case of an underground mine these algorithms does not fit because of the dynamic environment. With the advancement in Micro-Electro-Mechanical Systems (MEMS), now a days transceivers working at 2.4GHz shows better performance in localization and are available at a reasonable price [37]. The better performance in localization is possible due to the high-directivity antenna and very high operational frequency. The presence of additional noise is relatively less and thus it gives higher accuracy in localization within a small range of area.

Liu et al. studied the transmission performance of WSN near mine-working face at 2.4 GHz frequency. All the electromagnetic wave properties are incorporated in their theoretical model and are compared with the experimental one. The effective transmission distance was studied for IEEE 802.15.4 known as ZigBee protocol [38, 39].

RADIO FREQUENCY PROPAGATION MODELS

3 Radio Frequency Propagation Models

A wireless propagation model can be defined as a mathematical expression or an algorithm for predicting radio characteristics of a particular type of environment. There are two types of wireless propagation model i.e. deterministic model and empirical model [40, 41]. The deterministic model has a very impractical drawback of not fitting into the real environment properly, however for low frequency waves; the results produced by the deterministic model are approximately equal to the actual result, with a very low rounding error. The variations due to environmental effects are largely insignificant in minute scales. But the operating range is very less in the high frequency channel as compared to the low frequency channel and hence elements present in the surroundings have a significant effect on propagation. The propagation models for wireless network are of three types i.e. free space propagation model, two-way ground model and log normal model. With the exception of the log normal model, which is empirical in nature, the other models are deterministic. These models are described in brief and the mathematical representations are given as follows.

3.1 Free space propagation model

It is a simplified model which assumes line of sight communication between the transmitter-receiver pair and there is no obstruction present between them. The mathematical representation of the model can be written as

$$P_r(d) = C_T\left(\frac{P_t}{d^2}\right) \quad (1)$$

Where, P_r and P_t represent the power received and power transmitted respectively. C_T is the constant depending on the transceiver and d is the distance between the transmitter-receiver pair.

3.2 **Two ray ground model**

This model is obtained by modifying the above model after taking into account the effect of reflection of signals. It is also assumed that both direct and reflected rays are used for communication. In this model the distance between the transmitter-receiver pair is much greater than the height of their individual heights and it can be represented as

$$P_r(d) = C_t \left(\frac{P_t}{d^4}\right) \tag{2}$$

Where, C_t is the constant representing transceiver characteristic in the two-ray ground model.

3.3 **Log-distance model**

It is an analytical and empirical model which can be mathematically represented as

$$P_r(d) \propto \left(\frac{P_t}{d^{\eta}}\right) \tag{3}$$

Where, η represents the path loss factor or distance power gradient.

The actual results vary from the results derived using log-distance model. Hence for hostile environments like underground mines, models have to be developed by using shadow fading phenomenon.

At high frequency, power loss is different for different locations owing to obstructions present in the path between two communicating devices. In Figure 1, a typical illustration of this fact is given where the dotted circle shows the ideal boundary of operation for an omnidirectional antenna placed at the centre, but the bold line shows the actual boundary of operation with a minimum and maximum range of R_1 and R_2 respectively due to presence of various obstructions. For this purpose empirical model is chosen over the deterministic model to predict or calculate power received at a particular distance from the transmitter [42].

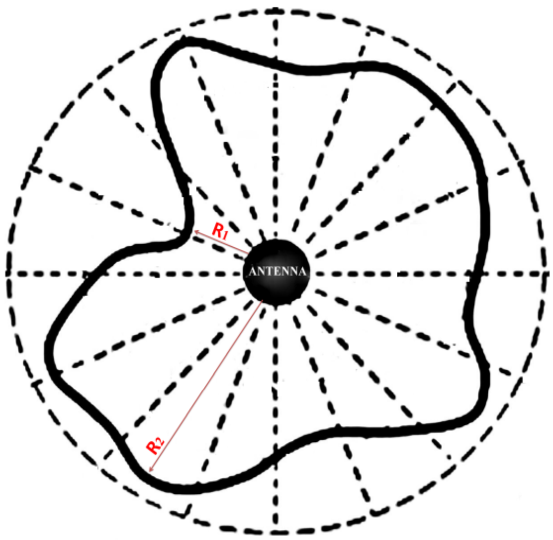


Fig.1: Variation in operation range due to fading of signal radiated from the omnidirectional antenna

Moreover the power loss can be subdivided into two parts on basis of fluctuation around the average path loss, i.e. Multi-path fading and Shadow fading. In case of Multi-path fading, the transmitted signal reaches the receiver through two or more paths causing both constructive and destructive interferences near the receiver which in turn leads to phase shifting and addition of noise. So, in a dynamic environment, where both the transmitter and receiver are stationary, the Received Signal Strength (RSS value) varies randomly due to the movement of objects and small changes in the environment. The long-term average of RSS values represents the effect of shadow fading of signal that is caused by the presence of a constant barrier present between the transceivers [42].

Although Time of Arrival (TOA), Angle of Arrival (AOA) and Time Difference of Arrival (TDOA) provide higher accuracy in most cases, they fail in a harsh mining environment [43, 44]. Therefore, Received Signal Strength Index (RSSI) based model for localisation has been developed. This low-cost RSSI based localisation provides less communication overhead with lower implementation complexity. The distance or range of signal could be calculated accordingly to the loss factor of the environment from the RSSI based equations (4) and (7).

3.4 **Shadow fading model and parameter determination**

The Log distance model can be represented more accurately by introducing a Gaussian distribution variable to represent the fading or fluctuation of received signal strength. The modified model is called Log-normal Shadowing model and it is most appropriate for wireless sensor networks since it is all inclusive in nature and can be easily configured according to the target environment [45]. The mathematical equation for the above relation can be defined as

$$PL(d)(\mathrm{dB}) = \overline{PL}(d_0)(\mathrm{dB}) + 10\eta\log_{10}\left(\frac{d}{d_0}\right) + \psi(\mathrm{dB}) \quad (4)$$

Where,

$$PL(\mathrm{dB}) = 10\log_{10}\left[\frac{P_t}{P_r}\right] \quad (5)$$

and d_0 is the near earth reference distance. The random variable ψ is the Zero-mean Gaussian random noise whose probability distribution fiction is given by

$$p(\psi_{\mathrm{dB}}) = \frac{1}{\sqrt{2\pi}\sigma_{\psi_{\mathrm{dB}}}}\exp\left[\frac{-\left(\psi_{\mathrm{dB}} - \mu_{\psi_{\mathrm{dB}}}\right)^2}{2\sigma^2{\psi_{\mathrm{dB}}}}\right] \quad (6)$$

The value of η depends on the surrounding or propagation environment as per equation (4). The distance d_0 is taken to be one meter for simplicity of calculation and it can also be represented in the terms of received power or RSSI as

$$\left[\frac{\overline{P_r}(d_0)}{P_r(d)}\right] = \left[\frac{d}{d_0}\right]^{\eta} + \psi \tag{7}$$

In equation (4), there are two unknown terms i.e. η and ψ which should be determined from experiments. The linear regression analysis for the data set with distance and received power as attributes gives the η value, which can be further used for that particular place with unknown distance and known received power to localise a wireless node.

In equation (4), the $\mathrm{Var}(\psi) = \sigma^2$ and $\mathrm{E}(\psi) = 0$, so it can be mathematically proven that $\mathrm{Var}(\sigma\psi_1) = \sigma^2$ and $\mathrm{E}(\sigma\psi_1) = 0$. This relation shows that the ψ function has the same distribution as ψ_1, where ψ_1 represents Zero-mean Gaussian distribution with unit variance. Equation (4) can be modified as

$$PL(d)(\mathrm{dB}) = \overline{PL}(d_0)(\mathrm{dB}) + 10\eta\log_{10}\left(\frac{d}{d_0}\right) + \sigma\psi_1\ (\mathrm{dB}) \tag{8}$$

Assuming maximum error with 95% confidence interval, the $\sigma\psi_1$ value can be replaced by 1.96 σ, which gives

$$\sigma_{i(exp)} = Y_i = \left(\frac{PL(d_i)}{1.96}\right) - \left[\left(\frac{\overline{PL}(d_0)}{1.96}\right) + \left(\frac{10\eta\log_{10} d_i}{1.96}\right)\right] \tag{9}$$

But, from the experiment carried out in the coal mine, the observational analysis shows that the standard deviation varies as a function of distance and on the basis of huge amount of experimental evidence, we claim it to be a forth degree polynomial function

$$\sigma_{i(obs)} = \mathrm{a}{d_i}^4 + \mathrm{b}{d_i}^3 + \mathrm{c}{d_i}^2 + \mathrm{e}d_i + \mathrm{f} \tag{10}$$

Now the observational error ε can be defined as the difference of these two terms i.e., experimental and observational σ.

$$\varepsilon = \sigma_{i(exp)} - \sigma_{i(obs)} \tag{11}$$

For avoiding negative error and for solving this, the objective function ϵ can be written as

$$\epsilon = \sum_{i=1}^{n}\left[Y_i - \left(\mathrm{a}{d_i}^4 + \mathrm{b}{d_i}^3 + \mathrm{c}{d_i}^2 + \mathrm{e}d_i + \mathrm{f}\right)\right]^2 \tag{12}$$

To obtain the values of the coefficients of the polynomial, i.e. a, b, c, e, and f, partial derivative method is adopted and it can be mathematically represented as the following set of equations

$$\frac{\partial\epsilon}{\partial a} = -2\sum_{i=1}^{n}\left[\left(Y_i - \left(\mathrm{a}{d_i}^4 + \mathrm{b}{d_i}^3 + \mathrm{c}{d_i}^2 + \mathrm{e}d_i + \mathrm{f}\right)\right){d_i}^4\right] = 0 \tag{13.1}$$

$$\frac{\partial\epsilon}{\partial b} = -2\sum_{i=1}^{n}\left[\left(Y_i - \left(\mathrm{a}{d_i}^4 + \mathrm{b}{d_i}^3 + \mathrm{c}{d_i}^2 + \mathrm{e}d_i + \mathrm{f}\right)\right){d_i}^3\right] = 0 \tag{13.2}$$

$$\frac{\partial\epsilon}{\partial c} = -2\sum_{i=1}^{n}\left[\left(Y_i - \left(\mathrm{a}{d_i}^4 + \mathrm{b}{d_i}^3 + \mathrm{c}{d_i}^2 + \mathrm{e}d_i + \mathrm{f}\right)\right){d_i}^2\right] = 0 \tag{13.3}$$

$$\frac{\partial\epsilon}{\partial e} = -2\sum_{i=1}^{n}\left[\left(Y_i - \left(\mathrm{a}{d_i}^4 + \mathrm{b}{d_i}^3 + \mathrm{c}{d_i}^2 + \mathrm{e}d_i + \mathrm{f}\right)\right)d_i\right] = 0 \tag{13.4}$$

$$\frac{\partial\epsilon}{\partial f} = -2\sum_{i=1}^{n}\left(Y_i - \left(\mathrm{a}{d_i}^4 + \mathrm{b}{d_i}^3 + \mathrm{c}{d_i}^2 + \mathrm{e}d_i + \mathrm{f}\right)\right) = 0 \tag{13.5}$$

The above set of equations can be solved in the matrix form, to obtain the coefficients

$$\begin{bmatrix} \sum_{i=1}^{n}{d_i}^8 & \sum_{i=1}^{n}{d_i}^7 & \sum_{i=1}^{n}{d_i}^6 & \sum_{i=1}^{n}{d_i}^5 & \sum_{i=1}^{n}{d_i}^4 \\ \sum_{i=1}^{n}{d_i}^7 & \sum_{i=1}^{n}{d_i}^6 & \sum_{i=1}^{n}{d_i}^5 & \sum_{i=1}^{n}{d_i}^4 & \sum_{i=1}^{n}{d_i}^3 \\ \sum_{i=1}^{n}{d_i}^6 & \sum_{i=1}^{n}{d_i}^5 & \sum_{i=1}^{n}{d_i}^4 & \sum_{i=1}^{n}{d_i}^3 & \sum_{i=1}^{n}{d_i}^2 \\ \sum_{i=1}^{n}{d_i}^5 & \sum_{i=1}^{n}{d_i}^4 & \sum_{i=1}^{n}{d_i}^3 & \sum_{i=1}^{n}{d_i}^2 & \sum_{i=1}^{n}d_i \\ \sum_{i=1}^{n}{d_i}^4 & \sum_{i=1}^{n}{d_i}^3 & \sum_{i=1}^{n}{d_i}^2 & \sum_{i=1}^{n}d_i & n \end{bmatrix} \begin{bmatrix} \mathrm{a} \\ \mathrm{b} \\ \mathrm{c} \\ \mathrm{e} \\ \mathrm{f} \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{n}Y_i{d_i}^4 \\ \sum_{i=1}^{n}Y_i{d_i}^3 \\ \sum_{i=1}^{n}Y_i{d_i}^2 \\ \sum_{i=1}^{n}Y_i d_i \\ \sum_{i=1}^{n}Y_i \end{bmatrix} \tag{14}$$

By knowing the coefficients and path loss index for a particular place the standard deviation and the power loss due to fading can be calculated for new set of data with known RSSI and unknown distance, for accurate localisation.

EXPERIMENTATION

4 Experimentation

4.1 Instruments and set-up

A pair of XBee series-1 modules, one being used as a transmitter and the other as a receiver, which implement ZigBee protocol, each capable of transmission or reception, were used for wireless communication at 2.4 GHz. The specification of the XBee module is given in Table 1. Each of the XBee modules is configured by setting the preferred data rate, modulation technique, lapse rate between packets and other parameters using X-CTU software by mounting the modules on the XBee USB adapter (which has an onboard 3.3V low drop voltage regulator and Light Emitting Diode (LED) indicators for RSSI, Associate and Power) and then connected to a computer’s Universal Serial Bus (USB) port through a FT232 USB to serial converter. There are two modes of operation for XBee module; in Transparent Data Mode (AT) the signal coming to the Data IN (DIN) pin is directly sent to the receivers, while in Application Programming Interface Mode (API) (which was used in this study), the data is sent in the form of packets that include the receiver address along with a feedback for the delivered packets, payload information and various parameter settings to increase the reliability of the network and to send the signal safely over the wireless network [46]. The module has a mounted rubber duck wire antenna or whip antenna, which radiates in a nearly omnidirectional pattern. As there are very little distortions in the radiation pattern, it is considered that the antenna radiates equal power in all azimuthal directions.

Table 1. Specifications of XBee module

Parameters	Property
Raw Data Rate	2.4 GHz: 250 kbps (ISM band)
Maximum Range	Indoor: 30m; Outdoor (Line of Sight): 100m
Receiver sensitivity	-92 dBm (1% Packet Error Rate)
Channels	16 channels
Addressing	Short 8 bit or 64 bit IEEE
Temperature	-40 to +85 deg. Celsius
Channel access	CSMA-CA (Carrier Sense Multi Access- Collision Avoidance)

This module also supports Universal Asynchronous Receiver/Transmitter (UART) Interface which is beneficial for clock setting and connecting it to a microcontroller. The ATMEL Atmega-32 Microcontroller (14.7456MHz crystal) development board was used which has a compatible UART serial communication integrated circuit along with Electrically Erasable Programmable Read-Only Memory (EEPROM), Static Random Access Memory (SRAM) and in-system self-programmable flash memory of 1024, 2k and 32k bytes respectively. It has an in-built reverse polarity protection and the 7805 voltage regulator has a heat sink for continuous dissipation to supply 1amp current constantly without over-heating. The Request to Send (RTS) and Clear to Send (CTS) module pins can be used to provide flow control. CTS flow control provides an indication to the host to stop sending serial data to the module. RTS flow control allows the host to signal the module not to send data in the serial transmit buffer through the UART. Data in the serial-transmit buffer will not be sent out through the Data OUT (DOUT) pin as long as RTS is de-asserted or set high. The UART connections for the transmitter and receiver module are shown in Figure 2. The module operates in a low voltage range of 2.8-3.4 volt, but for the whole setup, a pair of 12V- 1.3Ah DC battery of lead-acid type was used, one for each node. This battery can be replaced by a cap lamp battery used in underground mines in compliance with Directorate General of Mine Safety-India (DGMS) standard. A Liquid Crystal Display (LCD) is programmed and connected to the microcontroller unit present at the receiver to display the desired output. The used transmitter and receiver units are shown in Figure 3.

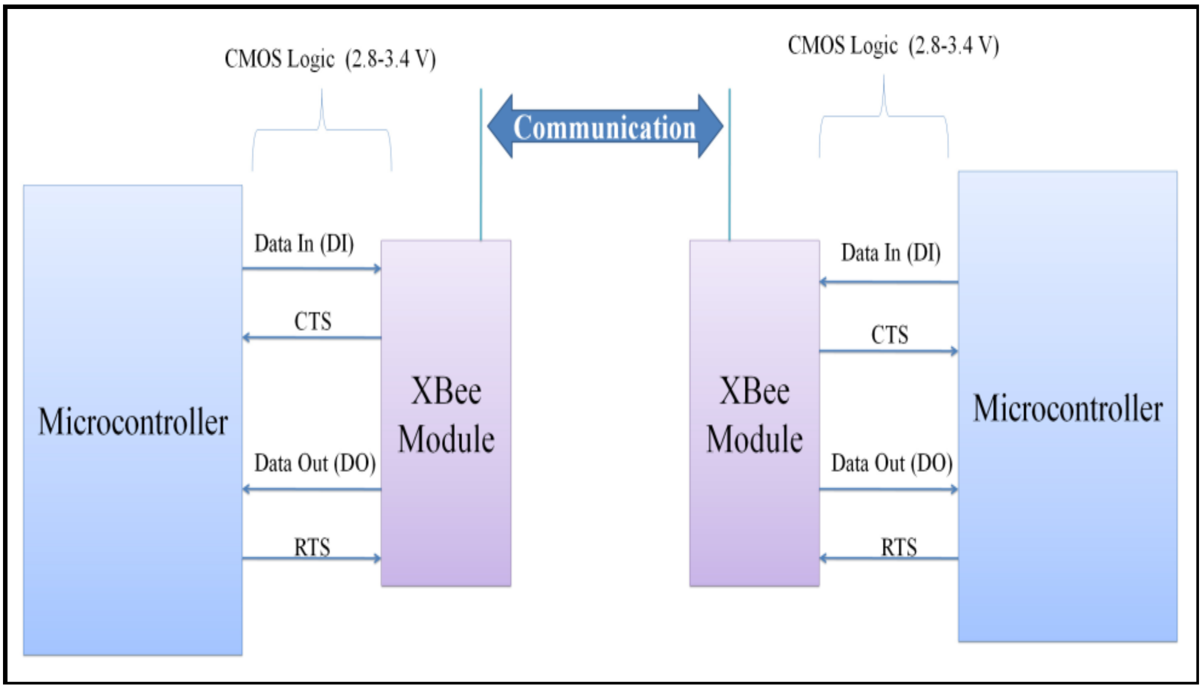


Fig.2: UART connections for the transmitter and receiver module

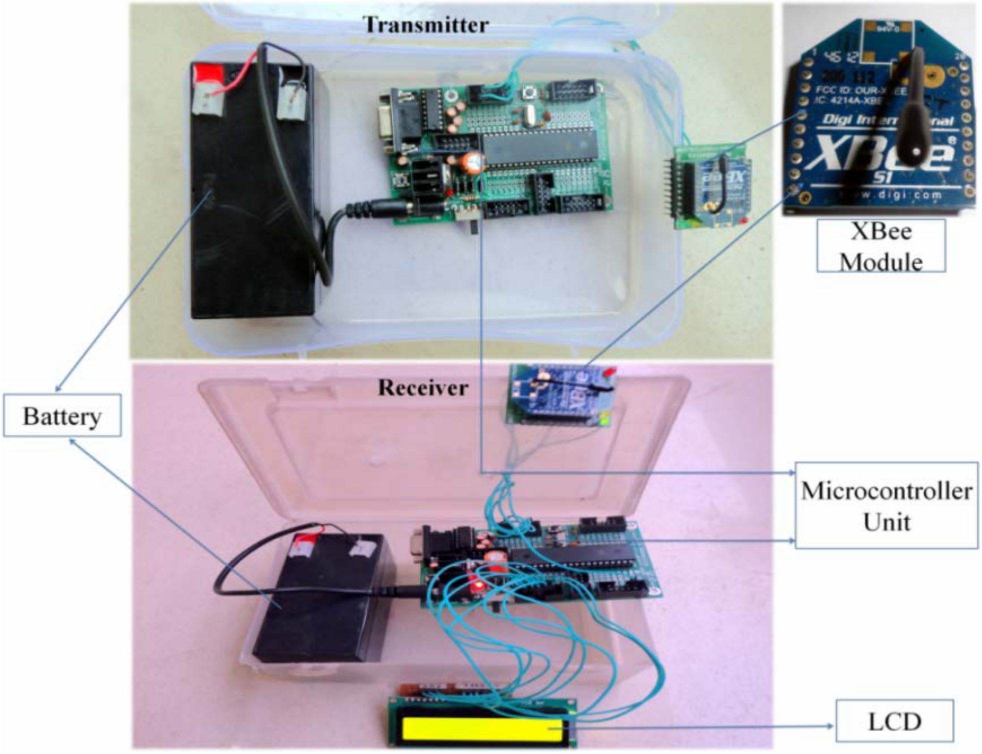


Fig.3: Transmitter and Receiver unit

For use in underground mine, the electronic instrument must be intrinsically safe to avoid any fire hazard. Since ZigBee protocol based wireless modules have been used in underground mines worldwide, they can be considered as intrinsically safe for most of the underground mining scenarios in India [3, 47]. Parameters required for the XBee module to be intrinsically safe are specified in Table 2 [48]. The ZigBee protocol is based on the Carrier Sensing Multiple Access (CSMA) with Collision Avoidance (CA) channel access to provide energy saving, latency and negligible error in the received data packet. Direct Sequence Spread Spectrum (DSSS) modulation is used in the PHY layer that has high resistance for noise or jamming. ZigBee standard supports star, tree and mesh network, thus permitting numerous applications. In sleep mode, it uses only $0.1\mu A$ that helps in energy saving during its idle period. It supports AES-128 encryption that converts a 128 bit plain-text to a 128 bit cipher text. It has the capacity to acquire more than 256 Peer to Peer connections in a master-slave configuration; which is very high compared to other wireless protocols used in day to day life.

Table 2. Parameters required for intrinsically safe instrument

XBee Series 1 IEEE 802.1.5.4 Properties	**Values**
Maximum power at antenna connector	2mW
Maximum current at antenna connector	7mA (AC current at 2.4GHz)
Sum total of all capacitance on PCB	757pF
Sum total of all inductance on PCB	60nH
Largest capacitor on PCB	220pF
Largest inductor on PCB	56nH

The experiment was divided into two parts namely RSSI and Range test; RSSI test provides the data for determining path loss index and various parameters affecting the localisation and fading of power and Range test gives the operation range of aforesaid module in different underground mine scenarios.

4.1.1. ***RSSI-test***

The first set of readings was taken at the longwall-face with shearer, hydraulic power supports, AFC, Stage Loader and other machinery which obstructed the wireless signal. To avoid fast fading of signal, the readings were taken in a static environment free from the presence of moving machinery or men in between the transmitter-receiver pair. The second set of readings was taken beside the belt conveyor system, in running condition, installed in the gate-road of the mine, which would have created some fast fading.

4.1.2. ***Range-test***

The range test was conducted in three different places, i.e. near the longwall-face, the belt-conveyor system and in the inclined mine-car pathway.

4.2 Experimental procedure

Firstly, RSSI-test was performed and readings were taken by fixing the transmitter node at the beginning of the longwall-face close to the hydraulic powered roof support at a height of 1.5m from the floor. Both the transmitter and receiver setups were kept at a distance of 1m and 2m from the chocks and the working face respectively. The transmitter node was programmed to send 100 packets with a delay interval of 500ms between two subsequent packets and LCD showed the average RSSI over these 100 packets. Twenty number of RSSI readings were taken at each position of the receiver node and the same procedure was repeated up to a distance of 20 meters with one-meter step size. The Packet Received Rate (PRR) was also calculated and displayed on the LCD at one-meter distance interval and all the readings were taken in the line of sight condition. The second set of readings was taken on gate-road near the belt-conveyor system. The transmitter node was fixed at a location exactly 1m above the floor, half a metre away from the belt conveyor and the receiver node was kept at varying distances (1-20m) from the transmitter node along the passage.

The Range-test for the XBee module was then carried out sequentially in all the three areas by fixing the transmitter node at a particular location and moving the receiver node away from the LCD till it showed a ‘0’ value for the RSSI and indicated the packet sent by the transmitter could not be received beyond that particular distance.

RESULTS AND ANALYSIS

5 Results and Analysis

5.1 Case study

Data was collected from GDK-10A incline, located at Ramagundam Area-III of Singareni Collieries Company limited (SCCL), Karimnagar District, Telangana, It covers an area of 855.7Ha between longitude 79^0 33′ 45″ to 79^0 35' and north latitude of 18^0 38′ 15″ to 18^0 41′ 45″. In Figure 4, a schematic layout of longwall mine is provided. The mine was started on 6th September, 1985 and production commenced from February, 1990. The Seam-1 is extensively developed and the minimum and maximum depths are 175m and 310m respectively with a seam thickness of 6.5m.The mining carried out at GDK-10A is of retreating type and the operating range is 2.8-3.6m. The crossing point and ignition point temperature of Seam-1 are 131^0C and 155^0C respectively. The percentage of moisture and ash content are 5.79 % and 32.66 % respectively. Bokkalvaagu (seasonal nallah over the mine) flows from west to east over this property.

The surface area is flat to undulating terrain with a gentle slope towards north-east and south. The surface reduced level varies from 856m to 866m. The coal seam is approached by driving two tunnels at a gradient of 1 in 4.5 and 1 in 5 for haulage and man way purpose to a distance of 450 and 500m respectively. Trunk roadways are developed with the help of Side Discharge Loader (SDL) and Road Headers and these are developed along the top section of the seam with sandstone roof. All the gate roadways for longwall panels are developed by Road Headers in the bottom section, with coal roof. The mine floor is mainly grey sandstone and a coal roof with a clay band of 0.30m.

Both the head and tail gate-roads are parallel driven through the seam-1. The gate-road wall surface is rough and water percolates from the strata and the gate-roads. The gate-road bearing the belt conveyor system has an average height and width of 3.6 and 4.2m respectively. The conveyor belt is at a height of 1.32 to 1.4m from the floor. The belt has a width of 0.8 to 1.2m with a capacity of 1200TPH and mainly made of rubber material. The belt conveyor system is supported by a steel structure. The average lump size carried by the belt conveyor is of 200×200×200 mm^3. The roof supports are generally wire-mesh type with bolts and girders.

The length of longwall face is around 150m and width around 1km with an average depth of 350m from the surface. Anderson made Double Ended Ranging Drum (DERD) shearer is used with a diameter of 1.83m and a web width of 0.85m and it has a cutting capacity of 800TPH at 3 m min^{-1} and 1600TPH at 6 m min-1. Caterpillar made Independent Front Suspension (IFS) based hydraulic powered roof supports are provided with a bearing capacity of 4×800 T and support density of 110-120 $\mathrm{T\,m^{-2}}$ along with PMC-R controlled 101 hydraulic chocks used in a face. Anderson made bridge type stage loaders are used in gate-road to transport the coal from Armoured Face Conveyor (AFC) to belt conveyor. The 260m long DBT made AFC is used in a face with a pan size of 232×844×1500mm^3 and deck plate thickness of 35mm at an average chain speed of 1 m s^{-1}.

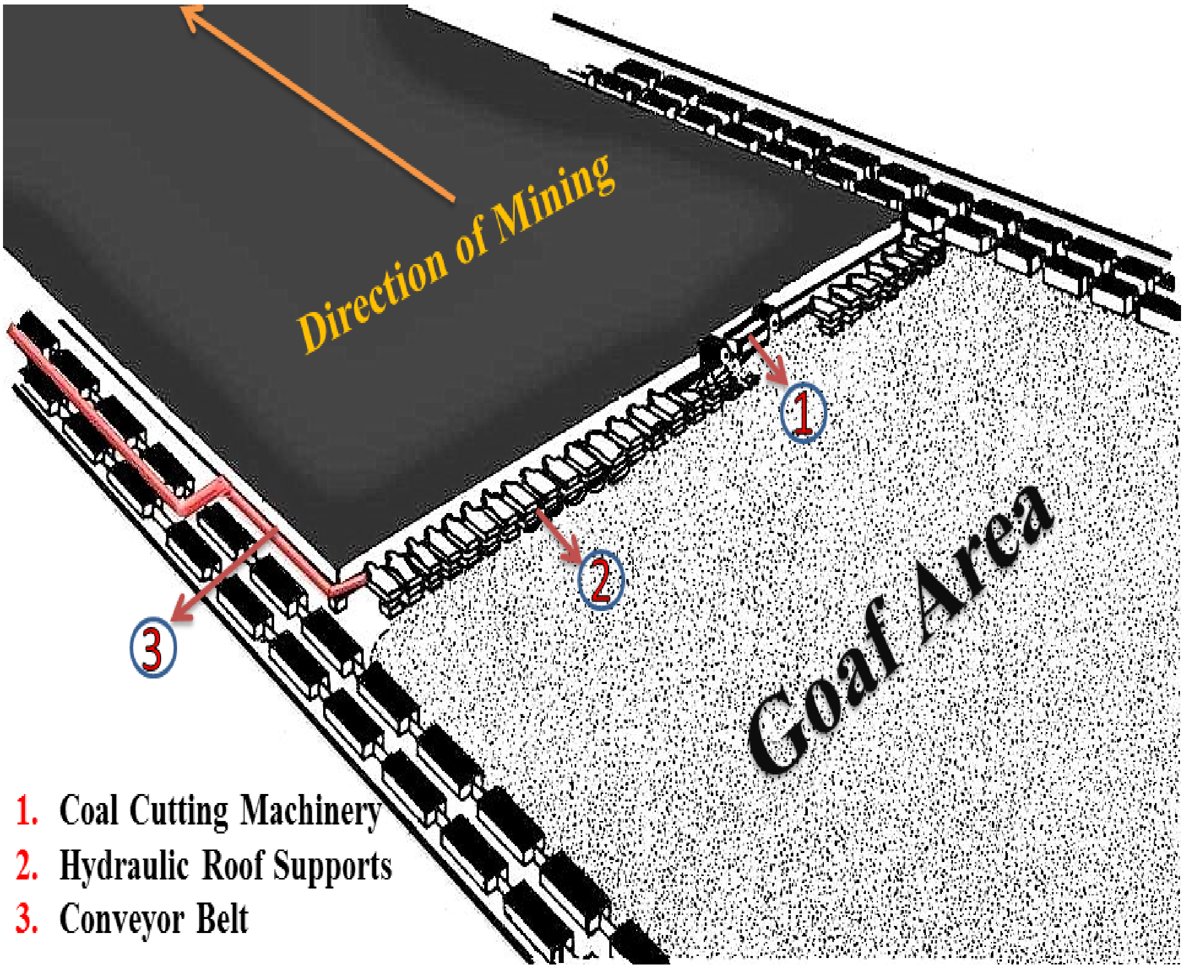


Fig.4: Schematic layout of longwall mining method

5.2 Results

The data collected near the working face and the gate-road belt-conveyor passages are represented in Table 3 and 4 respectively and the standard deviation was calculated for each set of RSSI values on every location.

The Standard Deviation (SD) can be calculated as

$$SD = \sqrt{\frac{\sum(X-M)^2}{n-1}} \tag{15}$$

Where, M = Mean and X = Different values of RSSI.

Table 3. Data collected near the longwall face of GDK-10A.

Distance (m)	**M (dBm)**	**SD (dBm)**	**PRR (%)**
1	-51.65	0.48936	100
2	-57.65	2.00722	100
3	-71.5	4.54799	96.59
4	-69.8	3.67924	96.76
5	-73.95	5.78996	96.29
6	-76.1	4.93004	95.83
7	-76.85	5.83343	95.7
8	-78.45	6.88665	95.07
9	-80.25	6.04261	95.08
10	-76.55	6.60522	95.45
11	-76.8	5.94491	95.65
12	-81.15	4.56828	93.92
13	-80.95	3.64872	93.89
14	-81.85	4.22119	93.9
15	-79.35	3.54334	94.2
16	-80.95	4.20443	93.77
17	-82.6	4.87097	92.71
18	-81.6	3.93901	93.85
19	-84.15	4.51051	90.05
20	-86.85	4.88041	86.2

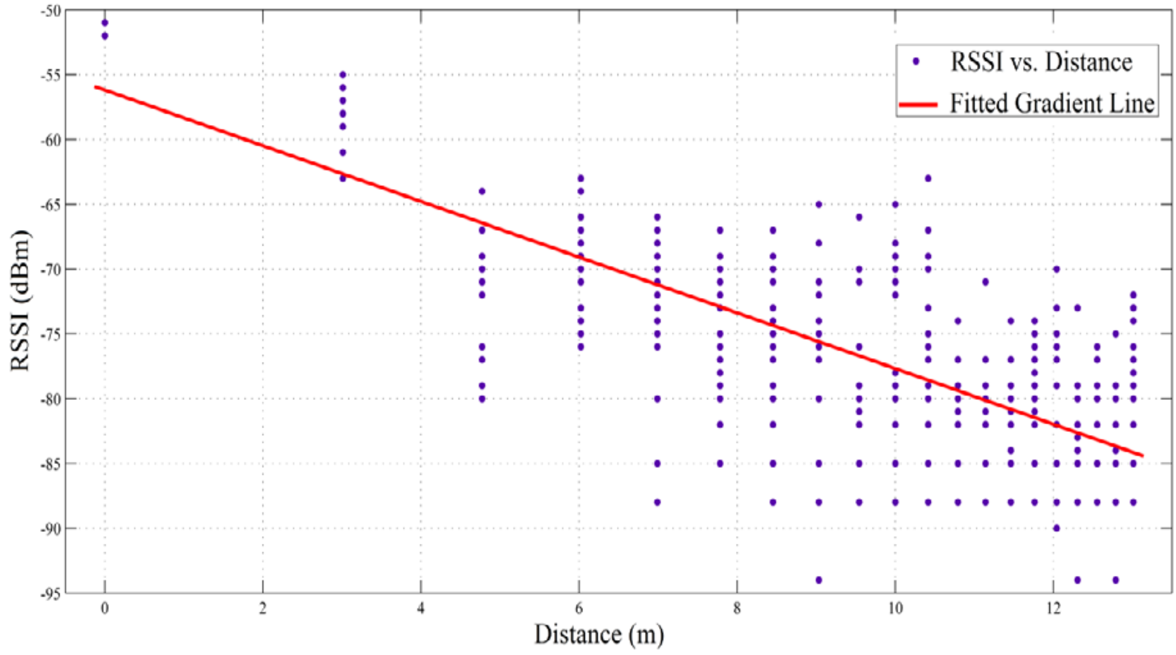
Table 4. Data collected near the gate-road belt conveyor

Distance (m)	**M (dBm)**	**SD (dBm)**	**PRR (%)**
1	-54.2857	3.48056	99.37
2	-60.0952	1.92106	99.3
3	-68.5714	7.59402	95.73
4	-67.0476	7.89087	95.22
5	-67	7.75887	96.19
6	-73	4.12311	96.04
7	-73.6667	6.5904	95.98
8	-70.6191	5.45414	96.53
9	-73.1905	6.14261	95.9
10	-68.2381	5.76052	96.3
11	-66.1905	4.44491	97.24
12	-69.5714	3.35517	96.83
13	-69	3.6606	96.89
14	-75	5.12119	95.5
15	-75.3333	4.23478	95.81
16	-79.8095	4.7394	94
17	-75.5714	3.99464	95.14
18	-76.5714	5.59081	94.63
19	-74.5455	5.41363	94.99
20	-83	5.54076	92.8

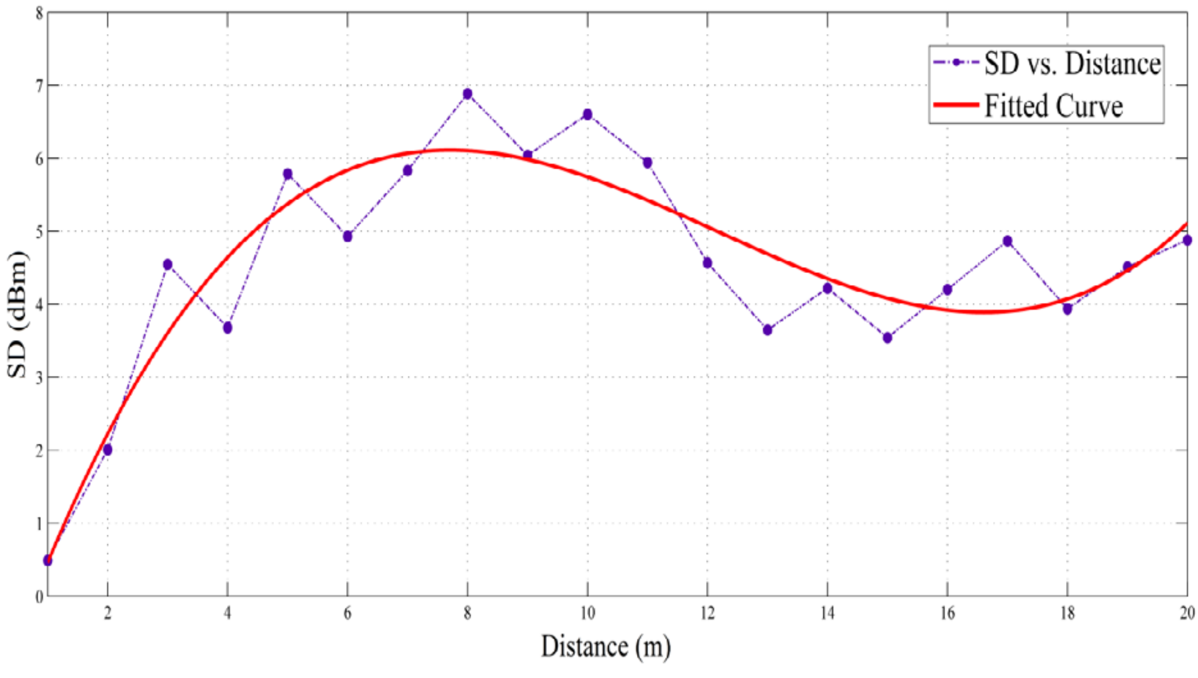
5.3 **Analysis**

*5.3.1. **Analysis of data collected near longwall face***

The MATLAB version 7.6.0.324 r2008a was used for the linear regression analysis model and the slope of the fitted line provides the path loss index for the corresponding place where the experiment was carried out. Figure 5 (A) depicts the scatter plot of received signal in dBm for longwall working face corresponding to the logarithmic distance. The straight-line is fitted using the linear regression analysis and the path loss index near the longwall face was found to be 2.14 which indicate the presence of more number of obstructions causing the fading of the signal. This implies that more number of repeaters should be placed and the inter node distance should be kept small as compared to typical outdoor scenario for which the index is 2. Due to the presence of metallic bodies, the fading is more and the power transmitted was degraded gradually, but the homogenous obstructions present in the surroundings and static nature of the environment offered less standard deviation from the mean RSSI values. The standard deviation is more concentrated in the region of 3.5 to 6. The values of PRR show a dependency on both standard deviations and received power with a higher correlation with the former. For the first 3 to 4m, the signal is less affected by the waveguide property of the tunnel and afterwards the effect increases gradually, but a trade-off is set up between the distance covered and the wave guide effect leading to a fluctuation of RSSI over a small range. As discussed in the section 2, the curve fitting was done to set up a relation between the standard deviation and distance to determine the coefficients for the longwall mining area as shown in Figure 5 (B). The coefficients *a, b, c, e* and *f* of fourth degree polynomial are found to be 2.626E-06, 0.006176, -0.2276, 2.403, and -1.721 along with R^2 and Root Mean Square Error (RMSE) of 0.8332 and 0.6958 respectively.



A)



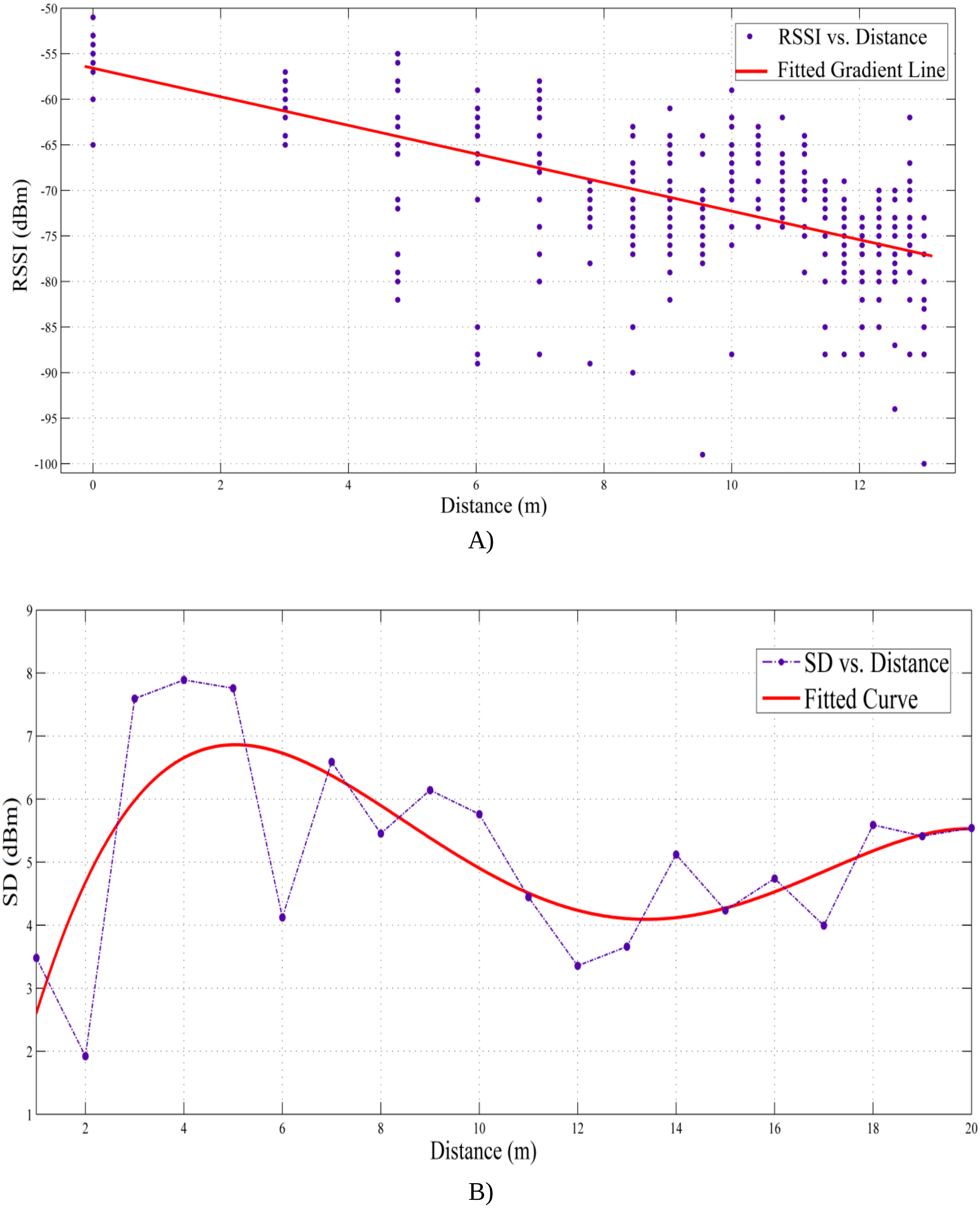
B)

Fig.5: A) Variation of RSSI with respect to distance near the longwall-face. B) Relation between standard deviation and distance near the longwall-face

5.3.2. ***Analysis of data collected near belt-conveyor gate-road way***

For the belt-conveyor gate-road, the path loss index was found to be 1.568, using linear regression analysis. Figure 6 (A) depicts the scatter plot of RSSI vs. the logarithmic distance. The lower value of power loss compared to the longwall-face was due to the predominant effect of the waveguide property of tunnel. The standard deviations (more concentrated in the region of 4 to 7.5) from the mean RSSI values were high as compared to the longwall-face area due to presence of inhomogeneous surroundings like different support systems, material and spacing between them, machineries, variable coal lump size carried by the belt and other distributive obstructions. Due to the movement of the belt conveyor carrying coal lumps with variable sizes, some fast fading was found, as indicated by the dispersal of data from the fitted line. The signal loss for a particular place was found to be more, as compared to its consecutive place readings, each taken at one-meter distance, due to the presence of girders over the receiver. The presence of less metallic bodies in the gate-road compared to the longwall-face lessened the fading effects. The signal propagation was mildly affected by the steel structure because the nodes were located higher than the belt conveyor support structure. Figure 6 (B) depicts the curve fitting for the fourth degree polynomial and the coefficients for determining the standard deviation as a function of distance was found to be -6.685×10^{-4}, 0.3418×10^{-1}, -0.5813, 3.599 and -0.4563 for a, b, c, e and f respectively. R^2 value of 0.474 and RMSE value of 1.281 indicate the fluctuation of standard deviation due to fast fading.

From the range-test, it was found that the XBee module provides satisfactory results up to a range of 40-45m, 60-65m, and 75-85m for the longwall-face, belt-conveyor gate-road and mine-car pathway respectively.



A)

B)

Fig.6: A) Variation of RSSI with respect to distance in the belt conveyor gate-road. B) Relation between standard deviation and distance for the belt conveyor gate-road

CONCLUSION

6 Conclusion

6.1 Conclusion

This study reveals that the efficiency of a communication system is dependent on the underground mine-surroundings. Before implementing any wireless system in underground mines, the path loss index and the variance of Gaussian distribution representing the shadow fading effect for that place should be determined. This helps in determining the distance at which repeaters should be placed in order to enhance the signal and localise the sensor node from its received signal strength. The XBee module facilitates satisfactory wireless communication over an adequate range of operation with negligible packet error rate. Following conclusions are drawn from the work,

- With increasing number of physical obstructions, the value of the path loss index increases, resulting in total loss of signal beyond a particular range.
- The PRR depends upon transmitter-distance and dynamic behaviour of the surroundings.

6.2 Scope for future work

The experiment was carried out in a hazard-prone underground coal mine. The experimental results may vary for different underground mines other than coal, due to the variation in earthy material, the dimension of tunnels, passages, galleries and working areas depending on the mining method adopted. So, future investigations should be made in various type of underground mines. In this work, two nodes have been used for experimental purpose; to ensure viability of ZigBee protocol further study may be carried out to analyse the network performance using more than two nodes.

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