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Performance analysis using IoT based underground miner's tracking and wireless voice communication system

This paper addresses an integrated wireless-fidelity (Wi-Fi) and radio frequency identification (RFID) based wireless system which has been developed for tracking of miners, wireless communication between miners and officials on surface. The system provides a walk through model in mine display and can predict mine-hazards. The system has been developed for providing emergency response using Internet of Things (IoT) enabled devices for tracking of trapped miners in a particular underground mine located using monitoring system and thereby sends real-time location to the concerned management and rescue team. The network performance has been analysed to assess the maximum operating distance, packet delivery ratio (PDR) and data communication capabilities. PDR was 6-7% more in normal surface conditions than mine environment for same transmission distance. This network analysis shows that with increase in distance between miner and the end device, the PDR decreases. Also increases in the number of hops in between end device and mine coordinator reduces the PDR.

Keywords: Packet delivery ratio, radio frequency identification, sensors

1.0 Introduction

Underground mining is considered one of the challenging fields due to its continuously varying environment parameters such as gases, temperature and humidity as well as the complex of geo-mining conditions. When these parameters cross the threshold limits it becomes hazardous for the miners working in underground mines. The potentially hazardous atmosphere, strata and hydrological conditions inside underground mines have mostly proved fatal for miners. A reliable monitoring, tracking and communication system is essential for safely working in harsh and continuously changing environment [1]. Many of mines are still using the manual tracking system to track which miners are in underground and there geological position. While using the manual tracking method at the beginning of the shift, foreman provides the list to the dispatcher with the list of miners names and where they would be positioned in the mine. If the miner changes his current location while in duty, he has to notify the same to the dispatcher using the dial phone inside the mine; simultaneously dispatcher updates the list of miners' exact location.

Manual tracking system has a number of limitations. In manual process miner location is provided within a section of working area which is quite difficult to point out the exact location of the miners and most of the time mines forget to provide the information about their current working location to the dispatcher. Nowadays to overcome the manual method several electronic tracking technologies developed [2]. In order to ensure personnel safety and boost mining operations, a robust and cost-effective miner tracking and communication system plays a vital role [3]. During evacuation process in emergency situations, there should be a provision of effective communication system for miners to interact, make decision and provide logistic support to the trapped miners [4]. It has always been challenging to design a robust and reliable network in underground mines due to the specific nature of mines [5]. To develop such reliable system, it is necessary to understand underground mines characteristics as well as different challenges faced by wireless and wired communication [6]. For devices to operate in such harsh environment, it should be made immune to high–moisture level, wide ranges of temperature and dust particles [1,7]. Generally, Wi-Fi based technology employed for the purpose of information exchange provides large delay, lower data transmission speed and data loss. To overcome the existing problem of wired communication system in underground mines, this effective technique has been developed for wireless communication [5].

To offer reliable means of communication with least amount of noise as well as ensuring personnel safety and

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protection of miners in underground mines, a portable and IP based voice communication system has been developed. Miners tracking and voice communication system helps to monitor miner's current location, path history display, emergency notification to the control room, warning of miner's entry into the restricted area, locating trapped miners, full duplex voice communication, to underground miners, display of important underground mine locations, etc. The paper presents the detailed information regarding the hardware and software parts of the developed underground Wi-Fi based voice and data communication system as well as its performance analysis.

2.0 Methods

2.1 System Description

The developed system is capable of providing a comprehensive wireless communication system based on Wi-Fi network for transferring sensor data, signals and from different locations of underground mine to a remote control room at surface as well as establishing wireless voice communication among miners and supervisors including tracking of miners.

This IoT-based system uses a single Wi-Fi network to transfer sensor data and voice from different underground mine locations to a remote-controlled room at the surface. The system also establishes wireless voice communication among miners and supervisors, including tracking of miners display. The hardware of the tracking system comprises cap lamp transmitter, wall receiver, access points and application software. Cap lamp transmitters are assigned to the underground miners. Access points and wall receivers are placed in strategic locations of underground mine galleries along the desired path for wireless communication by forming a dynamic mesh network. The software collects information from all the routers through a wireless network. This system also facilitates a portable wireless communication device for duplex communication, which allows both miners to speak and listen simultaneously, unlike walky-talky. These IP-based communication devices are used to communicate with a particular miner and also with multiple miners in broadcasting mode. Miners tacking and voice communication system of the present invention helps in monitoring miner's current location, path history display, emergency notification to the control room, warning of miner's entry into the restricted area, locating of trapped miners, duplex voice communication, voice broadcasting to the underground miners. Fig.1 depicts the implementation of miners tracking and voice communication module that uses a single Wi-Fi network for transferring sensor data and voice from different locations of an underground mine to a remote-control room at the surface as well as establishing wireless voice communication among miners and supervisors, including tracking of miners.

This is controlled by the microcontrollers and gives particular audio-visual alarm indications to miners working in highly explosion-prone areas. The system is designed to be intrinsically safe, flameproof and ingress protected for use in a hazardous underground environment. This system facilitates the development of a system to provide an emergency response using IoT-enabled devices for controlling different mining equipment and machinery to act according to the requirement in case of emergency/disaster. The controlling parameters relate to the operation of fan speed and switch off the power supply in case of increase in a high concentration of gases or explosion, tracking of trapped miners in the particular underground mine location using mine screen dashboard display and immediately sending SMS to the concerned

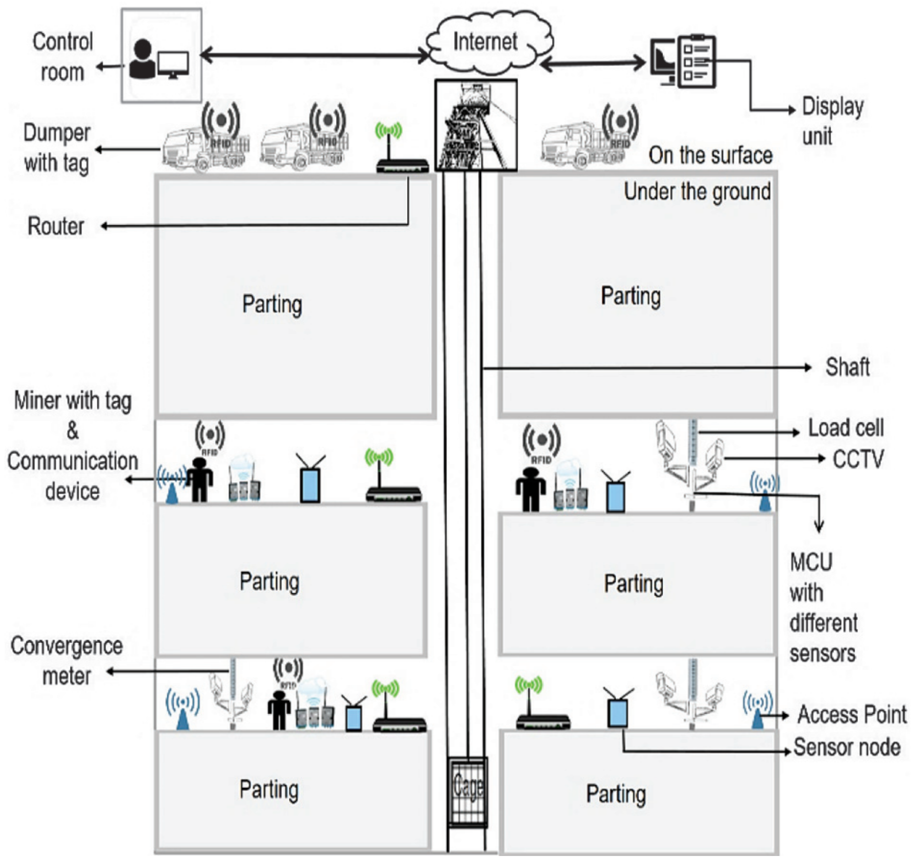

Fig.1: Schematic diagram of deployment of miners tracking and voice communication system in underground coal mine

Table 1

Device name	Device no.	Type (IS/FLP/IP)	Purpose
To be deployed below ground			
Wall receiver for miner's tracking	DM-WR-1	FLP & IP	Receiver devise for tracking and locating of miners working in underground mines
Cap lamp transmitter (miner's tracking device fitted in cap lamp)	DM-MT-1	IS & IP	Transmitter device for tracking and locating of miners working in underground mines.
Access point for wireless network	DM-AP-1	FLP & IP	For providing a network for voice, video, and data communication in underground mines
Wireless voice communication device	DM-VC-1	IS & IP	For facilitating full-duplex voice communication as well as broadcasting in underground mines

management, rescue team. This system has been developed by integrating hardware and software for monitoring, controlling and data processing of all the sub-systems.

2.2 Underground mines tracking module

The mine's tracking system includes the following modules are shown in Table 1

An IoT-based tracking system technology has the capability to track the miners in different location in every possible location with involving wireless mesh network (WMN) [8, 9].

In case of any kind of emergency occurs in underground coal mine getting the location information is valuable which is more important. The technology of RFID is considerably the most convenient method under such circumstances. Every miner has to carry the low-powered radio tags with their camp lamp embed, which has the ability to communicate with the ûxed transceivers mounted in underground mine. The location based information of the miner is extracted by tracking the previously occurred communication between the tag carried by a miner and the ûxed transceiver in continuous manners.

Flowchart diagram of the miner's tracking system developed for underground mine has been represented in Fig.2

Wireless routers and RFID receivers are configured and placed in underground mine are delimited in virtual map during router configuration in the system during configuration of routers. Miners and assets are categorised as per given RFID device. Device contains unique RFID transmitter, Node MCU and a panic button. Real time miners' tracking uses information sent by RFID through network created by the routers. The tracked data are shown in tabular from as well as mine map graphical form. The authorised user is notified using voice as well as text when panic button is

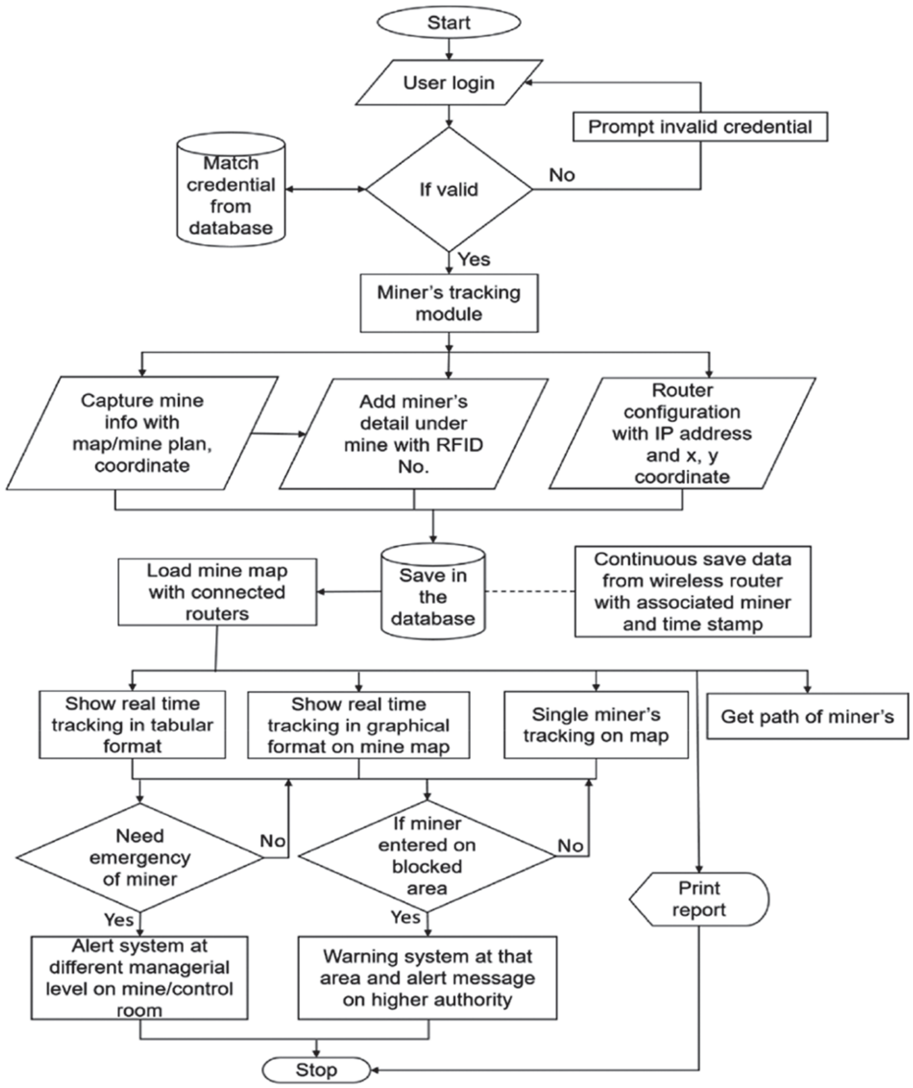

Fig.2: Flowchart diagram of miner's tracking system operation

pressed. Single miner path history is shown in map for each miner in a particular mine.

The robust system for tracking of miners offers larger range of communication between transmitter and receiver. A combination of Wi-Fi and RFID has been used to track the location of people and allow them to stay connected to the surface. Fig.3 shows block diagram of 434 MHz RF transmitter (Tx) that can be preferably attached to headlamp of miner.

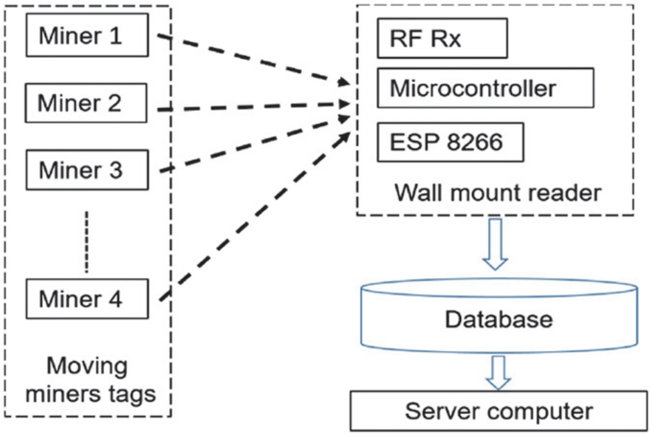

Fig.3: Block diagram of miner's tracking system

The RF transmitter transmits miner's ID to the nearest receiver. The ID is received by 434 MHz RF receiver (router), which adds its own ID to the miner's ID and send it to the server via node MCU. Each router has its unique ID. The tracking microcontroller based circuits have been used to track these RF transmitters. The tracker circuit is battery powered circuits which is carried by miner. Whenever, any miner comes in the range of the router circuit, the message i.e., miner and router ID (eg., M001 and R001) is transmitted to the online system. As positions of the routers are known beforehand, one can know by received message that which miner is near the respective router. Hence, exact position of the miner can be known inside an underground mine. A Wi-Fi module has been used to send data to the server. Miners tracking and voice communication module uses single Wi-Fi. The tracking system comprises RF (434 MHz) based custom active RFID tag, routers and application software. This system consists of two layers of data transmission, i.e. between miners and wall receivers, and between wall receivers and

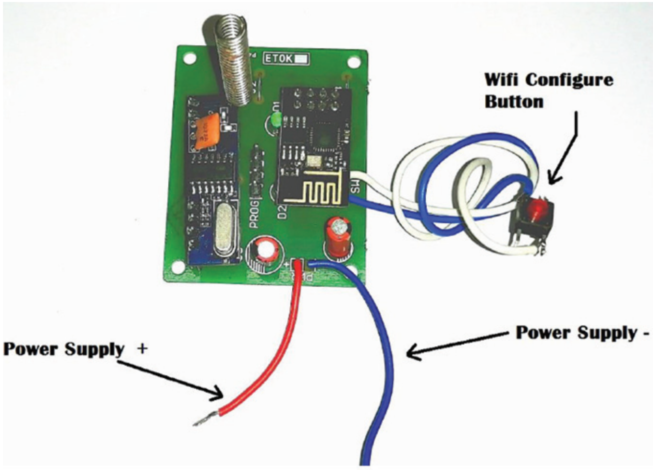

Fig.4: View of the wall receiver circuit

server computer. Real-time location of miners is displayed on mine map and data are saved for analysis. Custom made RFID device is meant for long range.

Miner and asset tracking device has been shown in Figs.4, 5 and 6. The tag has a range of 20m in line of sight and it consumes low power. The developed tag is very small and it can easily be installed in cap lamp carried by miner or on their wearables. The RFID tag communicates with nearest wall router that consists of mainly three components, i.e. RF receiver (Rx), microcontroller and ESP01 (Table 2).

Whenever any of the wall router senses or receives any tag ID from nearby RFID tag it passes the tag ID information along with its own pre-set ID information to the database in central server using a Wi-Fi network [10]. The Wi-Fi repeater has a communication range of around 90 m in line of sight. The RFID tag designed to be carried by miner also consists of an emergency button which sends an alert message to the server when pressed. By forming a dynamic mesh network, all routers are positioned in strategic locations along with the desired path for the purpose of wireless communication in underground mines [11].

The software collects information from all the routers through wireless network. When a tag comes in contact with the nearest reader, the tag information is sent to the server from the particular router and location of miner/equipment is displayed on mine map as well as tabular form in the surface control room [12].

TABLE 2: TECHNICAL SPECIFICATION OF TRACKING DEVICES

Parameter	RFID transmitter device (tag)	Wall receiver device (router)
Components	STM 8, RF transmitter (434 MHz), microcontroller	Microcontroller STM8RF receiver (434 MHz), NodeMCU (ESP01)
Tx frequencyrange	434 MHz	434 MHz
Tx supply voltage	3–6 V	3–6 V
Current consumption	11 mA	110 mA
Range	50 m (line of sight)	RF Tx range: 50m (line of sight) NodeMCU range: 150m (line of sight)

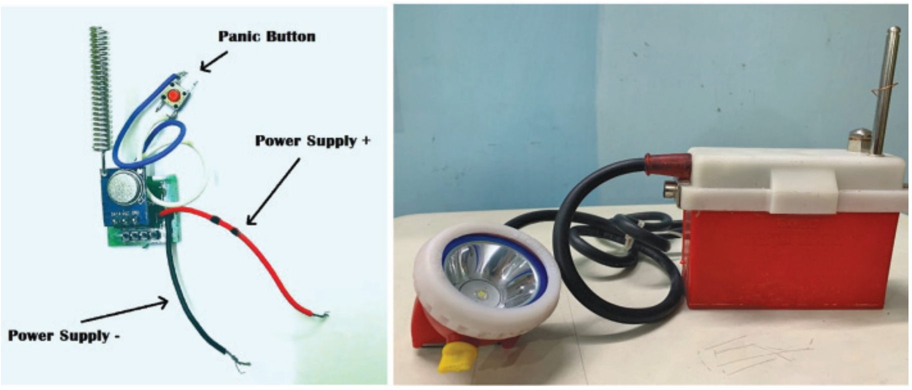

Fig.5: View of cap lamp transmitter

Fig.6: Miner and asset tracking device

2.3 Wireless Communication Module

A low cost, portable and compact size embedded device has been used for transmitting real time text, and voice over a wireless medium. The Wi-Fi based voice communication system uses Raspberry Pi to transmit and receive voice [13, 14]. To connect the Raspberry Pi with Wi-Fi and other Raspberry Pi, secured shell protocol (SSH) is first enabled using MobaXterm for secure data communication between transmitting and receiving nodes. This will allow audio to stream successfully from one Raspberry Pi to another in real time with 1 second delay. Advanced Linux sound architecture (ALSA) has been used for microphone settings which provides audio and communication functionality [15].

An IP-based portable communication device working on common WLAN network (2.4GHz 802.11b/g/n/ac) has been developed for full-duplex voice communication. This allows both the caller and receiver to speak and listen at same time with negligible delay. This device has been shown in Fig.7. It is capable of working in both common broadcasting mode and one-to-one mode of communications. It has been developed using Raspberry Pi 3B+ as motherboard for voice processing at 1.4 GHz with 1 GB DDR2 SDRAM. For powering this device, a standard 3.7V portable power supply has been provided. The low power requirement makes it perfect to use in underground mine application. The voice communication module first receives audio signals from audio circuit which is connected to a Raspberry Pi and then transmits them over Wi-Fi network to another Raspberry Pi [15, 16]. Flowchart diagram for voice communication device has been presented in Fig.8.

In Fig.8, a block diagram has been presented to show full-duplex communication between two miners via a router. The MATLAB simulink software has been used for establishing connectivity and transferring voices. A simulink model for voice communication has been created and deployed in Raspberry Pi boards to run standalone using Raspberry Pi hardware support package available in MATLAB software.

As voice communication requires very fast voice sampling and processing, Raspberry Pi is suitable for this purpose. It runs on Raspbian OS. All coding for voice communication has been done on Simulink, MATLAB. It contains 40 GPIO pins, 4 USB, headphone jacks, and ethernet port to which keypads, microphone and headphone have been connected as input and output devices. Deploy on boot system helps user to apply Simulink model only by giving power to the

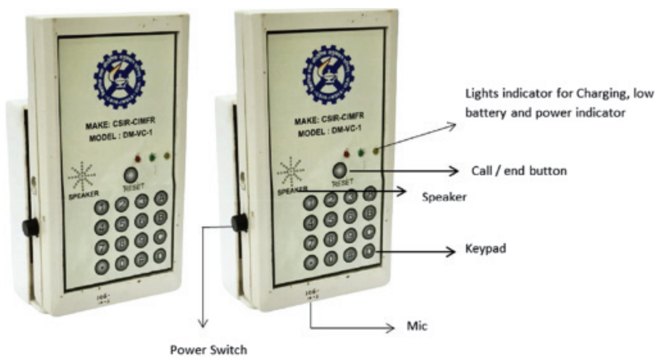

Fig.7 Miners voice communication device

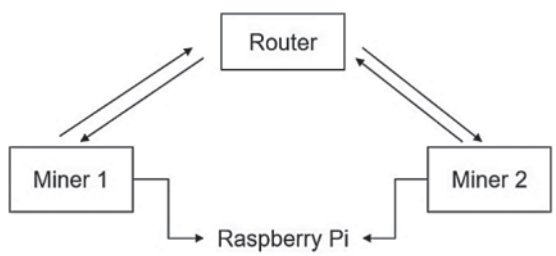

Fig.8: Block diagram of basic model for voice communication device

device, i.e. there is no need of deploying the model repeatedly.

Voice communication device consists of Raspberry Pi board, loud speaker, audio power booster circuit, audio capturing and processing module, matrix keypad and power supply unit as shown in Fig.9. The audio data processed by microphone circuit transmits over Wi-Fi to another device with a suitable audio quality [17]. Using IoT, the system allows Wi-Fi based wireless communication system to successfully transfer sensor data, signals, voice and videos from different locations of an underground mine to a remote control room [12]. It also allows miners to talk with each other over Wi-Fi network (Wi-Fi repeater) and circulates necessary information among themselves [9]. A connection is established to the specific person when keys are pressed on a matrix keypad. The developed communication device utilizes IP network to send or receive UDP packets to or from UDP host on the basis of set IP address and port parameter used by the associated UDP host.

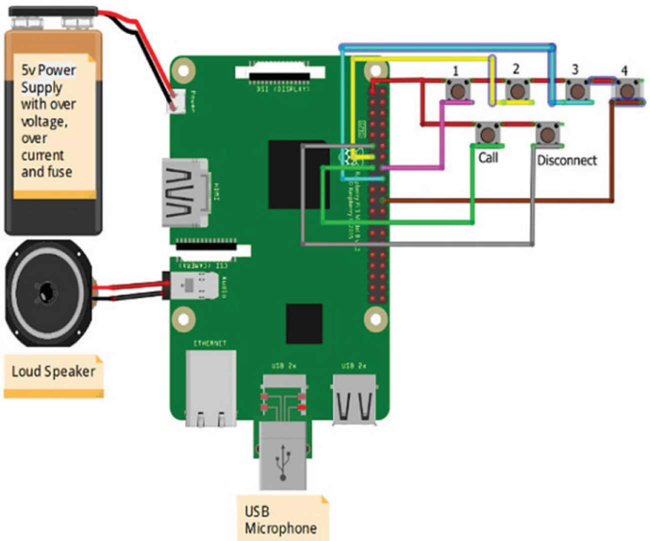

Fig.9: Internal connection diagram for voice communication module

Voice over Internet Protocol (VoIP) has been used for delivering voice data or multimedia in packets over IP network. These IP-based communication devices have been used to communicate with a particular miner. Wireless network for communication in underground mine consists of routers and voice communication devices. In order to put forward information, routing devices have been deployed. The distributed voice communication devices are the mobile terminal devices to transmit and receive voice. To extend network coverage area and find out the best path for packet transfer, routing nodes have been provided.

3.0 Results and discussion

To analyze the overall performance of WLAN network in underground mines, different tests have been conducted for:

- Finding out the maximum operating distance among miners, routers, RFID devices and communication modules.
- Evaluating data communication capabilities of router to distant miners and finalizing routing strategies for data communication

3.1 Performance in Underground Mines

To find out the maximum operating distance between router and miner, tests were conducted to evaluate the optimum positioning of routers in underground mines. For determining the operating distance:

- Router 'A' and miner's position 'M' were gradually varied from 30 to 50 m (Fig.10a) to calculate maximum allowable distance taking into account the packet loss factor.
- Distance between coordinator as well as end devices 'D1' and 'D2' was varied gradually from 30 to 50 m and 90 m respectively (Fig.10b), and data communication has been carried out simultaneously.

Tests have been performed by varying number of routers in the network to analyze data communication in multi-hop network topology. Fig.11b and 11c indicate single router and

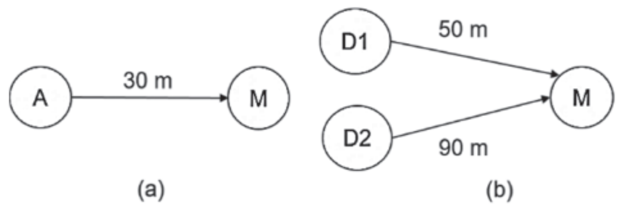

Fig.10: Communication between (a) router and miner, (b) two end devices and coordinator

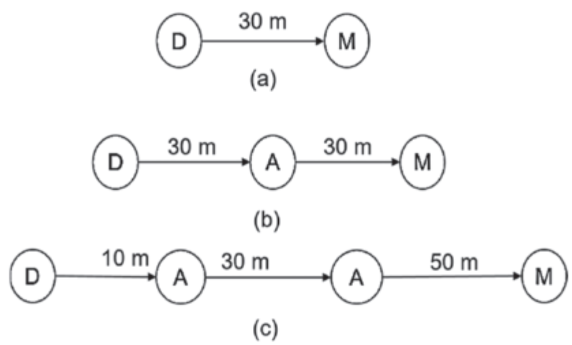

Fig.11: Establishing communication between (a) end device and miner, (b) end device and miner via single router, (c)end device and miner via two routers

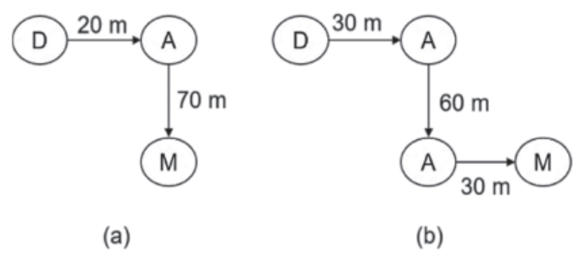

Fig.12: Communication between end device and coordinator through router placed in bends and tunnels

two routers placed respectively between end device and remote miner. The ratio of successfully transmitting data packets to its destination is known as packet delivery ratio (PDR). PDR value decreases when number of routers or hops was increased between end device and miner as reported by other researchers [18, 19].

Experiments were performed to test the routing path strategies for transmission of data from a tag to a miner in multi-hop topology. Fig.12 represents L-shaped and S-shaped routing path schemes, which are generally preferred in underground mines. In L-shaped routing scheme, only single router is present between miner and end device whereas, in S-shaped routing scheme, 2 routers are present in the path from end device to miner [20]. The percentage PDR in L-shape and S-shape routing strategies was measured as 96% and 97% respectively. There is a little deviation in PDR value in both cases, which was within acceptable limit.

3.2 Evaluation of Packet Delivery Ratio

On the basis of average value of PDR, efficiency of WLAN network, routers positioning, and maximum working distance among end devices, router and miners were evaluated. Various system parameters measured during experiments have been summarized in Table 3.

Table 3: Details regarding network parameters

Parameters of WLAN network	Specifications
Constant parameters	Packet injection rate: 298 ms. Number of packets transmitted by end devices: 100. Packet size: 16 bytes (user defined).
Variable parameters	Working distance, communication from end device to a remote miner. Routing strategies: L-shaped and S-shaped.

This experiment has been conducted two times to obtain working distance between miner and end devices. Various environmental parameters, taken into consideration for data communication have been summarized in Table 4. In case 1, tests have been performed considering various environmental factors in underground mines, whereas in case 2, all readings have been taken under normal surface conditions. The performance analysis of both cases have been presented by taking average PDR value obtained over a particular interval of time.

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Table 4: Environmental conditions during testing

Environmental parameters	Case 1	Case 2
Temperature (ºC)	25"40	29"34
Humidity (%)	81"92	25"40
Air velocity (m/s)	0.4"1.4	1.1–2.9
Methane gas concentration (%)	0–0.7	0

Analysis of total number of packets received by miner from a single end device and two end devices with respect to distance for case 1 has been shown in Fig.13. Average PDR value reduced from 99 to 87% with increase in distance from 10 to 90 m.

Fig.14 represents the measured data for case 2, which shows average PDR value reduced from 100 to 94% with increase in distance from 10 to 90 m. An observation can be

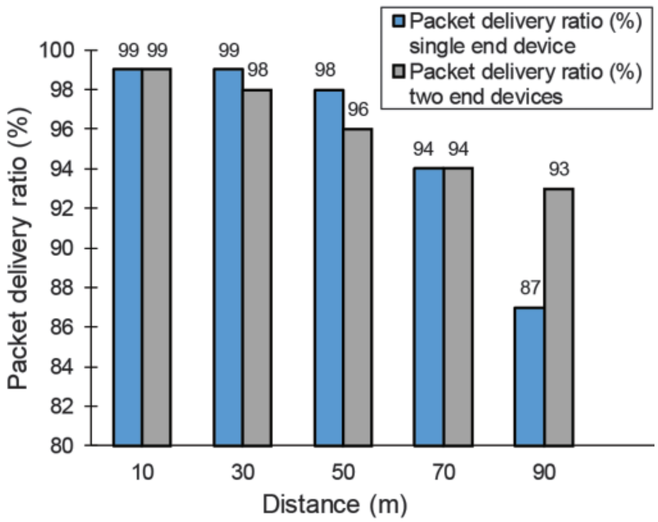

Fig.13 Variation of PDR with respect to distance for case 1

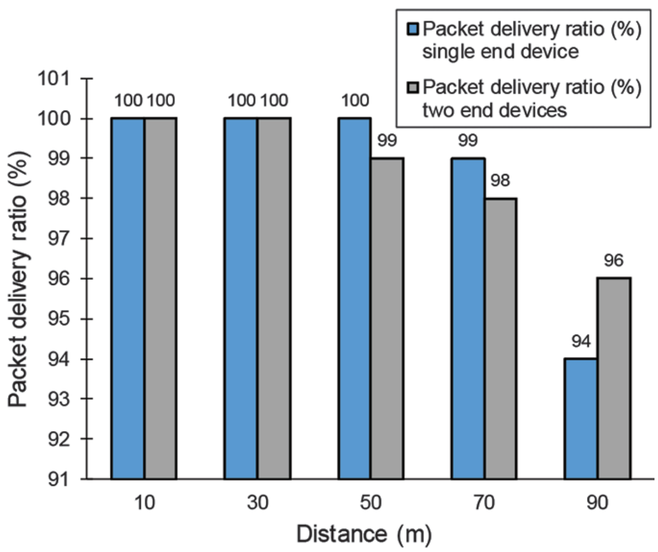

Fig.14: Variation of PDR with respect to distance for case 2

made from these graphs that PDR value decreased with increase in intermediate distance in both cases. Packet delivery ratio was 6–7% more in normal surface conditions than mine environment for same transmission distance.

4.0 Conclusion

The developed miners tracking and voice communication system allows wireless communication based on Wi-Fi network for transferring sensor data, signals, voice and from different locations of an underground mine to a remote-control room in surface. The system helps to monitor miner's current location, display path history, emergency notification to the control room, warning of miner's entering into the restricted area, location of trapped miners, full duplex voice communication, to underground miners etc. The system also provides a miner's tracking module which is capable of tracking any moving personnel with custom made RFID tags at any instant with previous location history. There is also a provision of emergency button for trapped or in-need miners. Thus, the developed wireless system is useful for efficient data and voice transmission, to improve monitoring, communication, safety and productivity in underground mines.

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