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Wi-Fi Direct based WSN Node Deployment in Underground Mine Tunnels

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Fast data transmission is becoming a key parameter in mine planning, operation, and safety. Therefore WSNs (wireless sensor networks) is taking a leading role in underground mine environment communication. WSNs can measure mine environmental parameters by sensors to provide quick and detailed communication for comprehensive assessment of the situation, during both regular operations and emergency situations. Nowadays, WSNs are developing very fast, getting more compact, energy and cost-efficient. On the other hand, underground mines have very specific working conditions characterized by narrow spaces, dynamic environments, and high humidity. This demands WSN nodes to be specifically arranged to be functioning efficiently considering limited throughput and energy resources. Wi-Fi Direct is a wireless connection type used in WSN and supported by many manufacturers around the world. This research will consider using Wi-Fi Direct and ad hoc networks for WSN and will analyze the deployment of WSN nodes in underground mine environments. The physical experiment measuring the performance of deterministic Wi-Fi Direct mode node deployment in Osarizawa experimental underground mine was conducted. The experiment indicated that the data packets can be sent without loss to a distance up to a 140 m in a straight tunnel with 4 m^2 cross-section area. The obtained results were applied to planned WSN node deployment at Tishinskiy mine site in East Kazakhstan.

Keywords : WSN, Wi-Fi Direct, Node deployment

1 INTRODUCTION

Underground mine workers are one of the most dangerous occupations in the World. Severe working conditions with high temperature, humid air, and narrow spaces have high durability requirements not only for machines, but for the involved humans as well. Development of deep underground mines is accelerating, and speed of ore production is rising, hence requirements to technologies are growing at the same pace. According to [1], only in China almost 42,000 casualty cases were registered in period between 2000 and 2006 in coal mines. Even in countries with strict mining safety labor regulations like USA, 506 casualties over period of 2000-2020 have been registered [2]. These information shows the need for continuing efforts to make underground mines safer.

Development of IoT and Wireless Sensor Networks (WSNs) gives a strong influence in application of smart devices in different aspects of everyday life. Environment and safety monitoring is the most popular aspect of the typical WSN devices. Application of such devices is popular in places where we can't install full scale sensing units due to harsh environment, safety limitations, or cases when environment monitoring systems are needed to be mobile or used for limited amount of time.

In underground mines, use of wireless network communications is bringing new capabilities in data transfer methods, subsequently replacing older environment monitoring models like use of in-situ monitoring by workers, use of voice telephone lines and walkie-talkies. WSNs are used to monitor environmental conditions of the mine including dangerous gas concentrations, health conditions of the mineworkers workers and machinery, physical parameters of the surrounding rocks to prevent rock falls and rock bursts [3]. Advantages of using WSNs include mobility of the devices, cost efficiency, simpler and quicker maintenance of properly managed network and faster, automated data transfer. However, current mining engineers raise the issue of unreliability of radio waves in underground tunnels and are cautious about using WSN as main way of communication, hence in most cases it is used as alternative backup communication and monitoring tool.

This research sets a goal of evaluating the deterministic WSN node deployment approach (based on Wi-Fi Direct and ad hoc networks) on actual mine conditions by testing the system in an in experimental mine. Received signal strength index (RSSI), throughput of connected nodes and signal propagation loss in straight tunnel geometry will be measured and analyzed.

2 RELATED WORKS

2.1 Wireless sensor networks

Typical underground WSNs, are composed of "nodes"- devices usually consisting of a sensor, controller, a data transmission antenna, and an energy source. A typical underground mine will have hundreds of nodes scattered throughout the mine.[4]

Nodes differ in functionality by serving as sensor nodes, sink nodes and end-users. Sensor nodes are usually located in the area of interest and serves as a network of self-organized sensing units for better data transmittance and energy efficient work of batteries and are managed by specially developed protocols. As for sink nodes, they are located closer to human operation zones and are designed to store and forward bigger amounts of data, and tend to be more powerful in data processing and have stable power supply. [5] (Figure 1.)

WSNs use a wide range of devices which work in various radio frequencies, including short and long radio waves, Wi-Fi infrastructure and ad hoc modes, leakey feeder and PLC (Power Line Communication).

Wi-Fi infrastructure mode is the most commonly used WSN type which uses IEEE 802.11 standard. Infrastructure mode uses a base station and distributes a wireless signal around the router at 2.4 GHz or 5 GHz radio wavelength frequencies. Performance of a Wi-Fi infrastructure mode depends on radio output power of base unit and its antenna, receiver device Wi-Fi sensitivity and interference from other radio frequencies. Use of this type of WSN in underground mines is restricted by the creation of additional infrastructure of base stations which consequently needs electric power source.

Leakey feeder technology transfers radio waves through a special wire with holes in its outer cover, through which the signal "leaks" to outer environment and "comes" back to cable. Due to leak of the signal, line amplifiers are used to charge up the signal for further transport of the signal down the cable and frequency is limited by 1GHz. Leakey feeder is used in underground mines as an emergency communication tool or for allocating the miners in the mine. However, the installation costs are substantial.

PLC is a technology which allows using existing cable lines for simultaneous data transmission by adding a modulator device. This technology can use different radio frequencies to transfer data in power lines that are usually limited by cable signal loss propagation properties. PLC is mostly used as hybrid communication network in underground mines by attaching Wi-Fi nodes to existing powerline cables which has to be in place.

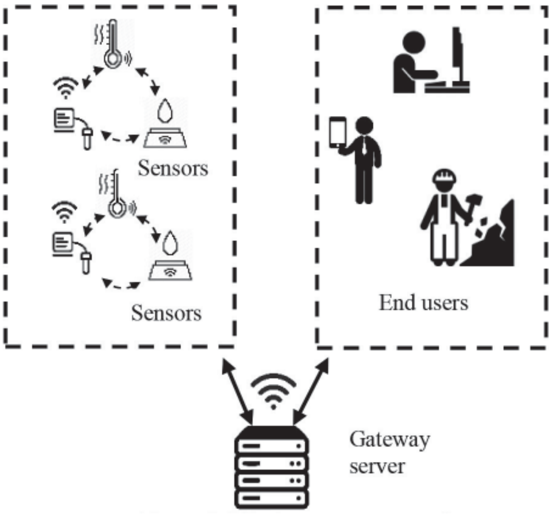
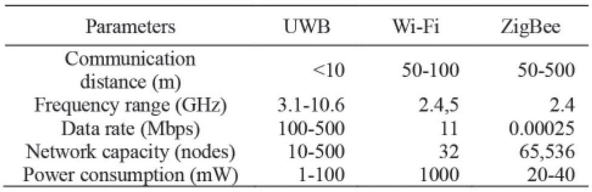


Figure 1 Wireless sensor network

Table 1 The comparison of common underground WSNs[6]



Parameters	UWB	Wi-Fi	ZigBee
Communication distance (m)	<10	50-100	50-500
Frequency range (GHz)	3.1-10.6	2.4,5	2.4
Data rate (Mbps)	100-500	11	0.00025
Network capacity (nodes)	10-500	32	65,536
Power consumption (mW)	1-100	1000	20-40

Wi-Fi Direct is one of the WSN types, the advantage of which is an easy connection between two devices without the use of routers and other complex network infrastructure. Wi-Fi Direct uses a frequency of 2.4 GHz of usual Wi-Fi networks, so it does not require any additional devices and almost any type of smartphone, computer or tablet can be used to connect to the Wi-Fi direct network. Wi-Fi ad hoc network uses multi hop peer-to-peer connection managed by protocols to avoid power consumption, connection interruptions and properly manage the connection topology. Unlike regular Wi-Fi networks, ad-hoc mode doesn't follow any special topology pattern and connects to any other available node.

Moridi et al. [6] considered the integration of ZigBee WSN system GIS and compared its performance with other wireless communication systems like Wi-Fi and UWB (Ultra-Wide Band) radio signals. According to Moridi, an underground communication system based on ZigBee network following IEEE 802.15.4 protocol can be utilized for mine environment monitoring and emergency communication via text messaging. Advantages of ZigBee network is low energy consumption and long-distance coverage. However, ZigBee networks have significant bandwidth limitation which only allow data transfer of no more than 250 Kbps. (Table 1) Same table shows that UWB has a low communication distance of less than 10m, and despite being able to maintain high data rate and low power consumption, it is hard to imagine that it can be used in underground mine conditions.

Ikeda et al. [7] tested the signal strength and bandwidth of Wi-Fi Direct network in experimental mine conditions between a moving target (representing mine worker), and a fixed WSN node (representing the sensor), which measures environmental parameters. According to his research, devices using Wi-Fi Direct mode can be used as a reliable tool to send sensor data by means of moving targets to the operational center. In comparison to ZigBee network, Wi-Fi Direct was less efficient in terms of energy consumption and signal propagation length, however the bandwidth and signal strength was significantly better. Ikeda [8], in his other paper discussed the possibility of transferring data from underground stress measuring accelerometer sensors to surface operating station by means of smartphone. Data transmission via smartphone showed throughput of 80 Mbps at a distance of up to 60 m.

2.2 Signal loss propagation

One of the main ways of measuring the WSNs capabilities for data transfer is tracking the received signal strength index (RSSI) and throughput, which is correspondingly affected by signal loss propagation. Many researchers including [5], [6], [9], [10] studied radio signal attenuation in underground mines. In general, as long as energy consumptions for transmitting the data is proportional to nth ($n \geq 2$) power of communication distance, shorter distance is preferable between nodes for better quality and energy saving reasons. However, in underground mine conditions, launching a big amount of sensor nodes might be a hard and unfeasible task. Hence, it is impossible to construct a perfect network. Thus, parameters like network lifetime, coverage area, node failure and installation cost have to be considered and main ones have to be prioritized depending on the goal of the WSN.

Path Loss, which is attenuation of radio signal through media, is a main parameter affecting distribution of WSN signal. The general formula for path loss in free space is,

$$L = 10 \log(\frac{4\pi d}{\lambda})^2 \quad (1),$$

where λ is wavelength, d is the distance. In actual cases, the general view of the formula doesn't consider parameters of the surrounding space, thus it has been modified by various authors to consider different influences of the environment. Zhang [11], created a model for tunnel line-of-sight (LOS) signal propagation loss which depends on medium permittivity and conductivity. Boutin et al.[12], proposed a radio signal attenuation and path loss model based on experimental measurements for LOS and non-line-of-site cases And came up with the modified formula of path loss,

$$PL_{dB}(d) = \overline{PL}_{dB}(d_0) + 10_{\alpha} \log(\frac{d}{d_0}) + X \quad (2),$$

Where $\overline{PL}_{dB}$ path loss value at d0; $10_{\alpha} \log(\frac{d}{d_0})$ is the reference path loss at d0, and X is a random Gaussian variable.

2.3 WSN node deployment

WSN node deployment scenarios follow two basic patterns based on the aim of the operation. Random node deployment, when nodes are spread over given territory, is used in cases when the position of the sensors are not important or there is little information about the interested territory and wide coverage is needed. The second way of deployment is deterministic deployment, when parameters of the research area are well known, and nodes are placed in predetermined locations. Decisions for node placement in deterministic approach is based on physical limits of the sensors, energy availability, connectivity, and coverage.

Both random and deterministic node deployment scenarios for underground mine environments were tested by different researchers. Zhou [13], Mudilu [14], used fuzzy logic approach to determine the best deployment scenarios during fire emergency situation in mines. Haifeng et al.[15], proposes energy optimal routing for WSNs to increase lifespan of existing networks. Among the published papers there is a deficiency in physical experimental studies conducted in an actual mine site measuring the performance of deterministic WSN node deployment.

3 SYSTEM DESIGN

3.1 Osarizawa experimental mine site

The Osarizawa mine is located in the north of Akita Prefecture, Japan (Figure 2). Main minerals in the area are chalcopyrite and pyrite, along the periphery of the deposit is sphalerite. The mine was used to mine galena and gold from host rock veins. First written records about copper mining from the mine are dated 16th century, however some unofficial sources mention mining activity in the area from 8th century. The mine entrance is located at the side of the mountain at an altitude of 500-600 m above sea level. Currently the mine is not in operation and is used as tourist attraction and is open to the public [16].

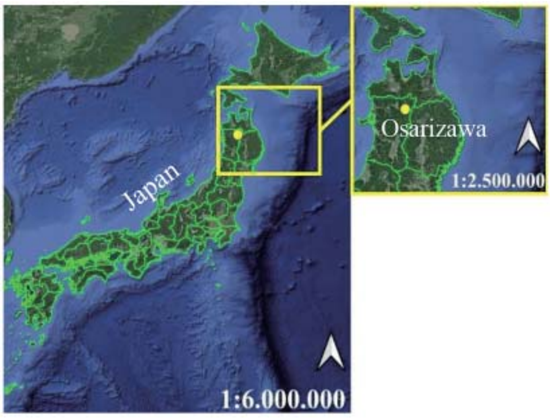


Figure 2 Osarizawa experimental mine in Akita Prefecture, Japan.

3.2 Experiment description

In this paper, the evaluation of a deterministic WSN node deployment scenario in tunnels is conducted to forecast WSN performance parameters in real mine conditions. The layout of underground mines is well suited for deterministic approach in comparison with random node deployment scenarios due to the dynamic environments of mine sites and predetermined locations of the tunnels and stopes.

The goal of this experimental study is to test WSN node deployment based on Wi-Fi Direct and ad hoc network devices in an actual underground mine by conducting experiments at Osarizawa experimental mine site and applying the experiment outcomes to deploy a WSN in a Kazakhstani mine site. The experiment at the Osarizawa experimental mine was conducted to test the performance of the system, which after receiving the environment monitoring data sent through an underground WSN, measures the signal strength and bandwidths parameters of WSN while performing the operation.

The experiment is conducted using Raspberry Pi microcomputers equipped with Cypress CYW43455 Wi-Fi chipset working on 2.4 GHz and 5GHz IEEE 802.11ac wireless standards under Wi-Fi Direct. In this experiment a 2.4 GHz frequency was used due to its better reliability in comparison with 5 GHz. One of the microcomputers was recording temperature and humidity via a DHT-22 sensor at a fixed location (Figure 3). The second one was used as a sink node where monitoring information was received and stored. Python coding was used to operate the sensors and to perform commands for measuring and storing the data at sensor and sink node.

According to experiment conditions, it is assumed that some nodes are connected to a sensor which monitors the environmental conditions, and miner's health conditions, while other nodes are used purely for data transfer purposes. Thus, they vary in energy consumption and data throughput. Wi-Fi Direct nodes are located at the walls of the tunnels and intersection area and transfer the data from one node to another until it reaches the data sink, where all data is accumulated until it is transferred to the surface data center.

The experiment was performed in part of the Osarizawa mine in

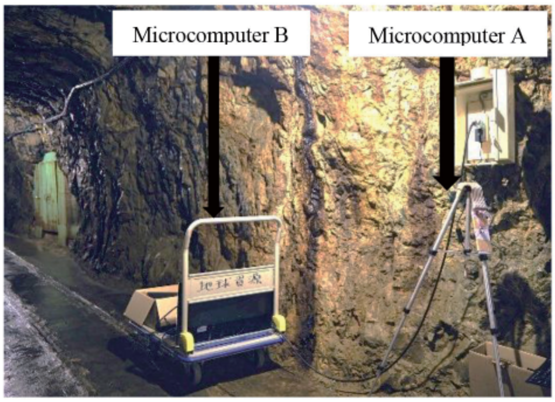


Figure 3 View of the experiment at Osarizawa mine site

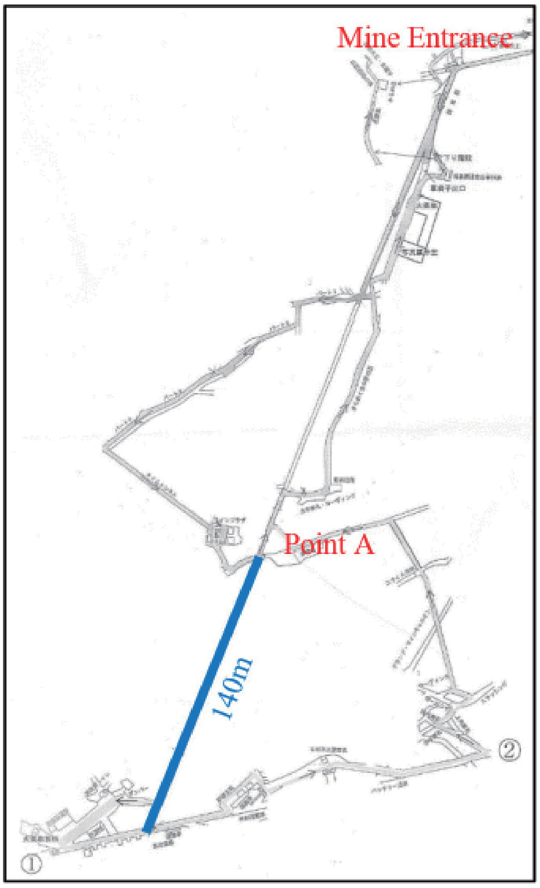


Figure 4 Location of the experimental tunnel at Osarizawa mine site. Highlighted area is a location of the tunnel

horizontal flat tunnel, approximately 500 m away from the entrance to the mine. The experiment was conducted in part of the tunnel with 140 m in length, 2 m height and width and LOS (line-of-sight conditions) (Figure 4). Microcomputer A (Point A) represents the sensor node that is fixed at the beginning of the tunnel, measuring temperature and humidity every second and sending the data via Wi-Fi direct network to microcomputer B (Point B), which is replicating the mobile sink node, where monitoring data processed and stored. Microcomputer B was placed to a transport cart for better distance measurements purposes (Figure 3). The RSSI and ratio of sent and received data packages between devices were measured simultaneously to monitor performance of the network. Microcomputer at Point A, located at the beginning of a tunnel at a height of 1 m and approximately 20 cm away from the wall. Mobile point B was moving along the tunnel and taking measurements of network performance every 5 m until it reached 140 m point, which was the end of tunnel (Figure 5).

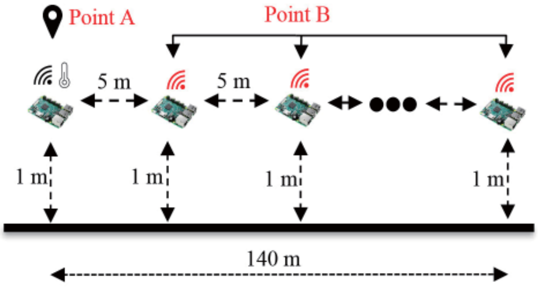


Figure 5 Experiment scheme at Osarizawa mine site.

Results from the experiment was applied to a 597 m long horizontal tunnel at Tishinskiy mine, located at the depth of 290 m below sea level. where one side of the tunnel is connected to a crossroad leading to stopes and mine exits and the other side leads to an active stope, where mining operation is undergoing.

Height of the tunnel is 3.5 m and width is 4 m. The tunnel is characterized by high humidity due to infiltration of groundwater. And there are other obstacles associated with mining activities like weighted dust clouds and operating machinery, which are expected to interfere with Wi-Fi signal.

3.3 Tishinskiy mine site

The case study site is located in Glubokoe district, Eastern Kazakhstan region on the west side of Altay mountains, 18 km south-west of the town of Ridder (Figure 6). The Tishinskiy ore field was discovered in 1958 during the explorational mapping of potential mining areas of West Altay mountains. The geological structure of the Tishinskiy ore field and deposit involves the Lower Paleozoic, Middle Devonian and Middle- Upper Devonian deposits, which are overlapped by loose Quaternary deposits of varying thickness. The ore-bearing rocks of the deposit are hydrothermally altered rocks of the Il’inskaya mineral group composed of carbonate-chlorite-sericite-quartz, less often sericite-quartz shales and micro quartzites. Lenses of solid polymetallic

Figure 6 Tishinskiy mine site location in Kazakhstan

ores are distinguished within the general outlines of ore bodies. The deposit is characterized by a large shear zone of hydrothermal alteration of volcanic-sedimentary rocks of subvertical dip, limited from the south and north by large tectonic faults and accompanying numerous other faults of smaller thickness. Tishinskoye ore body field, from a depth of -300 m (from the sea level), was classified as prone to rock bursts and rock falls. The deposit is located in mountainous terrain where the absolute surface elevations range from 640 to 750 m. The upper part of the ore bodies up to 430 m has been mined by a quarry, and since 1969-by an underground sublevel open stoping method. Ore is currently being mined at the “levels” 17 to 21 (absolute elevation -290 to -530 m). During the mining of “levels” 6 and “7”, intensive destruction of the pillars and the roof of the stopes were registered, and a sinkhole formed in the northeastern side of the open pit, which led to intense deformation of the upper part of one of the shafts.

With the beginning of mining at “level” 9, the destruction of rock and ore masses began from zones of self-collapse was recorded. These zones are confined to areas of stressed rocks near large tectonic faults. Further operation showed that wall collapse occurred at any exposure, filling the area with a moistened bulk mass. Originally mining operations are planned to continue until “level” 22, where mine depth will reach almost 1200 m from the surface.

The existing monitoring system in the mine site is not using any WSNs and is mostly done by handheld devices of mine workers. Rock mass movement monitoring is done from 5 survey control points on the surface by means of GPS trackers and 24 extensometers installed to the walls of the mine at different levels. In addition, mine workers do visual monitoring of stopes and tunnel walls once a month. Currently, further mining operations at the area of self-collapse has been stopped as per the decision of the operating company, until a detailed rock mass monitoring system is installed to the area.

4 RESULTS AND DISCUSSIONS

4.1 Experiment results

To prepare for the application of WSN node deployment at Tishinskiy underground mine, the experiment was conducted at the Osarizawa mine site. For the given case, to transfer the amount of data generated by sensor node, the RSSI should be no less than -80 dBm[17]. If values go lower, nodes will not be able to connect. If the connection occurs, throughput will not allow reliable data transfer. Experiments in the Osarizawa mine showed RSSI values higher than -80 dBm up until 140 m. The length of the tunnel didn’t allow further experiments to track RSSI values at distances longer than 140 m.

Results of Osarizawa experiment showed that actual measurement of RSSI are higher than the Free Space Path Loss model. (Figure 7). This might be the result of radio signal reflection from the walls of the tunnel which prevents dispersion of the signal in multiple directions. The comparably smaller scale of the Osarizawa mine limited the measuring of WSN communication performances to 140 m. Considering possible lower performance of WSN due to higher radio signal attenuation in tunnels of bigger tunnel cross sections in case of Tishinskiy mine site, an RSSI “safe value” of -60 dBm was recommended for node deployment. In this case, RSSI “safe value” means that all the data packets sent from one node to another are safe from being lost on their way due to radio wave attenuation. According to (Figure 8), the “safe value” of -60 dBm of RSSI intersects with WSN experimental results at 130 m, hence 130 m considered to be a reliable operational distance between nodes in deterministic node deployment scenario. The figure also shows decreasing trend of the RSSI values with the increase of distance, however there are notable fluctuations of the RSSI measurements points from the trend. This phenomenon can be explained by the rough walls of the mine tunnel which affects the reflection of radio waves.

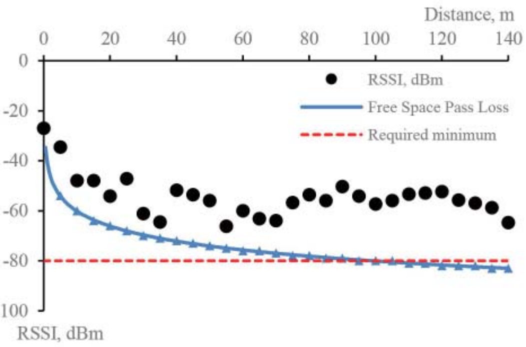


Figure 7 Osarizawa experiment RSSI measurements in comparison to Free Space Path Loss model

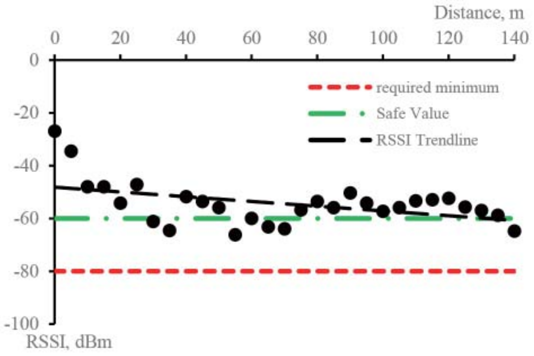


Figure 8 Osarizawa experiment RSSI measurement trendline against selected safe value of -60 dBm.

4.2 Tishinskiy mine site WSN node deployment

Experiment results in Osarizawa experimental mine gives opportunity to evaluate the potential WSN deployment in Tishinskiy mine. WSN deployment in Tishinskiy mine planned to be launched in straight tunnel with length of 597 m, height and width of 3.5 and 4 m, respectively “Safe value” of 130 m, derived from the experiment gives the result, that 6 nodes, including the sensor node, will be needed to send the data via Wi-Fi ad hoc network in the tunnel (Figure 9).

However, there are reasons that possibly leads to different results of the WSN deployment in comparison to the experiment outcomes. Firstly, different tunnel cross sections of Osarizawa and Tishinskiy, with respective tunnel cross sections of 4 sq.m. and 14 sq.m (Figure 10).

As the experiment showed, narrow tunnel size of Osarizawa mine decreased radio signal attenuation, to get stronger values at receiver side in comparison with Free Space Path Loss. Secondly, amount of the air weighted materials in the Tishinskiy mine is considerably higher in comparison with Osarizawa mine, due to active mining process. Measurements at Tishinskiy mine after

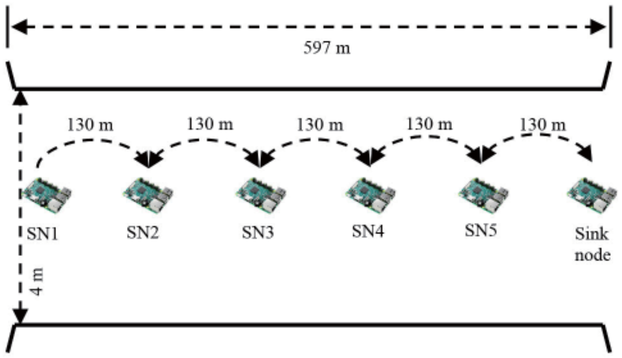


Figure 9 WSN node deployment at Tishinskiy mine tunnel. SN-sensor nodes.

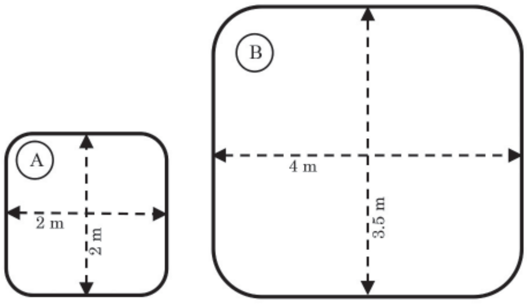


Figure 10 Comparison of mine tunnel cross sections of Osarizawa (A) and Tishinskiy (B) mine sites.

WSN deployment are planned to compare the results for further development of this research.

Cost of the planned WSN for environment monitoring of the at Tishinskiy mine is cheaper and less risky in comparison to current measurement scheme, performed by mine site engineers.

5 CONCLUSIONS

The application of WSNs have potential to make big impacts to mining industry, especially in chapters related to the health and safety of the workers, efficiency of the data circulation within the underground mining environment and increasing production. However, it is still admitted that application of WSN communication is not researched at full extent. Although a lot of theoretical and computational models have been presented in recent publications and conferences, only a few practical application cases are presented, which brings up the assumption that there is an issue of implementing the technology in situ.

Wi-Fi Direct and ad hoc networks have shown significant results and can be used as a reliable tool for data transfer in underground mine conditions. However, limitations of the given type of WSN are related to power consumption management and signal propagation loss due to harsh conditions of underground mines. Modern development of mobile batteries for existing sensors provides average life of WSN node no longer than 7 days[17]. Another issue is signal propagation loss in tunnels due to dust, tunnel wall roughness, water flow and other obstacles. More data of WSN performance from real mine sites should be collected to assess the impact of mine environments and related activities on the quality of signal strength.

In this research, the possibility of applying the results of WSN node deployment at experimental mine conditions to real mine condition are considered. Wi-Fi Direct network was used to transfer the mining environment data from sensor node to sink node. The experiment is conducted in Osarizawa experimental mine at Akita Prefecture, Japan, and the results are to be applied in an actual mine in Kazakhstan. The experiment results indicated that the data between two Raspberry Pi microcomputer based WSN nodes can be sent up to 140 m distance, with RSSI value not falling below -80 dBm. However, considering the risks related to different tunnel properties for industrial application case at Tishinskiy mine site, it was decided that RSSI value should not be lower than -60 dBm, subsequently according to Figure 8, the distance between nodes at a straight tunnel should not exceed 130 m.

Further development of the research is associated with performing the WSN node deployment at a Kazakhstani mine site described in this paper and continuation of data analysis. WSN used for the research is planned to continue its operation in long term for further data collection for improving the WSN node deployment parameters in real mining conditions.

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