Western Australia School of Mines
Department of Mining Engineering and Metallurgical Engineering

Underground Mining Monitoring and Communication Systems based on ZigBee and GIS

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This thesis is presented for the Degree of

Doctor of Philosophy
of
Curtin University

June 2016

DECLARATION

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature: --

Date: *06 June 2016*

To my parents, wife and son

For their endurance, understanding, and love

ACKNOWLEDGEMENTS

I would like to express my appreciation to my supervisors Associate Professor Mostafa Sharifzadeh and Professor Youhei Kawamura (Akita University, Japan) for their invaluable supervision, support, and encouragement. Without their support, this research would not have come to its current stage of development.

I wish to express my gratitude to Associate Professor Emmanuel Knox Chikutwe Chanda (The University of Adelaide), Dr. Hyong Doo Jang (Curtin University), and Dr. Markus Wagner (The University of Adelaide) who served as a co-operation to our teamwork. Their support, guidance, and inspiration were greatly supportive during the course of research.

I also want to give my thanks to Professor Roger Thompson (Curtin University) as the thesis chairperson, who makes my earlier scientific connections with my supervisors and provides invaluable supports to my field trips, conferences attending, and other administrative assistants.

I would like to thank the managements of Angas Zinc Mine (South of Australia) and Nickel West Leinster (Western Australia) for permission to use the mines as experiment site and to publish this thesis. Also, the assistance of their staff in setting up the underground experiments is hereby acknowledged.

I would also like to convey my sincere thanks to the managers of Hokkaido electronic equipment (HDK Company, Japan), Mr. Kamijima and Mr. Sawada, for the software and hardware developments and other technical supports about electronic devices.

I am very grateful to all of academic and support staffs of the Western Australian School of Mines (WASM) in Kalgoorlie Campus and thanks to my co-research fellows.

Special thanks to my siblings and in-laws for their encouragements and devotions.

PUBLICATIONS INCORPORATED INTO THIS THESIS

Some of papers have been published during the period of thesis preparation and details of previous publications are listed below.

Refereed journal papers

- **MORIDI, M. A.,** KAWAMURA, Y., SHARIFZADEH, M., CHANDA, E. K., WAGNER, M., JANTG, H. & OKAWA, H. 2015. Performance Analysis of ZigBee Network Topologies for Underground Space Monitoring and Communication Systems. *Tunnelling and Underground Space Technology*, Reviewing.

- **MORIDI, M. A.,** KAWAMURA, Y., SHARIFZADEH, M., CHANDA, E. K., WAGNER, M., JANTG, H. & OKAWA, H. 2015. Development of Underground Mine Monitoring and Communication System integrated ZigBee and GIS. *International Journal of Mining Science and Technology, 25, 811-818*.

- **MORIDI, M. A.,** KAWAMURA, Y., SHARIFZADEH, M., CHANDA, E. K. & JANG, H. 2014. An investigation of underground monitoring and communication system based on radio waves attenuation using ZigBee. *Tunnelling and Underground Space Technology,* 43**,** 362-369.

Conference Papers and Presentations

- **MORIDI, M. A.,** SHARIFZADEH, M., KAWAMURA, Y. 2016. A Comparative Performance Analysis of Wireless Sensor Network Topologies for Underground Spaces Monitoring. *9th Asian Rock Mechanics Symposium (ARMS9)*. Bali, Indonesia, in progress.

- SHARIFZADEH, M., KAWAMURA, Y., **MORIDI, M. A.** 2015. An investigation on applicability of Wireless Sensor Network in Underground Space Monitoring and Communication Systems. *11th Iranian and 2nd Regional Tunnelling Conference*. Tehran, Iran (Keynote Lecture).

- **MORIDI, M. A.,** KAWAMURA, Y., SHARIFZADEH & CHANDA, E. K. M. 2015. Underground Spaces Communication and Monitoring Systems integrated ZigBee and GIS. *ITA WTC 2015 Congress and 41st General Assembly*. Lacroma Valamar Congress Centre, Dubrovnik, Croatia.

- KAWAMURA, Y., **MORIDI, M. A.** & SHARIFZADEH, M. 2014. Underground Mine Communication and Monitoring Systems by Using ZigBee Technology. *ISRM International Symposium and 8th Asian Rock Mechanics Symposium (ARMS8).* Sapporo, Japan.

- **MORIDI, M. A.,** KAWAMURA, Y., CHANDA, E. K. & SHARIFZADEH, M. 2013. An Investigation of Radio Wave Attenuation for ZigBee Network in Underground Mines. *3rd International Workshop on Soft Computing and Disaster Control (SocDic2013).* Bali, Indonesia.

ABSTRACT

In the challenging environment and dynamic topology of an underground mine, reliable and effective communication is a high-stake issue, along with the objectives of safe and efficient mining operations. Automation through remote and automatic systems has delivered improvements in workplace health and safety for employees, operational management, energy and cost-effectiveness, and real-time response to events. In this context, Wireless Sensor Networks (WSNs) have been widely employed in underground monitoring and communication systems for the purpose of environmental monitoring, the positioning of workers and equipment, operational monitoring and communication system. Considering the capabilities of WSNs, a ZigBee network is adopted in this study.

The aim of this study is to propose a reliable and effective monitoring and communication system in underground environments, using new technologies. To achieve this, a ZigBee network-assisted Geographic Information System (GIS) is analysed to establish an integrated system for monitoring underground environment features, thereby preventing underground incidents, and facilitating bilateral emergency communications between surface operators and underground miners.

It is demonstrated how ZigBee network performance is optimised for such environments. ZigBee radio wave attenuation is investigated to evaluate a stable communication distance between ZigBee nodes at straight and curved tunnels in a real mine scenario. Experimental measurements of ZigBee radio wave attenuation are validated by simulation results. Based on the analysis of the experimental and simulation results, factors affecting radio waves attenuation in the junctions, curvatures and fields near and far from the source are also assessed. Stable wireless communication distances between developed ZigBee nodes in the experiments of underground Angas Zinc Mine were obtained 100 m and 70 m for straight and curved tunnels, respectively.

Various sensor node arrangements of ZigBee networks for underground space monitoring and communication systems are also investigated. The performance of ZigBee topologies is analysed in 12, 20, 30, 40 and 50-node scenarios for stationary

node deployment in underground environments. The metrics used for the performance evaluation include throughput, packet delivery ratio (PDR), end-to-end delay, energy consumption and network security. The results of evaluation confirm that the mesh topology is preferable in WSN design in relation to higher throughput, packet delivery ratio, and network security, whereas the cluster-tree topology is preferable in relation to lower end-to-end delay and lower energy consumption.

Attempts are made to make the system more effective and smarter in order to process and manage underground ZigBee data received into a control centre database using the GIS. ZigBee nodes are developed to sense environmental attributes such as temperature, humidity, and gases concentration, switching ON and OFF ventilation fans, and texting emergency messages. A trigger action plan for attributes monitored above the normal or threshold value limits is programmed into the surface GIS management server. It is designed to turn the auxiliary fans on remotely or automatically in orange (caution) conditions, and to send evacuation messages to underground miners in red (unsafe) conditions.

The approaches are generalised by modelling ZigBee networks with the more comprehensive and realistic representations of a monitoring and communication system for underground mines. A system design and model is developed based on the classification of results from an experiment undertaken at an underground mine in Western Australia.

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LIST OF ABBREVIATIONS

AC:	*Alternating current*
AOA_i:	*Angle of arrival*
CMS:	*Cable monitoring system*
dBm:	*Decibels milliwatt*
DC:	*Direct current*
DN:	*Destination node*
DV-Hop:	*Distance vector-hop*
GIS:	*Geographic information system*
GO:	*Geometrical optics*
GSC:	*Geosense coordinator*
GSR:	*Geosense*
IEEE:	*Institute of Electrical and Electronics Engineers*
LF	*Leaky feeder*
LOS:	*Line-of-sight*
LQI:	*Link quality indication*
LR-WPAN:	*Low-rate wireless personal area network*
MAC:	*Media access control*
mW:	*Milliwatt*
NLOS:	*Non-line-of-sight*
PAN:	*Personal area network*
PDR:	*Packet delivery ratio*
PHY:	*Physical layers*
RFD:	*Reduce function device*
RSSI:	*Received signal strength indicator*
RX:	*Receive mode*
SBR:	*Shooting and Bouncing Ray*
SDK:	*Software development environment*
SN:	*Source node*
TDOA:	*Time difference of arrival*
TOA:	*Time of arrival of signal*
TX:	*Transmit mode*
UWB:	*Ultra-wideband*
WPAN:	*Wireless personal area network*
WSN:	*Wireless sensor network*
ZDO:	*ZigBee device object*

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

Mining is one of the earliest industries to contribute to human civilisation (Hartman & Mutmansky, 2002). The importance of mining as a foundation for most industries has led to rapid progress, utilising the latest technological advancements. Increased demand for mineral products continues to drive global expansion of the underground mining sector, even though the substantial majority of ore deposits have already been exploited from the near-surface.

Underground mining is a risky operation due to its workplace characteristics. Many research papers have investigated factors leading to human casualties and injuries, recurring hazards, and unexpected costs in underground mines (Khanzode et al., 2011; Molina et al., 2011; Saleh & Cummings, 2011). Typical hazards associated with underground mining are poor lighting conditions, narrow spaces, rock falls, poor ventilation, wet conditions, communication constraints and structural complexity. Some studies have focused on operational problems such as fleet management including dispatching, routing and scheduling (Gamache et al., 2005). Others have explored geotechnical considerations such as ground movement and tunnel collapse (Ghorbani et al., 2012; Li et al., 2010) in order to improve safety and management efficiency in underground mining.

In the challenging environment and changing topology of a mine, reliable and effective communication is a high-stake issue, along with the objectives of safe and efficient mining operations. Automation through remote and automatic systems has delivered improvements in workplace health and safety for employees, operational management, energy and cost-effectiveness, and real-time response to events. In this context, Wireless Sensor Networks (WSNs) have been widely employed in underground monitoring and communication systems for the purpose of environmental monitoring, the positioning of workers and equipment, operational monitoring and communication systems.

WSNs form one of the most stimulating fields of computer science research and have contributed to home and industry communication and monitoring solutions over the past five decades (Silicon-Laboratories, 2012). However, they have only been appraised and applied in the mining industry during the last two decades.

Research on WSNs in underground mines has advanced for in the areas of gas detection and predicting collapses in coal mines. This industry has high event statistics. Reported annual statistics of fatalities from coal mines, especially in the USA and China, underpin the importance of utilising WSNs to minimise injuries, deaths, damage to equipment and unexpected costs (Li & Liu, 2009; Molina, 2011). Underground mining has benefited from the implementation of WSNs for strategic positioning of miners and equipment (Chehri et al., 2008; Tadisetty et al., 2003; Yin, 2011) and communication both in vocal and visual formats (Müller & Noack, 2011; Sicignano et al., 2013).

Considering the capabilities of WSNs, a ZigBee network is adopted in this study. ZigBee, based on IEEE 802.15.4 standard, is a new wireless technology which delivers greater benefits for monitoring and communication systems in underground spaces, compared to other WSNs. The first version of a ZigBee node was developed by ZigBee Alliance in 2004 (Longkang et al., 2011). It has acceptable communication distances between nodes, substantial node capacity within a network, low energy consumption by sensor nodes and low overall complexity. Also, ZigBee nodes, network installation and maintenance are very cost-effective compared with other underground WSNs. ZigBee does not require any access point or central node to transmit data between clusters. Although ZigBee network has very low data rate (250 kbps) for image, voice and video communication, it can deliver high-performance networking applications for data transmission between nodes (node to node relays) based on multiple wireless hops (Sharifzadeh et al., 2015).

The proposed system integrates a ZigBee network with a geographic information system (GIS) to enable the monitoring and control of underground mining applications from a surface office. GIS is a new technology and is used for spatial data analysis in order to capture, store, analyse, manage, and present data that is linked to locations (ESRI, 2012). GIS allows users to view, understand, question, interpret, and visualise data in many ways, revealing relationships, patterns, and trends in the form of maps, globes, reports, and charts.

This study demonstrates the innovative integration of ZigBee and GIS technologies into one system for communication and monitoring in mine tunnels. Underground safety and health concerns are significantly ameliorated through enhanced ventilation management and improved emergency text messaging. The integrated system receives data from developed ZigBee nodes and maps information in the GIS management server. The system can sense the mine tunnel environment and can communicate, and control the operation of the ventilations. Temporal ZigBee environment data including temperature, humidity and gas concentration readings are processed in the surface GIS management server. A trigger action plan is programmed to sound the alarm and remotely turn on auxiliary fans to clear the unsafe conditions when the monitored parameters exceed threshold values. The system enables emergency text messages to be communicated between underground tunnels and the surface.

1.2 PROBLEM STATEMENT

The core problems addressed in this study are the mitigation of underground mining incidents and the management of underground mining operations from a surface office by an effective monitoring and communication system.

The death toll in the underground mining industry over the last decade is presented in Figure 1-1. The narratives of the fatalities occurring between 2003 and 2010 were obtained for three countries (USA, India and China). It is obvious that despite the progress of safety technology over recent years, there are still considerable fatalities in this industry. Therefore, underground mining remains one of the most dangerous occupations (Chakraborty, 2012; MSHA, 2014; Wu et al., 2011).

In this study, an integrated system for underground mine monitoring and communication based on new technologies using ZigBee and GIS is proposed. ZigBee network is employed to sense the environmental attributes of tunnels and to manage ventilation system as well as establishing emergency communication with underground miners by texting message. This is merged with GIS services to create an automated system to provide 3D visualisation, programmed trigger action plans and multi-user operation.

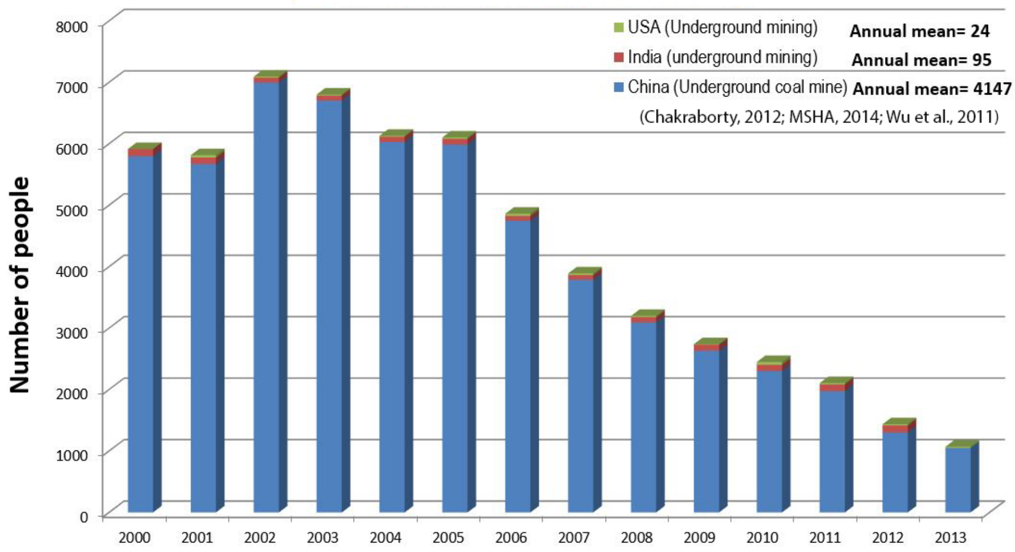

Figure 1-1 Death toll in the underground mining industry

The high quality of service and reliable message transmission through the network are crucial issues in dense industrial WSNs. This study also investigates an adequate sensor node arrangement of ZigBee networks for underground space monitoring and communication systems.

1.3 Objectives

In order to achieve a reliable system integration in the underground mines as a remedy for the difficulties and issues mentioned in the problem statement, the objectives of this study are as follows:

- Review the state of the art regarding the use of WSNs and particularly ZigBee networks in underground mines.
- Evaluate common WSNs for applications in underground mines and demonstrate how a ZigBee network performance is suitable for such environments. ZigBee radio wave attenuation is investigated to evaluate stable communication ranges between ZigBee nodes at straight and curved tunnels in a real mining scenario. Moreover, experimental measurements of ZigBee radio wave attenuation are validated by simulation results. Based on the analysis of the experimental and simulation results, factors affecting radio waves attenuation in the junctions, curvatures and fields near and far from the source are also assessed. Finally,

stable wireless communication ranges between developed ZigBee nodes in the underground Angas Zinc Mine is posited to be 100 m and 70 m for straight and curved tunnels respectively. The development of a ZigBee network application compared to other WSNs in underground mines is also endorsed.

- Investigate various sensor node arrangements of ZigBee network for underground space monitoring and communication systems. The performance of ZigBee topologies is analysed in 12, 20, 30, 40 and 50-node scenarios for stationary node deployment in underground environments. The metrics used for the performance evaluation include throughput, packet delivery ratio (PDR), end-to-end delay, energy consumption and network security. The results of evaluation confirm that the mesh topology is preferable in WSN design in relation to higher throughput, packet delivery ratio, and network security, whereas the cluster-tree topology is preferable in relation to lower end-to-end delay and lower energy consumption. The analyses show that the mesh topology creates a more reliable monitoring and communication network with an adequate quality of service in underground spaces and tunnels. Therefore, greater end-to-end delay and energy consumption are not major concerns for the mesh topology in underground mine applications, based on the acceptable data latency and the use of mine power.
- Analyse an automated underground mine monitoring and communication system based on the integration of new technologies to promote safety and health, operational management and cost-effectiveness. The proposed system integration of a WSN-assisted GIS enables monitoring and control of underground mining applications from a surface office. Based on the capabilities of WSNs, a ZigBee network is adopted for near real-time monitoring, ventilation system control and emergency communication in an underground mine. ZigBee nodes are developed to sense environmental attributes such as temperature, humidity, and gases concentration, switching ON and OFF ventilation fans, and texting emergency messages. A trigger action plan for attributes monitored above the normal or threshold value limits is programmed into the surface GIS management server. It is designed to turn the auxiliary fans on remotely or automatically in orange (caution) conditions, and to send evacuation messages to underground

miners in red (unsafe) conditions. Multi-user operation and 3D visualisations are other benefits achieved in the proposed system.

- Assess the controllable and uncontrollable parameters for the establishment of a ZigBee network for underground mines. Accordingly, the methodology for designing and modelling an underground mine monitoring and communication system is generalised. Further procedures for a ZigBee network implementation in an underground mine are proposed. For the physical verification of these procedures, an experiment is carried out to design a ZigBee network model based on the results obtained in an underground mine in Western Australia for communication distances under different conditions. In addition, another experiment is performed to validate this model by testing system functions and applications including temperature, humidity and illumination readings, message texting, and the control of ventilation fans through the tunnels of this underground mine. The system operates successfully and demonstrates the reliable outcomes of the system functions and applications.

1.4 Scope and limitations

This investigation was conducted to develop underground mining monitoring and communication systems so as to promote safety and health, operational management and cost-effectiveness. The proposed system integration of a ZigBee network-assisted GIS enables monitoring and control of underground environment attributes. The potential functions and applications of the ZigBee networks for underground communication and monitoring is illustrated in Figure 1-2. These functions and applications assessing sensor nodes' abilities are classified as follows.

(a) Safety and health approach

- Air quality and quantity measurements
- Determination of workers' locations
- Emergency and safety communications
- Gas detector and fire alarm
- Geotechnical monitoring

(b) Operations management and control

- Real-time monitoring of underground mine operations from a surface control centre
- Improving the underground operation cycles (scheduling)
- Traffic control (signals)

Consequently, approaching high security in the safety and health matters and improving operation management based on the proposed system will considerably increase the cost-effectiveness in underground mining projects.

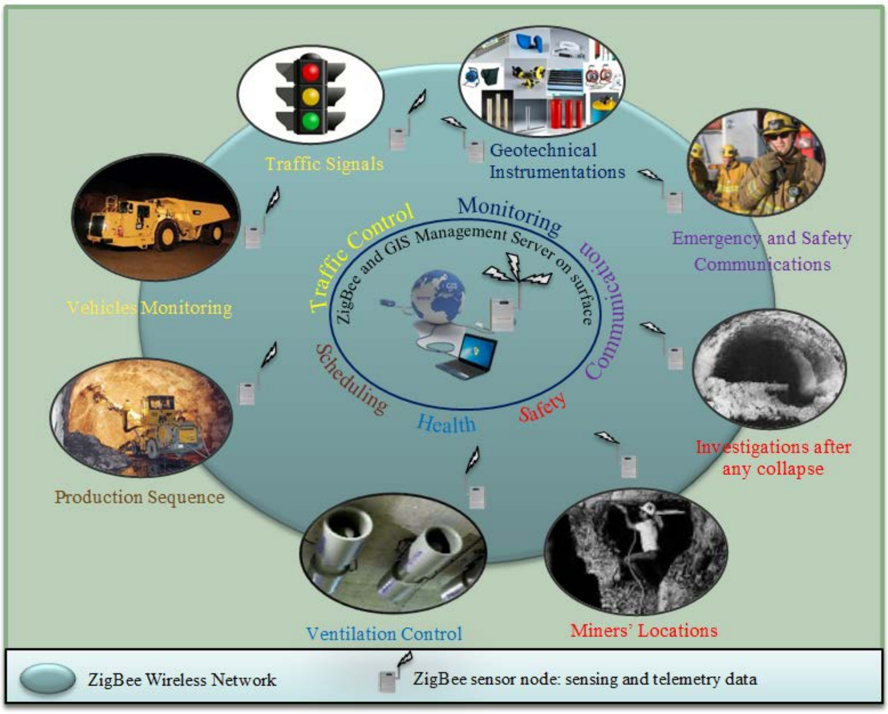

Figure 1-2 Potential functions and applications of the ZigBee network in underground mines

The limitation of the study is first concerning about ZigBee nodes employed in the tests. These are laboratory version which have less ability in the feature of antenna gain compared with updated industrial ones. Second, the outcomes are generalised based on the underground mine sites of the case studies. Finally, there is an uncertainty where uncontrollable parameters such as tunnel wall distortion and roughness, the detail of the dielectric constant and conductivity of rock mass effect on findings. Also, within the scope of the research topic, there is little prior research on using system integration of ZigBee and GIS for the applied functions and applications in underground mines.

1.5 Significance and relevance

The study proposes a new system integration for the monitoring and communication of underground mines using ZigBee and GIS. This will significantly improve health and safety issues and management difficulties in underground mining. The finding of this study will benefit the engineering profession, considering the important role it plays in the development of today's industries. Hence, the greater worldwide demand for ore deposits has necessitated safer and more productive approaches through the automation of mining techniques. Therefore, the significance of the study is summarised as follows:

- This study could be beneficial in this era of system integration engineering where new technologies are being utilised.
- The study could contribute to the expansion of knowledge of WSNs. The emerging functions and applications of smart wireless sensors in mining activities could influence relevant research in fields such as modern computer science, wireless communication and mobile computing.
- Furthermore, the study could promote mining automation and mitigate the current predicament of safety and health issues in underground mining.
- The study demonstrates and confirms a reliable system for underground mines to sense environmental attributes such as temperature, humidity and gases concentration, to manage ventilation fans, and to text emergency messages as a supportive communication system.
- The results pave the way for future researchers to think about utilising WSNs for other functions and applications in underground mining and similar industries.

1.6 Thesis structure

The logical structure of the thesis is shown in Figure 1-3. The thesis comprises seven chapters, summarised as follows:

Chapter 1 presents an introductory statement regarding the enhancement of safety and health, as well as operation management in underground mines. It also includes the objectives, scope and limitations of the research and offers conclusive and significant research contributions to the mining industry.

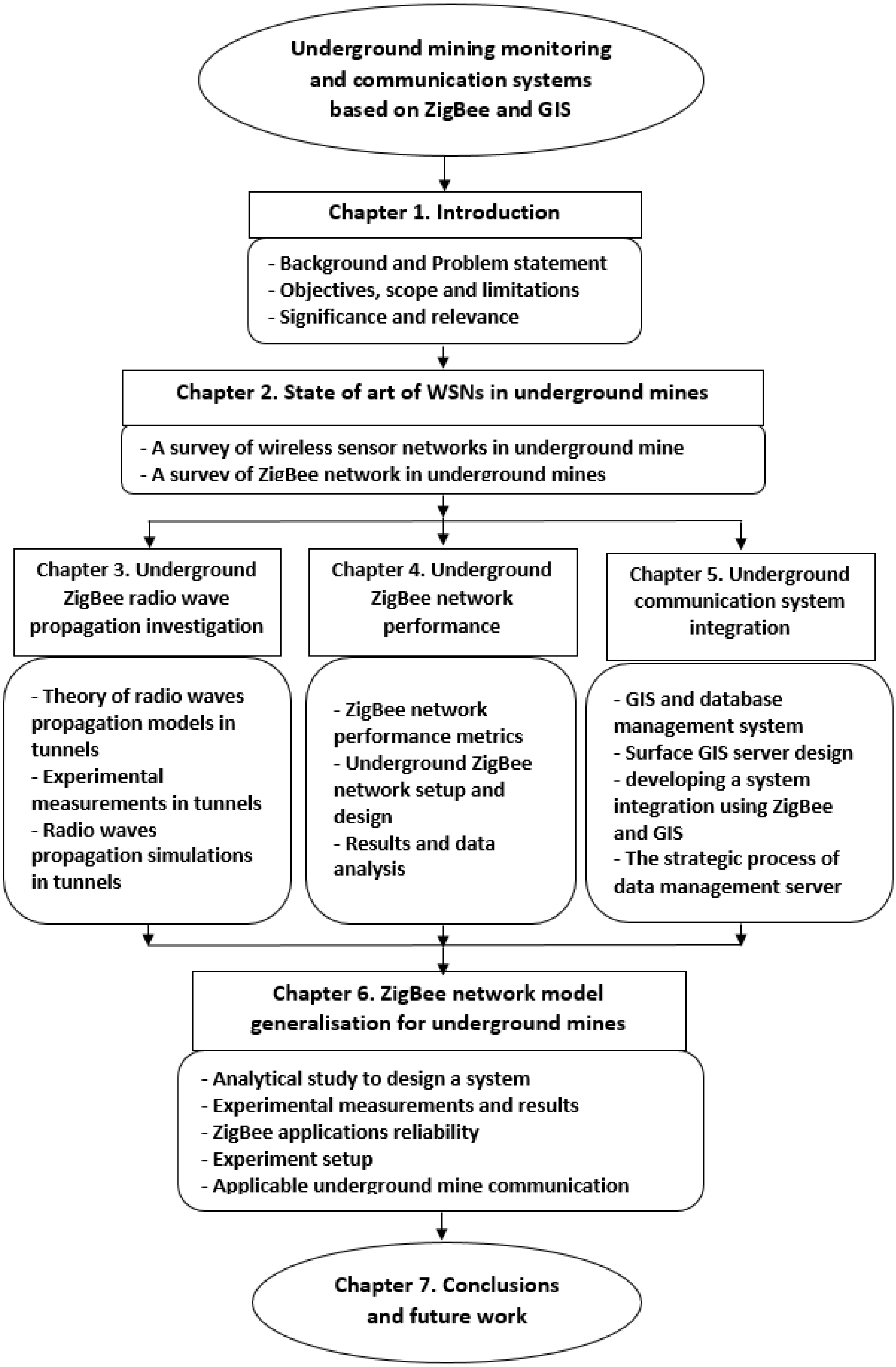

Figure 1-3 Structure of thesis chapters

Chapter 2 presents the state of the art of WSNs in underground mines, in relation to the innovation of remote and automatic systems against the backdrop of fewer skilled and unskilled mining personnel. It also surveys the essential features of ZigBee networks in underground environments compared to other WSNs, and presents the relative strengths and weaknesses of ZigBee networks in these environments.

Chapter 3 analyses the attenuation theory of radio waves in underground mines. It investigates the influences of openings, features and operations of underground mines on the behaviour of WSNs' radio wave propagation. Then, it discusses the measurement of ZigBee communication distances by comparing experiments and simulations results obtained in an underground mine.

Chapter 4 highlights the placement of the sensing nodes, an important factor in allowing efficient transmission as well as maximum security throughout the wireless network. It also investigates an optimal arrangement of ZigBee nodes by creating various scenarios of mesh and cluster-tree configurations, as well as LQI-related metrics evaluation in mine tunnels using simulation programmes to assess ZigBee network performance and security in underground mines.

Chapter 5 provides a design of system integration based on the ZigBee and GIS for the underground mines monitoring and communication. It develops a trigger action plan, programmed in the surface GIS management server, for the automatic response when monitored underground mine attributes exceed normal or threshold value limits. It also includes a design to turn the auxiliary fans on remotely or automatically in orange (caution) conditions, and to send evacuation messages to underground miners in red (unsafe) conditions.

Chapter 6 generalises the ZigBee network model for underground mines. It demonstrates what controllable and uncontrollable parameters influence a ZigBee network model design and how a ZigBee network is physically established in an underground mine. Then it presents a verification of the system design by physical experiments in the underground mine.

Chapter 7 concludes the study by re-presenting the essential findings, methods and designs for the establishment of ZigBee networks in underground mines. It then offers a contribution to the direction of future research.

1.7 SUMMARY

In this chapter, a general overview of underground mining problems in terms of safety, health and operational management has been provided and the main objectives of this study have been analysed. The relevance and contribution of this research project to the mining industry has also been highlighted. Finally, each chapter of the thesis has been briefly outlined.

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CHAPTER 2. STATE OF ART OF WSNS IN UNDERGROUND MINES

2.1 INTRODUCTION

Underground mining is the process of extracting deep ore-materials from the ground. Operations could be improved through a more comprehensive means of interaction between underground and surface communication networks. This two-way interaction would cover information regarding operations, risk and hazard analysis, safety management, and service and maintenance supports. Owing to the dangerous nature of underground mining, techniques of communication to monitor, control and ameliorate incidents are considered. It is claimed that monitoring and communication systems in underground spaces can be developed entirely using ZigBee networks, one of the WSN technologies. However, the reliability and performance of such systems are analysed in chapters to follow. The conceptual process of the literature survey of WSNs focusing ZigBee network is illustrated in Figure 2-1. According to this process, a critical survey of prior research on WSNs for underground mines is carried out before reasoning how ZigBee networks are adopted for underground mines in this study and pervious research. The claim is supported by reviewing and classifying the features of ZigBee networks and developed with arguments on the strengths of such networks in underground mines. The result of this process is the promotion of safety and operational management in underground mines through ZigBee network developments.

The remainder of this chapter is organised as follows: WSNs' architecture designs and applications in underground mines are surveyed in the second section. Then, common underground WSNs are evaluated and compared in order to assess an efficient WSN. The third section is a survey of essential features of ZigBee networks in underground environments. Finally, the related strengths and weaknesses of a ZigBee network establishment are presented.

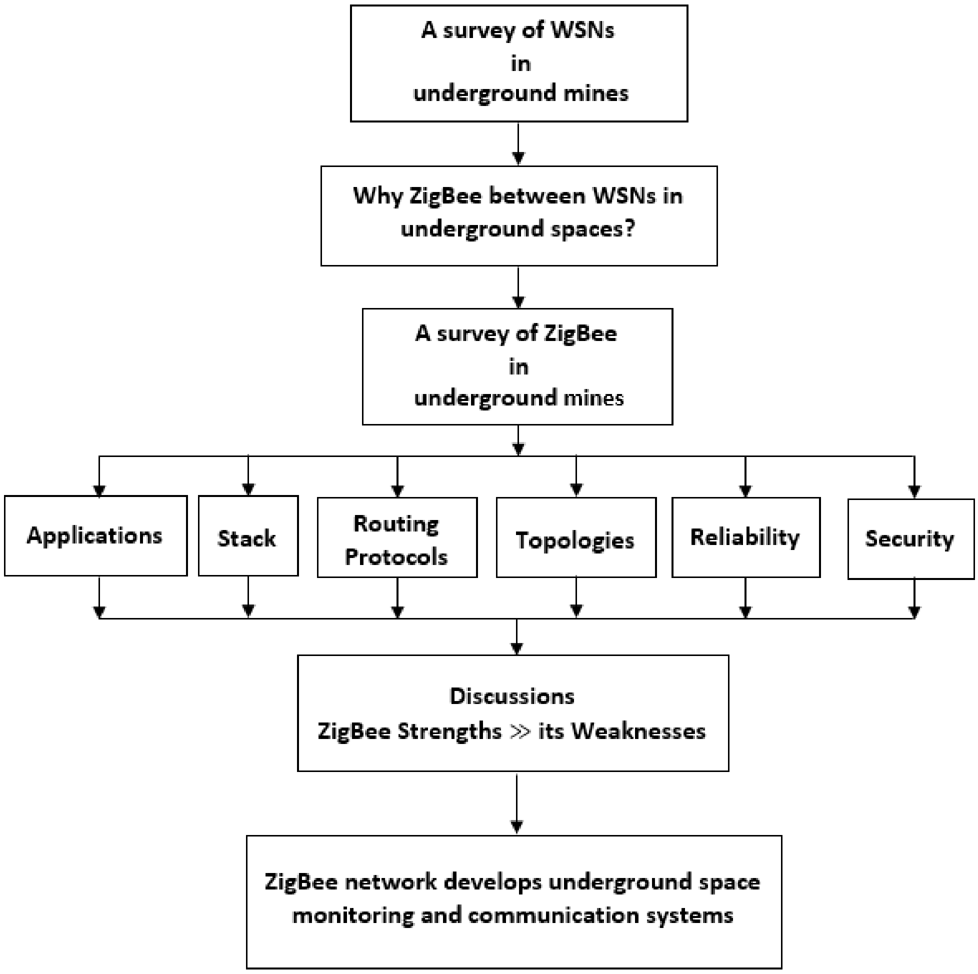


Figure 2-1 The conceptual process of literature survey in this study

2.2 A SURVEY OF WIRELESS SENSOR NETWORKS IN UNDERGROUND MINE

The mining industry has increasingly used new technologies over past decades. Increased demand for resources due to industrialization and urbanization of developing countries has been a catalyst for marked investment in underground mining automation (Burger, 2006).

Effective real-time communication may not only mitigate potential hazards but also be a decisive supporting factor during emergencies or even predict such conditions. While the use of technology in underground mining has moved from a simplistic to sophisticated history, electronic communication systems have only been in use for a relatively short time since the early 20th century. Underground communications became necessary because of repeated hazards events. Earlier communication equipment such as telephones (1913), and Walkie-Talkies (1966), supported mining operations considerably and reduced potential risks in underground spaces. Today communication systems are an integral part of mining and assist underground mining operations in achieving a greater degree of safety. In fact, assets have been maximised with the addition of advanced communication techniques compared to the traditional methods of exchanging information between sub-surface and ground-level offices.

Remote and automatic systems, operated by fewer skilled and unskilled workers, have brought more dependable health and safety to the workplace. This has meant greater cost-effectiveness, better management of technical problems, energy savings, more real-time responses to accidents, and better environmental monitoring of underground mines (Fisher & Schnittger, 2012).

The study of wireless sensor networks (WSNs) is one of the most stimulating fields of computer science research. This has contributed to home and industry communication and monitoring solutions over the past five decades (Silicon-Laboratories, 2012), whereas WSNs have only been appraised in the mining industry during the past twenty years. They are built from a considerable number of low cost and low power consumption nodes. These nodes are able to collect data and relay it to the base station or sink. Then, all base stations or sinks transfer the received data to a coordinator in the control room. These attributes of WSNs' nodes bring significant benefits to underground mine monitoring and operations. They are able to sense underground environmental variations, perform video surveillance, vocal or message communications, and trace miners and equipment location and operation.

Research on WSNs in underground mines has advanced for gas detection and collapse prediction in the coal mine industry. This industry has recorded a large number of events. Reported annual statistics of fatalities from coal mines, especially in the USA and China, underpin the importance of utilising WSNs to reduce the number of injuries, deaths and damage to equipment in order to minimise unexpected costs (Molina, 2011). Underground mining has benefited by the implementation of WSNs for strategic positioning of miners and equipment (Chehri, 2008; Wan et al., 2013) and communication in both vocal and visual formats (Junhua & Xiaozhou, 2012; Li & Lu, 2011).

Studies about the application of WSNs in the underground mining industry started gaining attention in 2003. The prominence of WSNs in academic and commercial publications from 2003 to 2013 is illustrated in Figure 2-2. This is based on an extensive electronic survey of over 382 peer review journal papers, 97 conference papers, 30 books, 367 dissertations, and 64 newspaper articles and trade materials. From the survey, it was realised that WSNs have mainly attracted research attention on the evaluation of WSNs' performance and their possible applications in underground mines. As seen in Figure 2-2, students also made an increasing contribution to the WSN benefits during these years. In particular, journals and conferences papers as contemporary sources of WSN investigation reached a zenith of 71 in 2012. These statistics demonstrate that significant academic and commercial investment has been placed in assessing WSNs over the past decade.

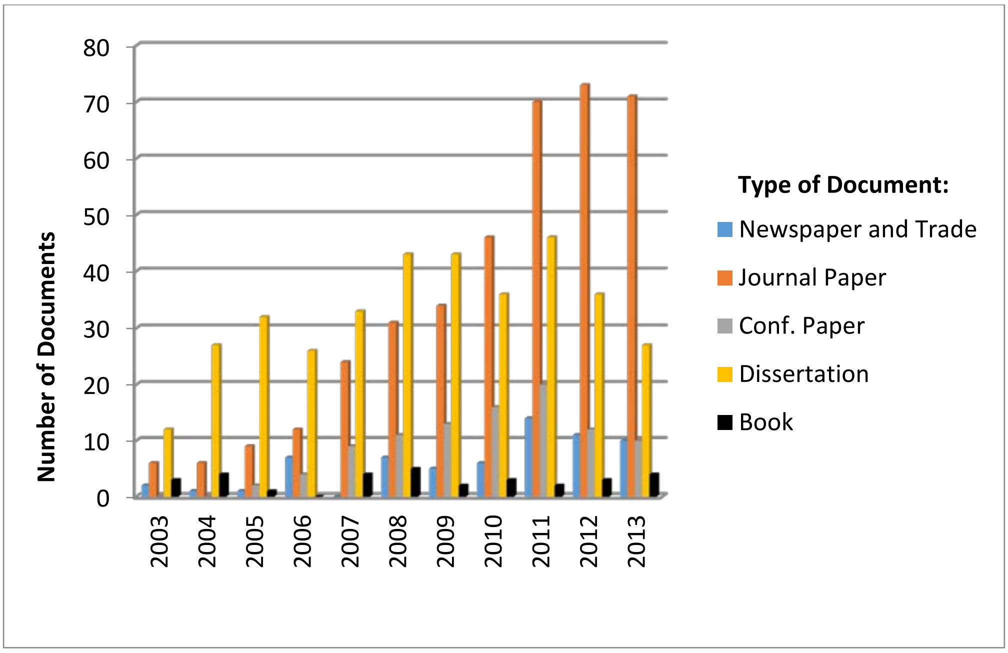


Figure 2-2 Studies on wireless sensor network (WSN) in underground mines from 2003 to 2013

2.2.1 *Why WSN in underground mines*

Increasing safety and health in underground operations is a priority in mining automation. WSNs have played a significant role in applying automation in the underground mining industry and are able to collect and transmit information that is characterized by physical and environmental attributes (Wei et al., 2007). WSN capability can also increase by attaching a variety of sensors for different applications such as mechanical, thermal, biological, chemical, optical, and magnetic monitoring. Sensor features can also benefit underground mine networks (Karl & Willig, 2005) and are largely involved in wireless communication, self-organisation and flexible topology. They allow easy expansion following mining progression as well (Haifeng et al., 2011).

I) Ad-hoc network ability: WSNs can be structured as autonomous networks by automatically setting up a considerable number of nodes via wireless links as well as not requiring technical infrastructure in establishing WSNs (Buratti et al., 2009). Every node can be a router for the nearby nodes simultaneously while it runs its performing standard functions. Such a structure supports a robust monitoring and communication system comprising many nodes compared with a wired network which is very likely to fail due to cable damage in harsh and narrow underground spaces.

II) Self-configuration and self-healing: WSNs provide flexible topology arrangements and fault management. In the case of node failures or any disconnection in the network coverage, the system will enable other possible routes to maintain network functionalities. The self-configuration and self-healing abilities have removed the dilemma of diagnosing and frequent repairing and monitoring network failure without compromising mining operations.

III) Scalability: the number of sensor nodes deployed in a WSN can range from hundreds to thousands in one network. This sensor networking is sufficient to cover all required underground mine monitoring and communication applications (Al-Karaki & Kamal, 2004). In such a wide network, data transmission can proceed in a well-arranged node deployment when an event occurs anywhere within the mine.

IV) Power usage: WSN nodes are usually battery-powered. This enables them to continue monitoring and communicating regardless of mine site power fluctuations. There are substantial challenges regarding energy-saving mechanisms such as radio optimisation, data reduction, sleep/wake scheduling, energy-efficient routing, and battery depletion. Furthermore, recently manufactured batteries can operate on either DC or AC power based on their battery charge or the mine site power supply, respectively. Switching between battery and the mine site power results in extended battery life, and nodes are thus able to continue longer data transmission during power outages (Moridi et al., 2015).

V) Sensor nodes capability: sensors are responsible for sensing environment features while nodes act as wireless data transmitters through the network and these combined operations centralise in a single device called a sensor node. Low cost, low power consumption are prominent capabilities of WSNs sensors providing the sensing the surrounding environments and interacting through wireless communication nodes (actors). More importantly, WSN nodes have a reliable transmission capability with small size, low power, and low complexity of establishment (Akyildiz & Kasimoglu, 2004). Hence, WSNs are advantageous and profitable for underground mining.

The primary advantages of wireless networks compared with other communication techniques are real-time data transfer, and simple and cost-effective establishment without the need for wire-transmission. Therefore, wireless communication mitigates problems of line breakage through underground collapse or machinery malfunction whilst stabilising operational functions.

2.2.2 *WSNs architecture design in underground mines*

Functional practicality is an advantage of the individual node system architecture of WSNs in underground mining. As main tunnels in underground mines are kilometres long, a WSN can enable connections of small branch tunnels networks to the main tunnel network. Moreover, the network architecture of WSNs is based on restrictions, sensor node features, and required applications within the system. Each node sensor performs a sensing task for detecting specific events. For example, a single ZigBee node can contain up to 240 sensors and run multiple applications (Daintree-Networks, 2006). A sink which also is a specific node is responsible for collecting sensing data reported from all the sensor nodes located in branch tunnels and transmits data to a task manager located in the main tunnel or on the surface. If the sensor nodes are unable to communicate with the sink, intermediate relay sensor nodes are placed between them.

Several WSNs with different ranges are sometimes used to cover underground monitoring and communication systems. Each WSN can also include multiple nodes within a designated area. A typical WSN architecture in underground mines comprising environmental and operation monitoring, communications and localisations is shown in Figure 2-3. Node data is transferred to a control centre by wire or wireless connections. Data is sent to the operator and client via SMS or/and Email after automatic saving and processing (Ghorbani, 2012).

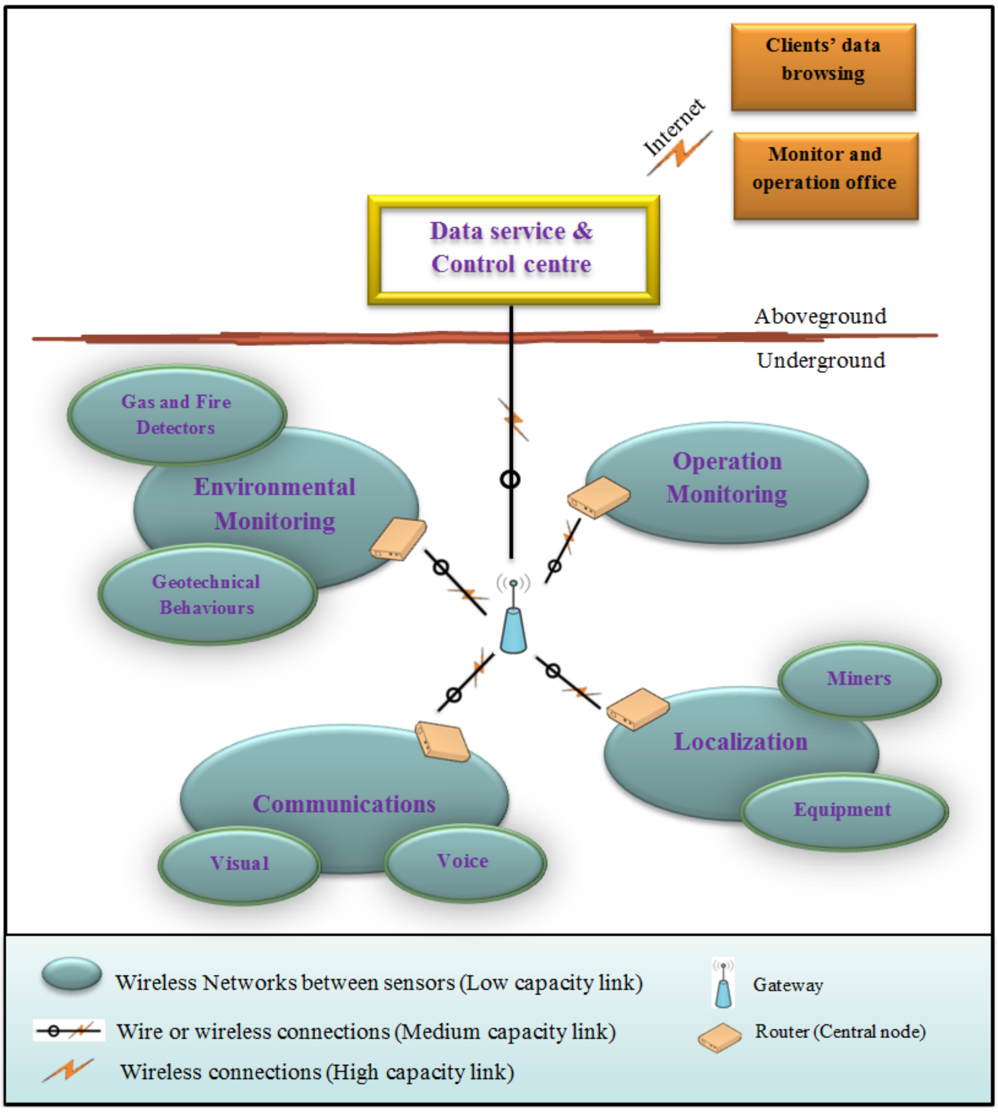


Figure 2-3 Typical WSNs architecture in underground mines

The architecture design of recent underground WSNs is based mainly on the technology chosen. For example, ZigBee technology is selected for communication between nodes and gateways (or sinks) in the high frequency range, while Wi-Fi or UWB are employed for medium frequency communication. Alternatively, for the purpose of reducing risks associated with power cables in underground mines, long-range technologies such as internet or WiMAX have been adopted for the communication between a control centre and clients' operators (Gisbert et al., 2013).

2.2.3 *WSNs applications in underground mines*

The applications of WSNs have to some extent brought significant improvements to safety and health, risk assessment, enhanced production, and operating costs reduction in most underground mining aspects. WSNs' applications directly rely on sensor technology capability for detecting physical environment attributes. It is also notable that the ability of real-time data telemetry makes WSNs' applications vital in predicting and preventing incidents. Based on the author's literature review, applications in underground mines are classified into three groups: monitoring, communication and tracking. Figure 2-4 illustrates the proportion of WSN application studies in underground mines.

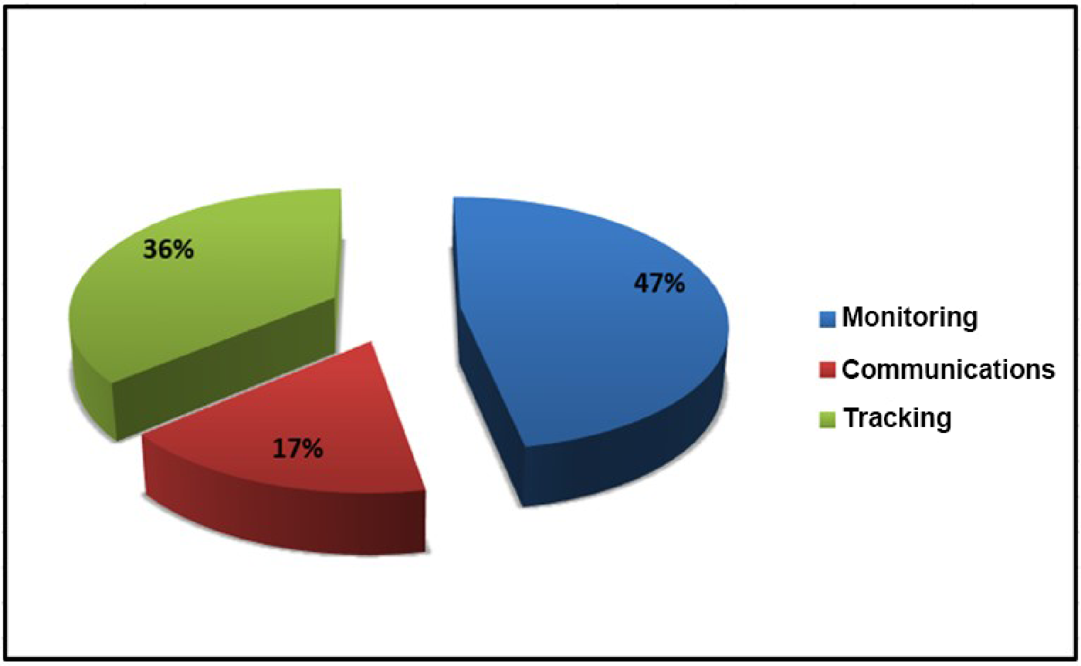


Figure 2-4 Percentage of conducted studies on WSNs' applications in underground mines

As shown in this chart, 47% and 36% of these studies have concentrated on monitoring and tracking, whereas only 17% on communication because of numerous required underground applications in monitoring and tracking. This was impractical using technologies that existed before WSNs. In addition, the importance of monitoring and tracking is becoming more evident as they have delivered an integrated solution to the major concerns in underground mine management, particularly in coal mines. On the other hand, the successful use of semi-wireless communication systems such as Leaky Feeder-Based System and Ethernet, and wireless communication services like Walkie-Talkie System and Bluetooth reduces research in the area of WSNs. The possible WSNs' applications in underground mines that were examined and classified in studies during the last decade are illustrated in Figure 2-5. The details of each area are investigated in the sections that follow.

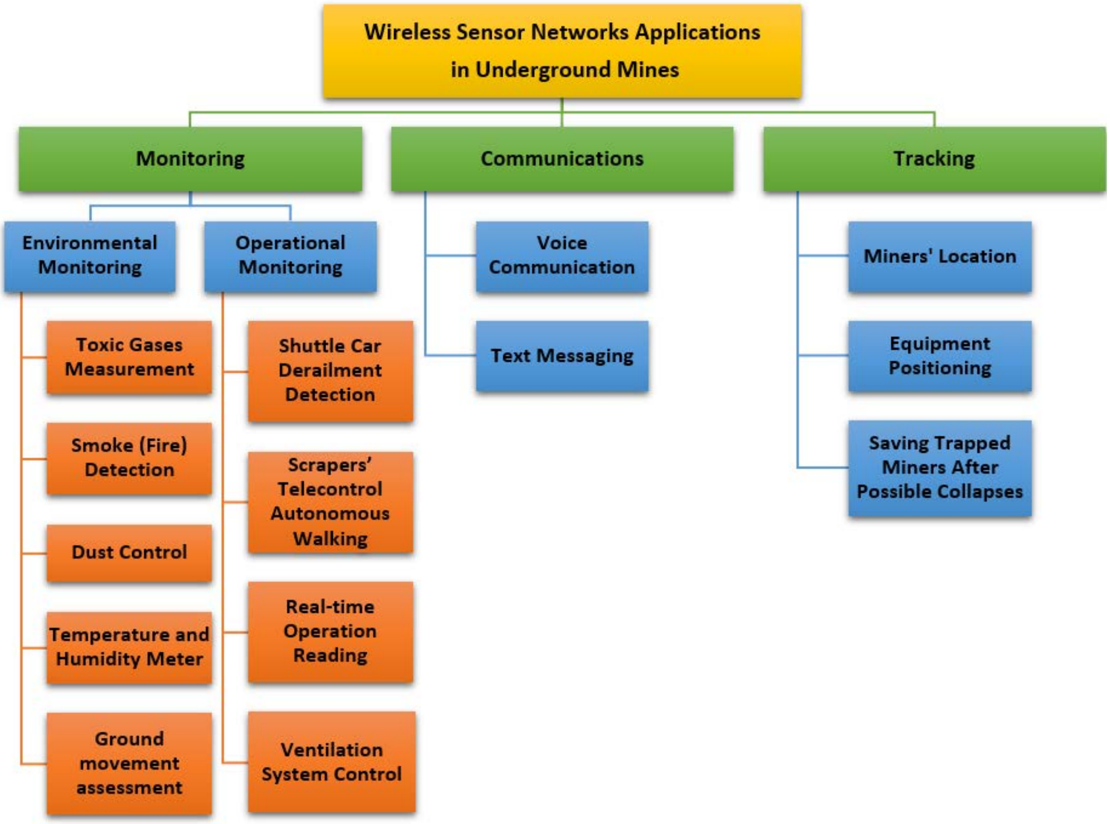


Figure 2-5 Possible WSNs' applications in underground mines during last decade

2.2.3.1 Environmental monitoring

The most important application of WSNs in underground mines is to help minimise the effects of natural disasters by monitoring the environment. Various types of sensors are being used to measure environment attributes, such as gas concentration, temperature, humidity, and ground acceleration (geotechnical instrument), to provide real-time safety and health data from underground operations. Analysis of the data is vital in mining management and incident prevention. Although other monitoring systems could be utilised in underground tunnels, WSNs significantly refine the surveillance for overall care of mining personnel. For example, sensors can be more easily and densely installed compared with wired ones, and managing a specified underground area in emergency conditions will be more efficient, based on the received local detailed data.

Minute sensor nodes also render WSNs more useful to sense dark, dusty and narrow underground spaces which are travel paths for large mine machinery. These nodes could be deployed in top corners or ceiling of tunnels. In addition, deploying sensor nodes, that are in places distant from incidents, helps maintain a durable and sustainable wireless network. Monitoring the concentration of toxic gases particularly in coal mines is another beneficial application of these sensors. As they are able to be developed and employed in wet areas, advantages of WSNs become more conspicuous in the presence of aquifers and mining operation water by which chemical or mechanical devices lose their sensitivity.

Studies in underground monitoring using WSNs have widely focused on evaluating applications of fire detection, concentration of noxious gases, and other environmental features such as temperature, humidity and air pressure in mines (Pandit & Rane, 2013; Sun et al., 2010). Continually measuring dangerous gases such as methane, carbon dioxide and monoxide which can lead to explosions or fire in coal mines makes WSN research important in the context of underground mining.

Operation management is another perspective of WSN research in underground mines. In 2009, Li & Liu suggested a Structure-Aware Self-Adaptive (SASA) WSN system for rapid structure variation detection, caused by collapses in underground mines, regulating mesh deployment of sensors. As fires are still a major factor causing fatalities and injuries in the mining industries, research has examined various methods and WSN types for abrupt fires in underground coal mines (Bhattacharjee et al., 2012; Wei, 2007). El Kouche Alma'aitah, Hassanein, & Obaia (2013) investigated a WSN platform to monitor the erosion conditions of mining machinery to prevent ignitable sparks. Zhang, Yang, Han, & Kim, (2014) also introduced an integrated system capable of repeating inspections based on the WSNs and Cable Monitoring System (CMS) to improve underground coal mine safety.

Operational monitoring through WSNs is also considered to improve safety issues and operation management in underground mines. For example, Yin (2011) simulated a program to evaluate underground scrapers' tele control autonomous walking, merging WLAN and ZigBee technologies. In addition, Wan et al. (2013) presented a derailment monitoring system in endless rope continuous tractors. Real-time monitoring of shuttle car operations, derailment detection, alarming and parking were expected from this system. The ability of audio sensors equipped with powerful, high-sensitivity and low-consumption microphones, also supports search of trapped miners after collapses in tunnels (Akyildiz & Stuntebeck, 2006; Molina, 2011). Furthermore, since air ventilation deficiency in underground mines is a critical issue to the occupational safety and health for mine personnel, air quality is improved by adding auxiliary fans to the ventilation system equipped by the automatic or remote reaction of sensor nodes (Moridi, 2015). It is generally recognized that studies focusing on operational monitoring should be performed in actual cases to achieve meaningful results in mine production scheduling.

Finally, an efficient underground monitoring system is usually designed with multiple requirements of sensing and reacting applications to prevent gas explosions and collapse (Bhattacharjee, 2012; Li & Liu, 2009; Pandit & Rane, 2013; Wei, 2007).

2.2.3.2 Communications

Leaky Feeder (LF) is a semi-wireless communication system which has been recently used for the distribution of voice and data in underground mines. This system has very costly network establishment and maintenance and lacks standardization. Furthermore, its functionality to transmit data is limited to line-of-sight transmissions as transmission cannot pass through solid rock. It also becomes damaged and inoperative as a result of underground collapses or accidents.

An alternative solution for underground communication systems based on WSNs are to incorporate video, picture, voice and text messaging communications (Pandit & Rane, 2013; Qu et al., 2012; Yarkan et al., 2009). The proposed optical WSNs for underground communication systems are not reliable for emergency situations due to the presence of smoke and dust, and the shortage of lighting. Expensive cameras are also required. Hence, studies have focused more in the ability of voice communication (Sicignano, 2011) and text messaging (Moridi, 2015) using WSNs in underground mines.

Researchers have dealt with signal propagation techniques of WSNs in confined environments like tunnels and underground mines to propose real-time response as well as provide communication effectiveness in emergency situations. Specific conditions of tunnels such as rough surface, different shapes, sharpness edges and curvatures have an influence on signal strength reduction. Under these conditions, cost-effective designs on the software and hardware of underground voice communication can be investigated using Wi-Fi under the IEEE 802.11 standard (Müller & Noack, 2011; VAMVU & BARBU, 2013), and ZigBee under the IEEE 802.15.4 standard (Pandit & Rane, 2013; Yin, 2011).

2.2.3.3 Tracking

Tracking to estimate miners' and equipment location in underground mines has been another challenge. Since WSNs have a potential ability to include such applications, some theoretical models of sensor node localization have been proposed for environment monitoring, miners' localisation and vehicle tracking (Song et al., 2011). In order to achieve these purposes, sensor deployment strategy involves creating extensive and dense monitoring and tracking systems. Improvement in the energy efficiency of nodes in order to prolong the lifespan of WSNs is achieved by this strategy (Chen et al., 2008; Haifeng, 2011; Wu et al., 2010). In addition, an optimal positioning algorithm will effectively make the network secure and time saving (Salap et al., 2009).

There are several factors such as communication mode, location method, topology and routing protocol which would be considered when estimating methods of stationary and mobile node locations (Chen et al., 2009). Thus, positioning algorithms are categorized using a triangle measuring method based on triangulating arrival signals parameters, or employing the scene fingerprint method through scene features and the adjacent method to determine the zone of any moving node. The triangle measuring methods including signal intensity (RSSI), time of arrival of signal (TOA), time difference of arrival (TDOA) and angle of arrival (AOA) are widely used for positioning systems in underground mines (Longkang, 2011).

Analysing studies on localization show that RSSI and TOA methods are also pertinent because of their precision and their suitable hardware. The RSSI method is cost-effective and generally used with a DV-Hop algorithm to calculate the distance for a mobile node from closed anchor nodes in underground mines (Chen, 2009; Wang & Shen, 2009; Xu et al., 2012). The TOA method has also been investigated for higher positioning precision (Chehri et al., 2009).

2.2.4 *Underground WSNs evaluation*

Wireless sensor networks (WSNs) have been utilised in underground mines as a way to enhance safety and productivity and reduce operational costs (Bhattacharjee, 2012; Chehri, 2009). The common WSNs for monitoring and communication systems in underground mining are mainly comprised of Bluetooth technology, ultra-wideband (UWB) technology, Wi-Fi technology and ZigBee technology. The system architecture of these WSNs in underground mines is illustrated Figure 2-6.

For the investigation of applicable and reliable wireless systems, the main features of underground WSNs are illustrated in Table 2-1 (Bandyopadhyay et al., 2009; Bluetooth SIG Inc, 2013; Jinyun et al., 2009; Kawamura et al., 2013). As shown in the Table 2-1, Bluetooth has a limited applicability because of its short communication distance between nodes (i.e. requiring a high number of nodes per tunnel) and its low network capacity. However, UWB meets a sufficient data rate, network capacity and low power consumption per node but the communication distance restriction can cause congestion of nodes in tunnels. Thus, traffic routing would be a major problem in utilising a UWB system.

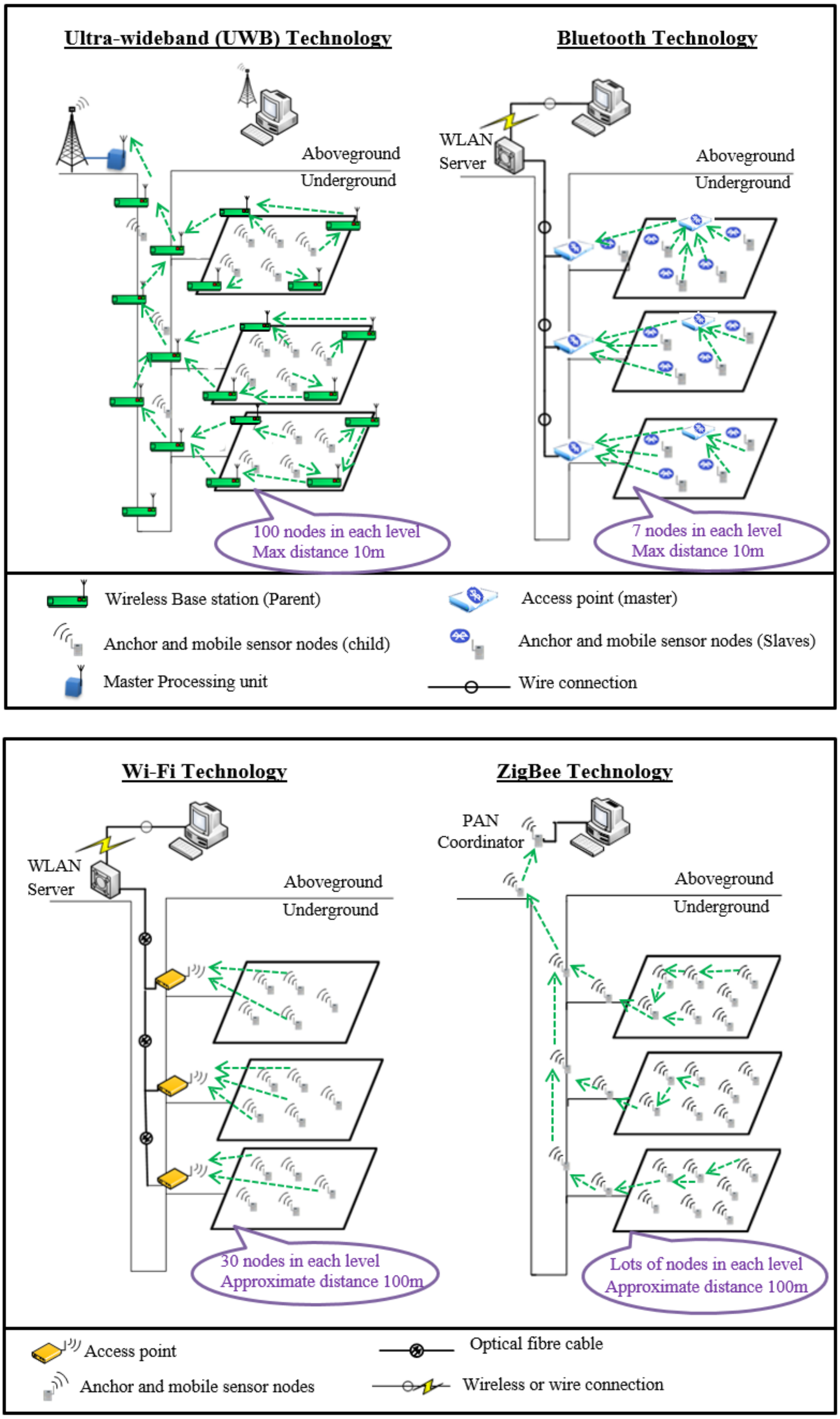


Figure 2-6 System architecture of common WSNs in underground mines

Table 2-1 Comparison of common underground WSNs

Parameters	Bluetooth	UWB	Wi-Fi	ZigBee
Communication distance (m)	10	< 10	50-100	50-500
Frequency range (GHz)	2.4	3.1 - 10.6	2.4 or 5	2.4
Data rate (Mbps)	1	100-500	11	250×10^{-3}
Network capacity (nodes)	7	10-500	32	65536
Power consumption (mW)	1-100	30	500 -1000	20-40
Complexity	High	Medium - High	High	Low

On the other hand, Wi-Fi is a common wireless technology utilised in underground mines because it has adequate communication distance and a high communication speed. Some negative aspects of this network are high power consumption nodes, the need for infrastructure access points for clusters, continuous power supply and access point connections for cabling. Additionally, there is no multi-hop network topology between Wi-Fi nodes even though data is capable of being transmitted between nodes and access point.

ZigBee is a new wireless technology which combines current technical advances compared with other WSNs for monitoring and communication systems in underground mines. It has greater communication distances between nodes, substantial node network, low energy consumption and low complexity, as shown in Table 1. Also, ZigBee technology has very cost-effective nodes, network installation and maintenance compared with other underground WSNs. nor does it require any access point or central node to transmit data between clusters. Although ZigBee network has very low data rate (250 kbps) for image, voice and video communication, it is capable in providing networking applications for data transmission between nodes (node to node relays) with high performance based on numerous hops.

Recently, ZigBee has been used in the field of mine safety for a range of applications mostly in underground coal mines as an automatic meter reading system, security system and for remote control whilst supporting other WSNs (Chehri et al., 2011; Hongjiang & Shuangyou, 2008). This study proposes a monitoring and communication system for underground mines based on ZigBee network performance without other supporting WSNs. In fact, utilising central (sink) nodes or access points through another WSNs because of high power consumption and cable damage risk is eliminated. ZigBee is selected for its powerful networking capability through ad-hoc and multi-hop topology and considerable network capacity and cost-effectiveness. Based on this system, data from sensors (fixed nodes) and workers and vehicles (mobile nodes) locations in an underground mine could be transferred to a surface gateway for monitoring and bilateral communication.

2.3 A SURVEY OF ZIGBEE NETWORK IN UNDERGROUND MINES

ZigBee is a new wireless communication technology based on the IEEE 802.15.4 standard. This standard introduces ZigBee as a low rate and low power consumption technology for wireless personal area network (WPAN). The first ZigBee node was developed by ZigBee union in 2004 (Longkang, 2011). Due to the benefits of the features detailed below, ZigBee network is adopted for underground mine communication systems ZigBee nodes can last six months up to two years. They are also very low-cost compared with other WSN nodes and qualify for a free licence in the frequency bands, with the flexible range in operating frequency of 2.4 GHz around the world and regional bands of 868 MHz in Europe and 915 MHz in the USA.

ZigBee provides reliable infrastructure based on a mechanism of collision avoidance to prevent competition and conflict in sending data. It also avoids interference with other ZigBee networks which communicate on the same frequency nearby (Longkang, 2011). ZigBee networks can support up to 65,536 sensor nodes in one system. Real-time data aggregation enables it to provide bounded delay guarantees, so it is capable of collecting, processing and transmitting data in a very short delay time. It is capable of ad-hoc networking. In other words, sensor nodes including stationary and mobile ones can join the network autonomously and communicate together without existing infrastructure and central control. In addition, ZigBee nodes commonly have self-organization and self-healing abilities. Another prominent feature of ZigBee is multi-hop communications. Some ZigBee network topologies such as mesh networking are promoted with multi-hop ability. This allows a wireless network to forward data by hopping node to node until it will be securely received by the destination node. This ability, indeed, increases fault tolerance through the network, as well as having alternative routes for more secure and effective communications particularly in emergency conditions.

These significant features of ZigBee networks have substantially drawn researchers' attention of this technology to the area of underground mining. Figure 2-7 illustrates the trend of different studies in underground mines using ZigBee between 2003 and 2013. The bar chart is extracted from 23 newspapers and magazines, 138 journal papers, 86 conferences papers, 34 university dissertations, and 19 books including book chapters. Therefore, in the earlier years of ZigBee development, underground applications were introduced primarily via newspapers and trading company advertisements. However, research papers and conferences started to focus on this technology. There also have been substantial publications in this period such as dissertations and books on ZigBee, specifically focusing on the context of underground mining. The trend of studies has still increased after 2013 because of the electronical development of the ZigBee nodes in terms of functions and the considerable extension of antenna gain.

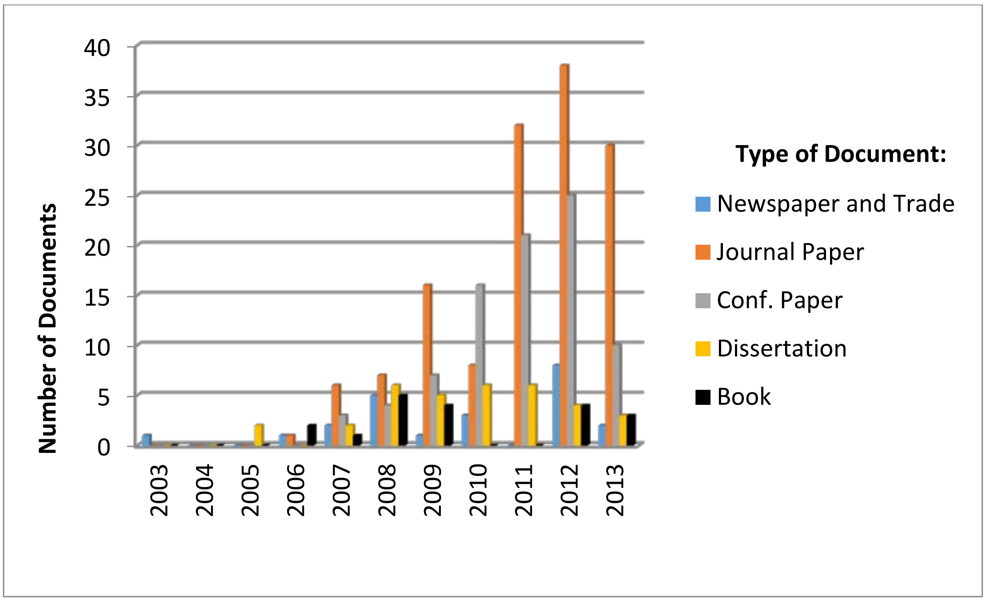


Figure 2-7 Studies on ZigBee in underground mines

In these studies, it is clearly observed that safety was the major aspect considered in a considerable number of research works on ZigBee technology for underground mining, particularly coal mines. The main investigations of these studies are analysed in the following sections.

2.3.1 *ZigBee applications*

This research presents three categories of underground ZigBee network applications including environmental monitoring, tracking and communication. Figure 2-8 chronologically illustrates the description of these applications based on analysing studies from 2003 to 2013.

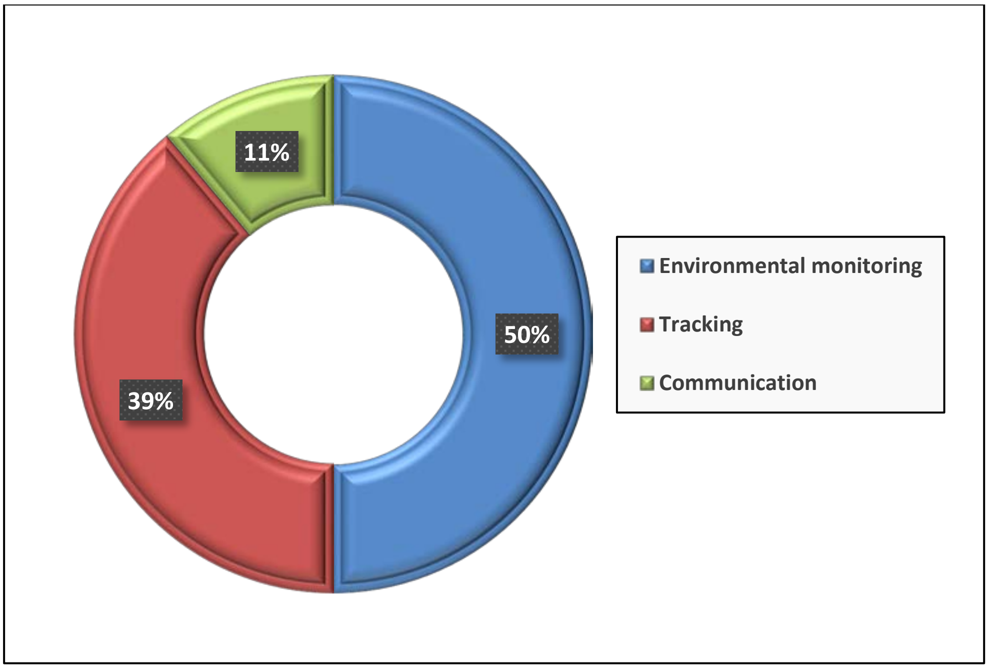


Figure 2-8 Breakdown of studies conducted on ZigBee applications in underground mines

As seen in Figure 2-8, more than 50% of studies have mostly focused on monitoring underground mine coal environment attributes, and 39% of studies investigated the most accurate algorithms as well as efficient and cost-effective methods for the positioning of mobile and stationary ZigBee nodes. Lastly, only less than 11% of studies examined the communication between surface and underground personnel by ZigBee network. Further explanation with regard to academic work on the ZigBee network follows.

The application of ZigBee networks relies on the sensor network applications which are able to communicate with physical layers of the ZigBee protocol. Sensor networks may consist of many different types of sensors which can be used for continuous sensing, event detection, event ID, location sensing, and local control of actuators (Leccese et al., 2014). The concept of micro-sensing and wireless connection of these nodes is a promising area for new applications. Underground mine applications based on stationary and mobile sensor nodes can be categorised as follows:

a) Potential applications of stationary sensor nodes (positioning):

- *Secondary (supportive) Communication:* based on voice communication or message texting in emergency conditions
- *Environmental monitoring:* measuring air quality and quantity as well as detecting gas and fire
- *Ground movement monitoring*: the periodic transmission of geotechnical instrumentation data
- *Production management:* the real-time transmission of equipment operational information

b) Potential applications of mobile sensor nodes :

- *Emergency mustering:* tracking miners and tagging systems
- *Traffic management:* monitoring mobile plant equipment and using traffic signals control
- *Production measurement*: improving the trip cycle for jumbo drills and longwalls, or configuring the payload of production vehicles

2.3.2 *ZigBee stack*

The protocol stack of ZigBee networks is comprised of four main layers. The logical arrangement of these layers is illustrated in Figure 2-9. The application layer and the network layer are supported under a ZigBee specification, and the media access control (MAC) and the physical layers (PHY) are supported through the IEEE 802.15.4 standard. ZigBee layers are often formed as upper layers of a ZigBee stack. There are sublayers, each of which have different functions.

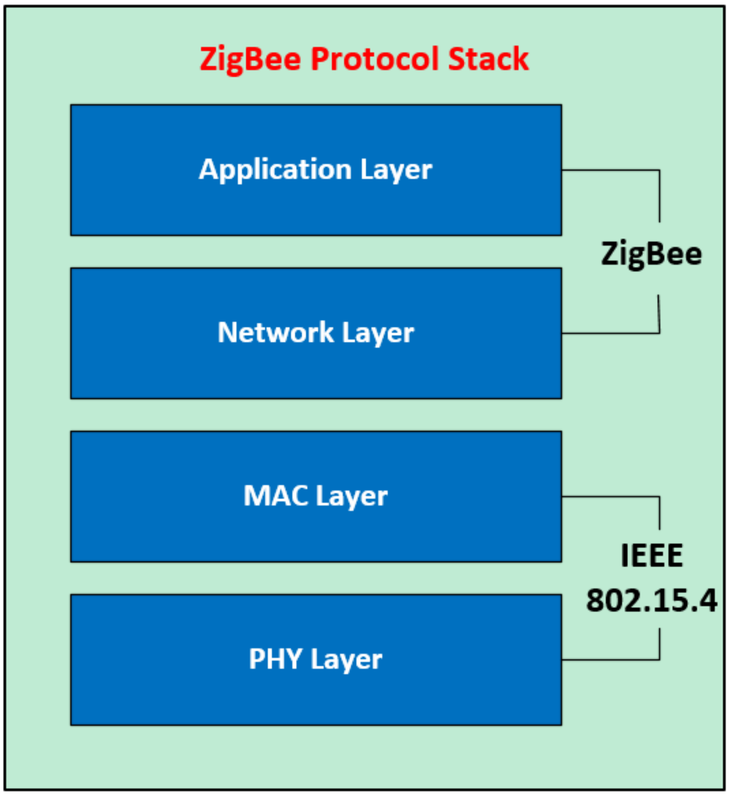


Figure 2-9 Logical arrangement of a ZigBee stack

I) Application layer: This layer provides a framework for distributed applications and it is divided into three sub-layers comprised of the application objects, the ZigBee device object (ZDO) and the application sub-layer. The application objects are the endpoint software which includes the tasks of each ZigBee node, for example, periodic reading of environmental conditions. A single ZigBee node can support between 1 to 240 application objects. At the same time, the ZDO defines the different roles of ZigBee communication within the network like coordinator, full function device or end device. It also allows nodes to detect each other and establish a reliable network. The application sub-layer supports a data delivery service and secures links for the application objects and the ZigBee device object.

II) Network layer: this layer is responsible for ZigBee network addressing and routing by broadcasting through a MAC layer. So, this layer makes sure that sent data packets are being received by the destination node, and joining or re-joining is secure.

III) IEEE 802.15.4: This standard, defined in 2003, specifies two layers of MAC and PHY for low-rate wireless personal area networks (LR-WPANs).

IV) Media access control (MAC): The MAC layer provides addressing and channel access control mechanisms (16 channel) that make it possible for several terminals or network nodes to communicate within a multiple access network.

V) Physical layer (PHY): Defines the means of transmitting raw bits rather than logical data packets through a physical link connecting network nodes and converts data packets to wireless signals (over-the-air) and vice versa. This layer supports three frequency bands of 2.400 GHz-2.484 GHz globally at a maximum rate of 250 kbps, 902 MHz-928 MHz at 40 kbps of data rate in the United States, and 780.0 MHz -868.6 MHz at 20 kbps in Europe. Link quality and energy detection measurement are also other functionalities of a PHY layer (Lu, 2011).

2.3.3 *ZigBee routing protocols*

A routing protocol determines the routes selected between sensor nodes in order to communicate. Routing as mentioned above is one of the major functions of the ZigBee network layer which is highly influenced by lower layers of MAC and PHY layers. Therefore, analysing these lower layers, such as the required communication range between nodes, plays a significant role in designing an efficient and reliable routing protocol for WSNs. Routing protocols are commonly categorized into two groups called proactive and reactive routing.

Under the proactive routing, also known as table-driven route discovery, nodes have to be set up in a certain topology before establishing the network. Each node ought to aware of nearby nodes in advance. Thus, nodes become active to discover surrounding destination nodes before transmitting data packets. Although this is a very efficient and reliable way to communicate, energy consumption and bandwidth occupancy are increased as all nodes are automatically updated and are always discovering other available routes.

The reactive routing, also known as on-demand route discovery, is where a node discovers routes on demand. Here, a node initiates a route discovery and adopts a path to a destination node when it as the source node has a packet to deliver. It is suitable for mobile nodes which have to alter communication topologies and paths over time through the network. As a result, the lesser consumption of energy and bandwidth is a salient feature of this routing protocol, but packet delivery becomes longer owing to routes discoveries for each transmission (Hamid et al., 2013).

These challenges have drawn academics' attention to investigate a wide range of new algorithms and solutions on ZigBee routing optimization largely for decreasing cost and power consumption and improve the reliability of packet delivery through the network.

2.3.4 *ZigBee network topologies*

Topology refers to the configuration of nodes (hardware) that establish a wireless network and how the data is transmitted within the network. ZigBee networks under the IEEE 802.15.4 standard support three different node functions including coordinator (gateway), full-function (router) and end-device. These functionalities are as follows:

I) Coordinator: This node sets up and controls the network as well as storing information required from other nodes. It operates as a terminal for other nodes through the network and is also referred to as a personal area network (PAN) coordinator.

II) Full-function: This node relays data transmission between the coordinator and other participating nodes as well as fulfilling duties such as environmental sensing. This type of node extends network area coverage and strives to maintain communication routes despite network congestion or possible node failure.

III) End-device: This node only can receive or transmit data. Accordingly, it must be set up for direct communication with the nearest full-function node or coordinator.

Because of the function of these nodes types, three network topologies namely star, cluster-tree and mesh (peer-to-peer) are predominantly supported by ZigBee specifications. Figure 2-10 illustrates how these topologies are differentiated to establish a network between nodes. First, in the star topology, a PAN coordinator has a responsibility to communicate with every single node through the network. This topology is appropriate for systems which need centralized and real-time communicable applications. Second, in the cluster-tree topology, every full-function node first connects directly with the network provided by a PAN coordinator, then invites other nodes in its branches to conjoin with the network and can be regarded as a coordinator for its own branch nodes. Third, in the mesh topology, each node can communicate with any node in its coverage area. It is observed that this topology is capable of being established as an extended network, based on the relaying data, by adding full-function nodes (Saraswala, 2013).

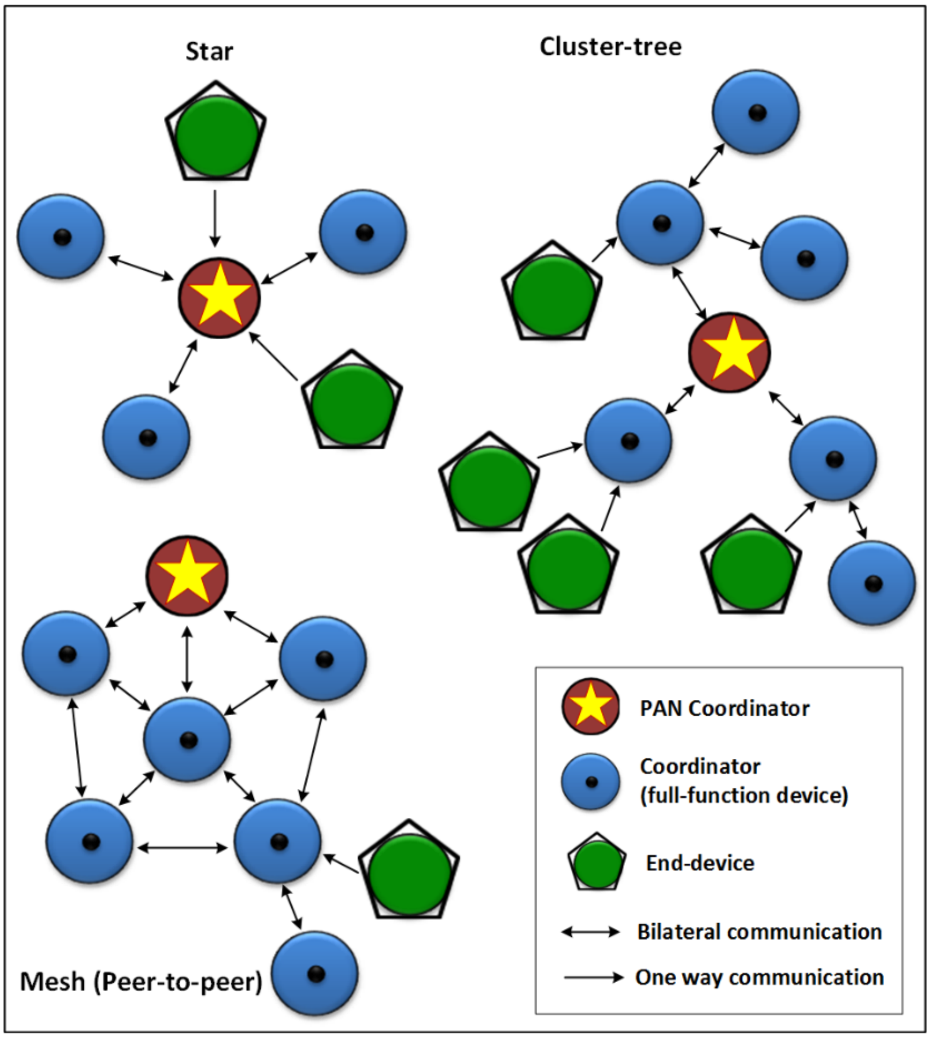


Figure 2-10 Network architecture of the three ZigBee topologies

The possibility of establishing ZigBee network in underground mines between a surface PAN coordinator and underground nodes, using the mesh topology strategy with the specified applications and easy expansion of the network, is the research challenge of this dissertation. In addition, all experiments in real cases, emulations and simulations are designed and analysed to prove this research hypothesis.

2.3.5 *ZigBee network reliability*

Ensuring the reliability of WSNs is mainly concerned with the possibility of temporary or permanent node failure within the network largely resulting from the deficiencies of battery-power and radio-based communication. This is of particular importance when designing an extensive and reliable ZigBee network for underground mine monitoring and communication systems. To provide higher degree accuracy and more reliable exchange of data through such a robust network, it needs to be secured and equipped along several possible routes. To avoid an unreliable communication in the linkage of sensor nodes, network design is not commonly focused on each single end-to-end delivery. In fact, the adjustment of network features and higher layers of application and network layers in a ZigBee stack can definitively improve the reliability of lower layers of the PHY and MAC layers. For example, different intervals of periodic readings must be managed for the application layers in order to avoid overloading or data-remembering failure by lower layers. It also is essential for sensor node applications to remove unnecessary data records and aggregation. Consequently, a number of characters such as worth-data priority, reading intervals management, and environmental effects on radio wave propagation all influence the network reliability (Baronti et al., 2007).

2.3.6 *ZigBee network security*

Sensor nodes in a wireless sensor network are limited in their computational power and communication resources. Due to these strict resource constraints, present network security mechanisms are inappropriate for this field of operation. Efficient encryption of measured data can be achieved at the cost of increased overheads in the length of the message. However, radio communications are the most energy consuming function performed by these nodes, hence the communications overheads have to be minimised to achieve system longevity. The security requirements of wireless sensor networks are defined as data confidentiality, authenticity, integrity and current validity.

I) Data confidentiality: Data confidentiality means keeping important transmitted information undisclosed from unauthorised personnel. This is particularly important in the case of wireless networks where data is transmitted using a radio frequency whereby any radio receiver can intercept data. Data confidentiality is usually achieved by encrypting the information before transmission so that only authorised personnel can decrypt transmitted information. Encryption is therefore classified into two categories: symmetric encryption and asymmetric encryption. In symmetric encryption, a secret key is shared between the authorised parties, while in asymmetric encryption, the sender encrypts the data with a public key and the receiver decrypts it using a private key. A strong encryption mechanism not only prevents message recovery but also prevents uncategorised parties from decoding even partial information about the message. This property is called semantic security, which implies that the encryption of the same plaintext two different times should give two different cipher texts (Perrig et al., 2002).

II) Data authenticity: Data authenticity provides a means to detect messages from unauthorised nodes thereby preventing such nodes engaging the network, that is, data authentication allows a receiver to verify that the data is sent by the claimed sender. This is particularly important in sensor networks where a hostile node can easily implant a large number of messages into the network (Baronti, 2007) causing other nodes to process these messages thereby decreasing their power resources. Therefore, a receiver of these messages should ensure that the message is desired from an authorised source. Data authentication can be achieved by calculating a Message Authentication Code1 (MAC) using a shared secret key for the transmitted data. This MAC is also sent simultaneously with the data. The receiver would also calculate the MAC for the received data using the shared key, and then compare this computed MAC value to the one sent by the sender of the data. If the two match, then the receiver recognises that the data has been sent from a valid sender (Perrig, 2002). This affirms message authenticity.

III) Data integrity: Communications in wireless sensor networks are based on broadcasts, hence messages can be easily intercepted and/or tampered via audio reception through the wireless medium. Data integrity provides a way for the receiver of the message to know if the data has been tampered while in transit by an attacker (Perrig, 2002). Data integrity is closely related to data authentication since the MAC also provides data integrity. The receiver of the data calculates the MAC and compares it to the one transmitted by the sender. If the two MACs match then it ensures that the data was not tampered with. In other words, if an adversary has tampered with the message then the MAC calculated by the receiver cannot be equal to the MAC that was initially calculated by the sender at the time of sending the message.

IV) Data freshness: Data freshness ensures that the received data is recent and that an adversary has not repeated old messages subsequently. Data freshness can be divided into two categories: weak freshness and strong freshness (Perrig, 2002). Weak freshness provides partial data ordering which prevents data from being replayed but carries no delay information (Baronti, 2007). Strong freshness, on the other hand, uses a request-response model to provide complete ordering of messages and delay estimation to prevent the data being held by an unauthorised user. Weak freshness is required for sensor measurements while strong freshness is required for time synchronisation within the network. One of the most common methods to provide data freshness is to use a monotonically increasing counter with every message and reject any messages with old counter values. However, every recipient would need to maintain a table of the last counter value from every sender. This method may be unfeasible in wireless sensor networks where the sensor nodes are memory constrained and would not be able to store such a table for even a moderately sized network.

2.4 Discussion

It is strongly believed that the advantages of ZigBee networks to underground mining outweigh its disadvantages. On one hand, there are some negative viewpoints in using ZigBee networks in underground environments. The significant infirmity of it through WSNs is that it is capable of data transmission with a very low data rate of 250 kbps. Although this is efficient for digital data telemetry, text messages and to some extent voice messages, video-data transmission might be impossible. This is because photo and video streams in dusty and dark environments is normally impractical in underground spaces.

Another concern regarding an extended ZigBee network might be an increase in multi-hops. As a result of the lack of central routers and gateways (coordinators), nodes are themselves routers. Thus, packets follow multi-hop routes and pass via mobile nodes before arriving at their final destination. This feature causes a serious vulnerability of wireless communications in underground mines owing to the possibility of violation of such nodes. Nevertheless, a ZigBee network possesses various features that enable it to mitigate these dilemmas in underground mines. The features of ZigBee are analysed in the following paragraphs.

I) Energy-effective: ZigBee is known for very low power consumption in WSNs. For one thing, a ZigBee network is very low energy-consuming both for node and protocol (IEEE 802.14.5) alike; see Figure 2-9. A ZigBee node also is much more energy-efficient with 20-40 mW power usage, compared to a Wi-Fi node with 500-1000 mW power usage, as shown in Table 1. This key feature definitely prioritises ZigBee with a debatable alternative choice of Wi-Fi for wireless network installation in industries and in particular, underground mining. In addition, the recent manufacture of new ZigBee nodes are associated with the lower power consumption of 1 mW.

ZigBee nodes are known for low power consumption because of efficient energy usage while transmitting radio signals, and more importantly due to intelligent battery power management in sleep mode. Such ability enables any ZigBee node to be programmed so as to switch automatically to the sleep mode when it does not need to record or transmit data. Power consumption during waiting time to communicate with surrounding nodes, while it is in the sleep mode, is even negligible. For example, for an output power of 1 mW of radio transmission, a ZigBee node normally consumes 75 mA at 3.3 V whereas it increases to 150 mA at 3.3 V for an output power of 100 mW. In other words, a high-power node consumes twice the power to transmit a data packet compared with a low-power node (Cirronet, 2007). In this situation, if these ZigBee nodes are awake only 5% of the time that is very active period of radio telemetry, the approximate average power consumption would be 5% as well for both cases. The battery, as the result of this, will have a life span of five years with a low-power node (1 mW) and four years and nine months with a high-power node (100 mW). Now, it is clear why it is claimed that ZigBee nodes with such a battery power can last many months to several years.

II) Cost-effective: ZigBee technology is most cost-effective for several reasons. Firstly, it has inexpensive modules compared with Wi-Fi modules. The details of this are illustrated in Table 2-2, (Rahman, 2014). As seen in this table, the establishment of a ZigBee network not requiring any access point is a more cost- effective solution for wireless networking in underground mines.

Table 2-2 Comparison of costs between ZigBee and Wi-Fi networks

WSN	Costs
ZigBee	Module: ~ $2.75 - $3.5 Cable: $0 Access point: $0/switch
Wi-Fi	Module: ~ $8 - $16 Cable: $0 Access point/switch: $20 - 50

There are different kinds of ZigBee nodes which give the flexibility to design even more cost-effective wireless networks. There is a low-cost node with a minimal memory requirement called Reduce Function Device (RFD). It can only function as a network device to record and send data, but unable to receive data or data telemetry. Secondly, a ZigBee network also comes with free licences to broadcast in the frequency spectrum. Finally, it provides very low maintenance costs owing to facilities with an inherent configuration and redundancy of nodes within the network. That is why a ZigBee network is introduced as a low-cost system for monitoring and communication in underground mines.

III) Frequency range Flexibility: ZigBee utilises the 2.4 GHz frequency band to support global operation, and affords other regional operations such as 868MHz in Europe and 915 MHz in the USA. Such flexibility contributes to improve the ZigBee network adaptability to the specified applications that need stronger output power or where less energy consumption is required.

IV) Multi-hop: ZigBee utilises a multi-hop routing that enables nodes to operate as a relay in order to deliver data from nearby nodes, and pass it to the final node (coordinator). This means that the range of communication between a node and coordinator can be extended. Therefore, it is one fundamental component in underground spaces for long distance wireless communication(Qandour et al., 2014).

V) Ad-hoc network: a ZigBee network is established spontaneously as nodes turn on and connect, and does not rely on base stations to coordinate the routes of communication between nodes. As a result, the nodes can be placed anywhere taking into account the restrictions of underground mine activities and environments, and the ZigBee network will automatically figure out the routes to communicate. ZigBee nodes also have self-organization and self-healing abilities to rebuild wireless networking at high potential node failure in underground tunnels. Furthermore, this fortifies the advantage of such a dynamic system for more underground mining applications based on the mobile nodes connecting together or alternatively to the fixed nodes through the underground wireless network.

VI) Large network capacity: ZigBee connection and communication among 65,536 wireless sensor nodes in one system is another proficient ability compared to other WSNs used in underground mines. This considerably reduces the costs of network establishment and maintenance and energy consumption, as well as eliminating locations and services of system infrastructure through the narrow environments. However, node capacity is restricted by network coverage, topology structure, and bandwidth requirements based on the types of applications.

VII) Reliable infrastructure: This is one of the most significant features of ZigBee networks considered for underground mines. Within such a network, each node provides reassessing relevant and alternative routes to ensure successful data delivery to the master point (coordinator). In fact, it includes a mechanism of collision avoidance to prevent competition and conflict in sending data. This ability of nodes allows ZigBee to provide a reliable network infrastructure in interference-rich environments.

VIII) Real-time data communication: ZigBee is capable of providing bounded delay guarantees on data delivery that is technically named real-time data delivery in WSNs. It takes almost 15 ms to complete a bilateral communication between two adjacent nodes (Li & Zhao, 2009). Such a network performance could certainly revolutionise underground mining management and safety, particularly in emergency conditions.

IX) Safety: ZigBee provides a data integrity check and authentication function.

Therefore, it is absolutely convincing that the weaknesses of ZigBee for underground monitoring and communication systems are outweighed by the strengths. These benefits not only promote health and safety difficulties in underground mines, particularly in coal mining, but also revolutionise management in underground mining operations.

2.5 Conclusion

This chapter made an attempt to discuss and summarize most of the pioneer and the recent approaches of WSNs' architecture designs and applications in underground mines. Clearly, the approaches have undergone an evolution to reach the state of the art, but there is still a long way to go for a robust and reliable underground space monitoring and communication system. However, the correlation and linkage between knowledge scope, existing techniques and practical experiments based on the past works have been established to prove the possibility of ZigBee networks for such a vital system in underground mines. It has been found that ZigBee features and its applications are adapted to the damp, dark and hazardous underground environments, and they can certainly make an improvement in safety and operations management in these environments.

CHAPTER 3. ZIGBEE RADIO WAVE PROPAGATION INVESTIGATION IN UNDERGROUND MINES

3.1 INTRODUCTION

The radio waves of WSNs' communication are more complex in underground mine environments. As the reliable communication is an effective element for safe and efficient mining, the analysis of the electromagnetic fields and the investigation of radio waves attenuation evaluating underground effective factors are essential.

In this chapter, a monitoring and communication system for underground mines based on ZigBee network performance without supporting other WSNs is proposed. Use of central (sink) nodes or access points is eliminated because of high power consumption and cable damage risk. In fact, ZigBee is selected for its powerful networking capability through ad-hoc and multi-hop topology, its considerable network capacity and cost-effectiveness. Based on this system, data from sensors (fixed nodes) and workers and vehicles (mobile nodes) locations in underground mine could be transferred to a surface gateway for monitoring and bilateral communication. Wireless network coverage for long distance is mandatory considering the spatial positions between the surface gateway and ZigBee nodes in underground mines. Therefore, investigations to prove the proposed system as a reliable and secure network are delineated as below:

- Stable communication distance for packet delivery
- Evaluation of network metrics
- Accuracy of the position of mobile nodes

Based on expanded knowledge of underground WSNs, the stable communication distance between ZigBee nodes is analysed in this chapter.

The conceptual procedure of the investigation of ZigBee radio wave propagation in underground mine in underground mines is illustrated in Figure 3-1. To investigate the stable communication distance between ZigBee nodes, first the theory of radio waves propagation models to simulate experimental measurements in the tunnel is described. Then, the methodology of experimental measurements and simulations on radio waves attenuation are provided. Finally, discussion and comparison of the results are presented.

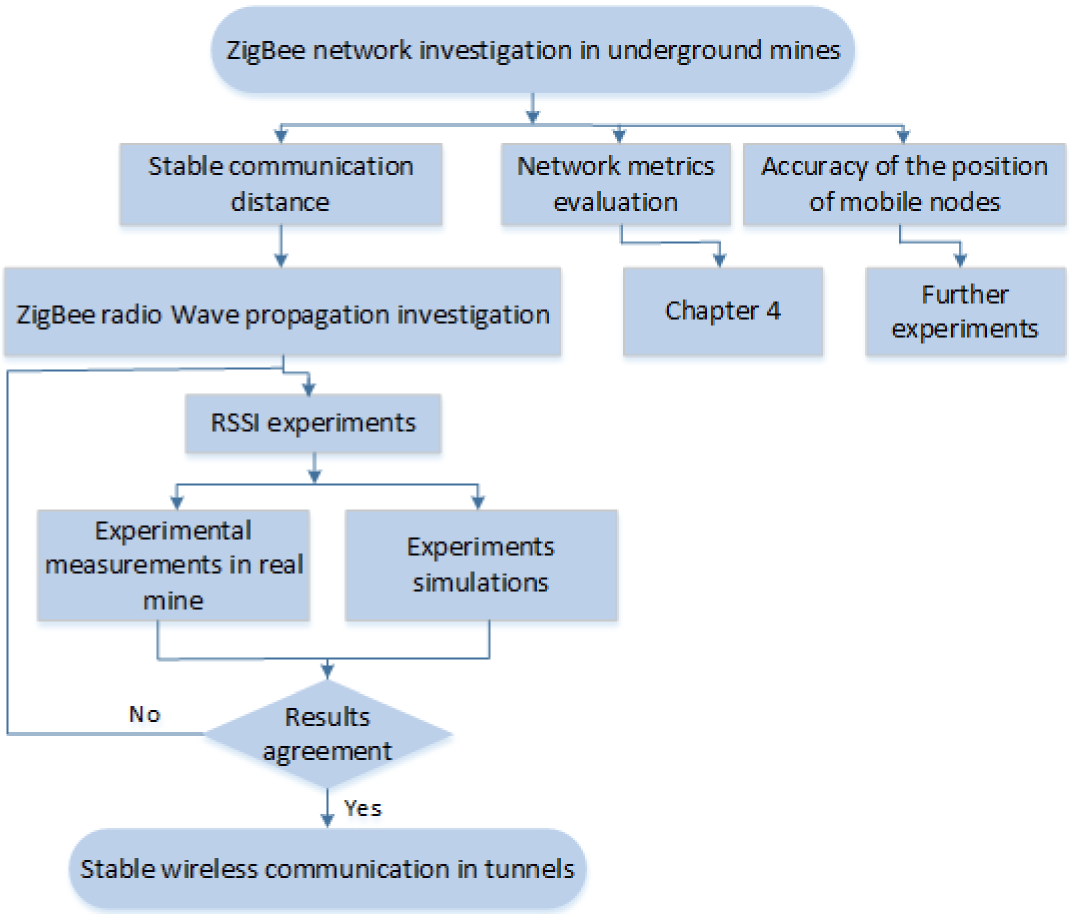


Figure 3-1 the conceptual procedure of ZigBee radio wave propagation investigation in underground mines

3.2 THEORY OF RADIO WAVES PROPAGATION MODELS IN TUNNELS

Radio waves propagation in underground mine environments is described based on tunnel channel models. There are different models to evaluate effective factors on the wave's attenuation of the tunnel environment. Practically, received power is predicted from the attenuation model by knowing the transmitter power level. For example, the radio waves propagation near the walls or floor of the tunnel can be simulated by the two-ray (two-slope) model where free-space model (Friis equation) is preferred for simulation in the hollow space of the tunnel. Moreover, the radio waves propagation is modelled with Rice distribution for line-of-sight (LOS) between the transmitter and receiver nodes in straight tunnel, and the Rayleigh distribution model is considered for non-line-of-sight (NLOS) passing over tunnel curvature

(Boutin et al., 2008; Lamminmaki & Lempiainen, 1998). Figure 3-2 illustrates typically practical measurements for attenuation trend and a theoretical model in a tunnel channel at the frequency of 2.4 GHz [after Hrovat and Javornik, 2013].

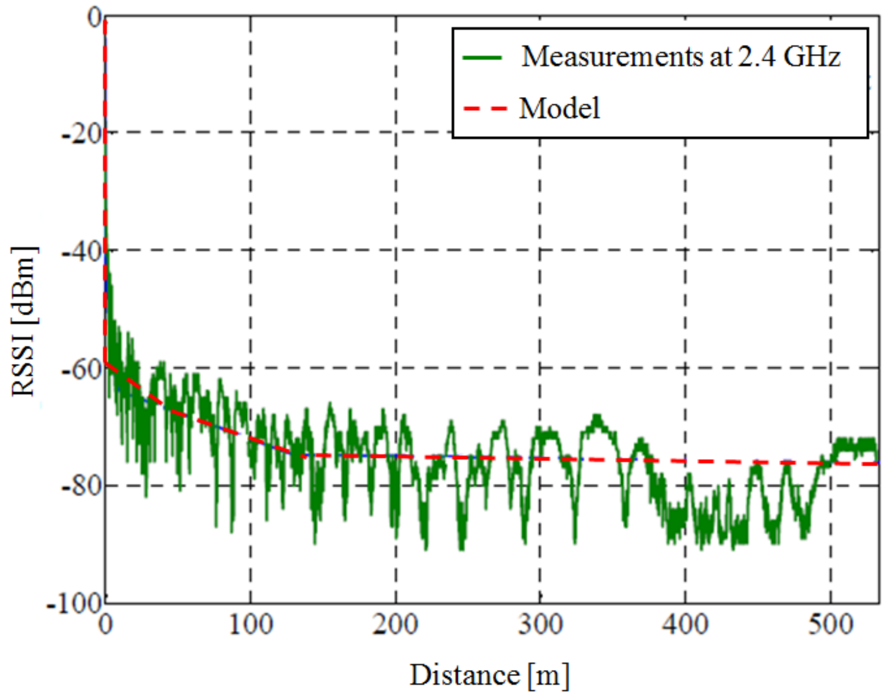


Figure 3-2 Typical attenuation trend for practical measurements and theoretical model in tunnel [after Hrovat and Javornik, 2013]

In this study, multimode waveguide model is investigated to simulate both near and far regions from the source by summing the power of rays received from reflections on the tunnel walls and the source. The excitation plane is used in the geometrical optics (GO) model of Shooting and Bouncing Ray (SBR) method to analyse different field distributions and attenuation coefficients (Zhi & Akyildiz, 2010). Based on this method, rays are first traced from the source then reflected rays from tunnel walls are calculated. According to this technique, Maxwell's equations and eigenfunctions, the received signal power (P_r) at the coordinate (x, y, z) would be obtained by Eq. 3-1:

$$P_r\,(x, y, z) = P_t\,G_t\,G_r\left(\frac{1}{E_0}\sum_{m,n} C_{m,n}\,.\,E_{m,n}^{eign}(x, y).\,e^{-(\alpha_{mn}+j\beta_{mn}).\,z}\right)^2 \qquad \text{Eq. 3-1}$$

where P_t is the transmitter power; G_t and G_r are the antenna gains of the transmitter and the receiver, respectively. m and n indicate the field of all significant modes.

$C_{m,n}$, $E_{m,n}^{eign}$, α_{mn} and β_{mn} are the mode intensity in the excitation plane, eigenfunctions, the attenuation coefficient and the phase-shift coefficient, as given by Eqs. 3-2, 3, 4 and 5:

$$C_{m,n} = \frac{E_0\pi}{ab\sqrt{1-(\frac{m\pi}{2ak})^2-(\frac{n\pi}{2bk})^2}} \sin(\frac{m\pi}{2a}x_0 + \varphi_x).\cos(\frac{n\pi}{2b}y_0 + \varphi_y) \quad \text{Eq. 3-2}$$

$$E_{m,n}^{eign}(x,y) \cong \sin(\frac{m\pi}{2a}x_0 + \varphi_x).\cos(\frac{n\pi}{2b}y_0 + \varphi_y) \quad \text{Eq. 3-3}$$

$$\alpha_{mn} = \frac{1}{a}(\frac{m\pi}{2ak})^2 Re\frac{\overline{k_v}}{\sqrt{\overline{k_v}-1}} + \frac{1}{b}(\frac{n\pi}{2bk})^2 Re\frac{1}{\sqrt{\overline{k_v}-1}} \quad \text{Eq. 3-4}$$

$$\beta_{mn} = \sqrt{k^2 - (\frac{m\pi}{2ak})^2 - (\frac{n\pi}{2bk})^2} \quad \text{Eq. 3-5}$$

In these formulas, $\varphi_x = 0$ if m is even number; $\varphi_x = \frac{\pi}{2}$ if m is odd number; $\varphi_y = 0$ if n is odd number and $\varphi_y = \frac{\pi}{2}$ if n is even number. The tunnel cross section of the model is a rectangle shape with $2a$ width and $2b$ height, and the origin of a Cartesian coordinate system is mounted at the centre of tunnel. $\overline{k_v}$, $\overline{k_h}$ and k are indicated for the relative electrical parameters for vertical/horizontal walls of the tunnel and the wave number as defined by Eqs. 3-6, 7 and 8:

$$\overline{k_v} = \frac{k_v}{k_a} = \frac{\varepsilon_0\varepsilon_v + \frac{\sigma_v}{j2\pi f_0}}{\varepsilon_0\varepsilon_a + \frac{\sigma_a}{j2\pi f_0}} \quad \text{Eq. 3-6}$$

$$\overline{k_h} = \frac{k_h}{k_a} = \frac{\varepsilon_0\varepsilon_h + \frac{\sigma_h}{j2\pi f_0}}{\varepsilon_0\varepsilon_a + \frac{\sigma_a}{j2\pi f_0}} \quad \text{Eq. 3-7}$$

$$k = 2\pi f_0\sqrt{\mu_0\varepsilon_0\varepsilon_a} \quad \text{Eq. 3-8}$$

where k_v , k_h and k_a denote the complex electrical parameters for vertical/horizontal walls and the air in the tunnel; ε_v, ε_h and ε_a are the relative permittivity for vertical/horizontal walls and the air in the tunnel; σ_v, σ_h and σ_a are their conductivity; ε_0 is the permittivity in vacuum space; and f_0 is the central frequency of the signal. The three areas are assumed to have the same permeabilityμ_0.

As seen in Figure 3-2, the intensity of received signal strength indication (RSSI) is one of the parameter to analyse the attenuation of radio waves (Chehri et al., 2010). RSSI is an indication of received signal power by a wireless node's antenna. The unit conversion between RSSI and received signal power is formulated as Eq. 3-9:

$$Y = 10 \ log_{10} X \qquad \text{Eq. 3-9}$$

where Y is defined as RSSI unit in decibels milliwatt (dBm) and X is unit for the power of the received signal in milliwatt (mW) The unit conversion was used to create positive values of RSSIs to calculate logarithmical average in this study. The intensity of the transmitted signal power is also expressed with dBm. The experiments of RSSI measurements were performed at Angas Zinc Mine in South Australia to evaluate stable communication distance between ZigBee nodes in underground mines.

3.3 EXPERIMENTAL MEASUREMENTS IN TUNNELS

3.3.1 *Study area description*

Understanding the experimental environment properties is a crucial aspect for the measurements and simulations of the radio waves attenuation in the underground mine. Angas Zinc Mine located near Adelaide in South Australia was selected as the study area. Figure 3-3 illustrates a section view of active and inactive zones in this mine. The experiments of RSSI measurements were completed in two tunnels of the inactive mining zones at -160 level and -75 level to avoid any interruption with mining operations. Tunnel cross sections are arch-shaped with 5.5 m height and 5.5 m width. The environment properties of the experiments were recorded to evaluate effective factors on the radio waves attenuation. The tunnels are hosted by the Angas Garnet Member of the Tapanappa Formation, and the ore-body is mostly composed of zinc and lead. There is not support system in the most parts of the tunnels due to surround by hard rocks. The long experiments lines show there are some wet areas caused by underground water inflow to the tunnels. Also, there are no other facilities such as cables, pipes, ventilation duct and vehicle access which may affect the propagation of radio waves.

3.3.2 *Apparatus and Setup*

ZigBee networks generally consist of apparatus such as coordinators (gateway), routers and end devices. Coordinator can transmit, receive signals, storage all network information, and connect to the PC. Router can transmit and receive data and manage the routes. End device performs environmental sensing or functions control, which often communicates with the nearest router.

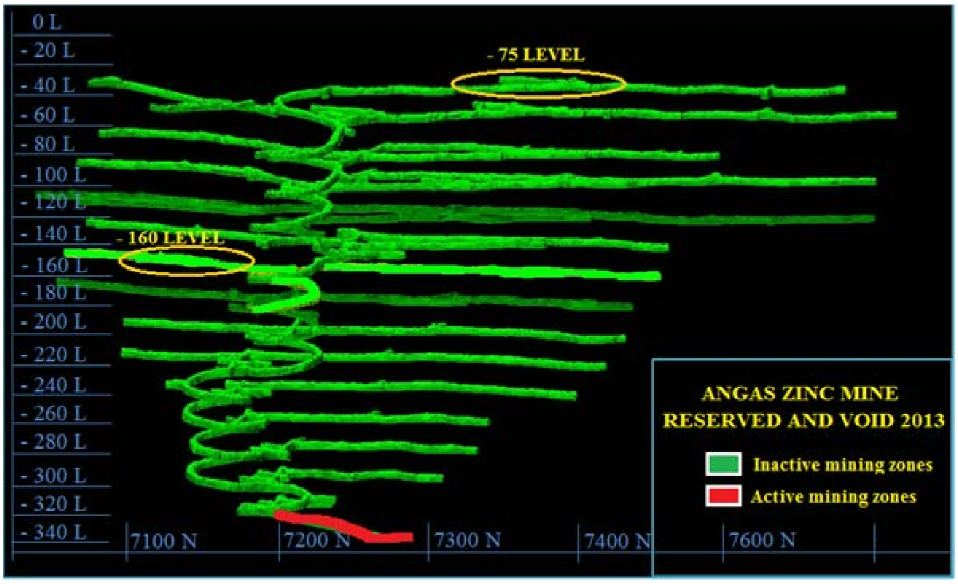


Figure 3-3 A long section view of Angas Zinc Mine

Based on the instruction manual, one ZigBee coordinator and two ZigBee routers were used to measure RSSI values in the experiments. “GeoSense Coordinator” as coordinator (GSC) and “GeoSense” as router (GSR) are illustrated in Figure 3 4. The GSC is the main terminal for connection between GSRs via the wireless network and ZigBee program by Ethernet cable. Finally, the received data within ZigBee network is recorded and stored by ZigBee program on the laptop. The GSC and GSRs were developed by our research group in the Geo-Sensing Laboratory at the University of Tsukuba, Japan in collaboration with HITACHI Corporation.

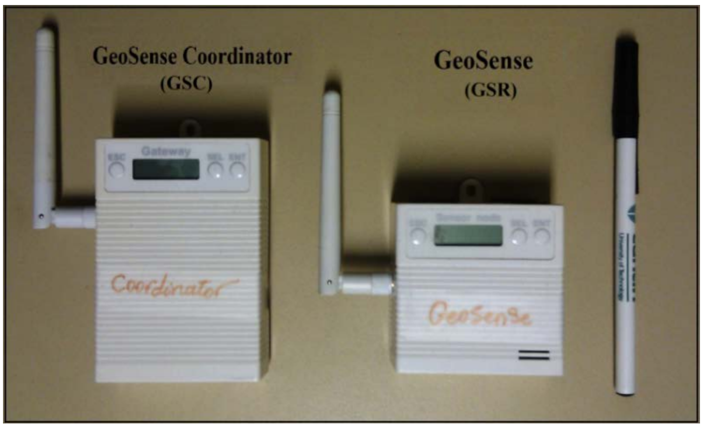


Figure 3-4 ZigBee nodes used in the experiments

3.3.3 *Experimental procedure*

The GSC was connected to the laptop (PC), and the GSRs (GSR1 and GSR2) were mounted on the tripods with a 1.5 m height to minimize the effect of radio waves distortion from the surface roughness of the tunnel's floor and walls. This provides to present clearly the radio waves behaviours in straight and curved tunnels in the prototype experiment. Likewise, in real case, sensor nodes would be mounted on the walls or crown of the tunnel with special spacer to reduce negative effects of surface on the radio waves propagation. Then, the RSSI measurement between GSR1 and GSR2 was recorded for a distance of 5 m. The measurements were continued by increasing the distance between GSR2 and GSR1 at 5 m intervals. For consistency of the results, the measurements were repeated at least 5 times per each interval. Figure 3-5 illustrates the procedure of RSSI measurements in the tunnels of Angas Zinc Mine. The measurements were continued until the power of the received signal between GSRs was disappeared.

The experiments were performed to measure RSSIs at different openings in straight and curved tunnels.

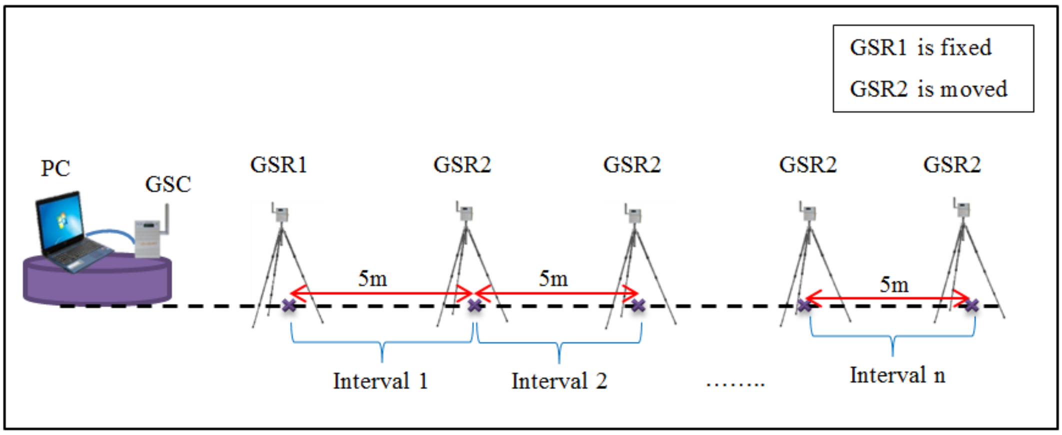


Figure 3-5 Experiments procedure to obtain RSSIs in Angas Zinc Mine tunnels

3.3.4 *Experimental results*

The attenuation of ZigBee radio waves in the underground mine was investigated at bandwidth 2.4 GHz. The experiments were conducted in straight and curved tunnels at different levels. Results and interpretations of these experiments are stated as following sections.

3.3.4.1 Straight tunnel

The first experiment was performed in a straight tunnel at the -160 level at 60 meters length. It was limited because of closed path. A layout of the radio wave attenuation in this level is illustrated in Figure 3-6. The experiment line was a LOS, and it was located adjacent (approximately 15 m) to an excavated ore-body. There are two junctions of the branches at around 10-20 m and 30-40 m. Figure 3-7 illustrates the radio waves attenuation based on the logarithmic average of RSSI values via distance between GSRs.

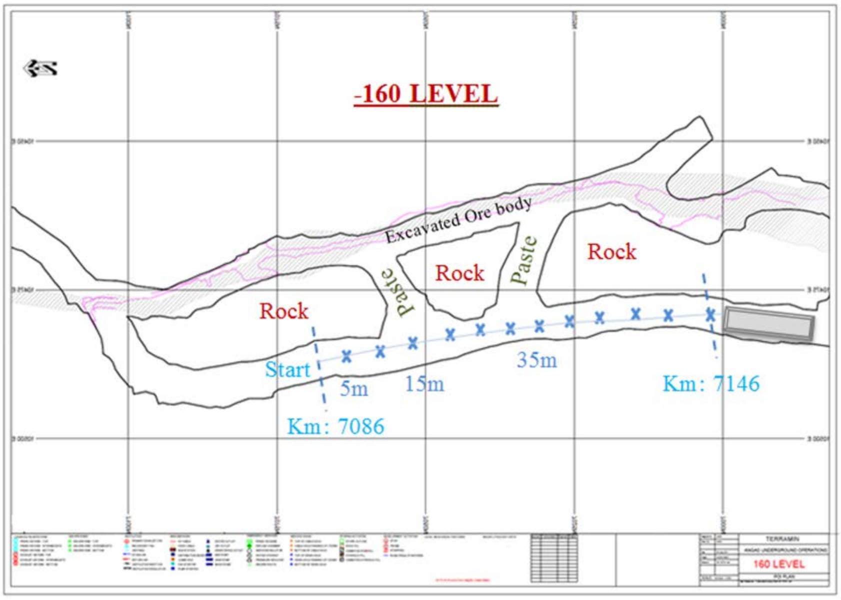


Figure 3-6 Layout of radio waves attenuation experiment in straight tunnel

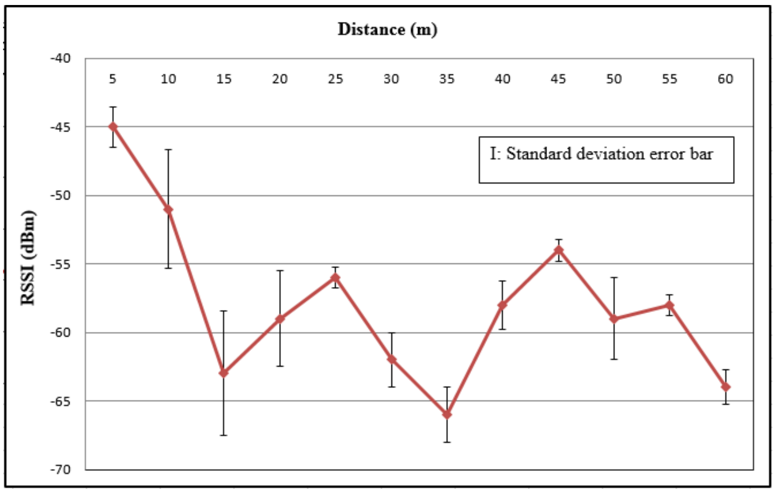


Figure 3-7 Results of radio waves attenuation experiment in straight tunnel at 2.4 GHz.

The RSSIs trend starts from -44 dBm at the shortest distance between GSRs to -64 dBm at 60 m apart. As a normal procedure, the graph indicates a gradual reduction of RSSIs at the other points along tunnel. There are two abnormalities in RSSIs trend in the locations of the junctions and two distribution fields that are discussed in section 3.5.

3.3.4.2 Straight tunnel

In the second experiment, the data was collected in a curved tunnel at the -75 level for up to 100 m length. Figure 3-8 and Figure 3-9 illustrate the layout and results of radio waves attenuation in this experiment. As shown in Figure 3-8, the line of the experiment was passing through a NLOS at 0-25 m, LOS at 25-60 m and several NLOSs between 60 and 100 m. There is an opening at 35-40 m. As seen in Figure 3-9, the logarithmic average of RSSI values in the curved areas of the tunnel declines sharply from -45 dBm at the starting point to -63 dBm at 25 m. It is because of the curvature and the effect of multiple modes in the near region. There is a sudden drop in RSSIs trend at around 35 m mainly due to the presence of the junction area in the opening location. The trend of a slow decrease in RSSI values continues in a straight tunnel of NLOS from 45 to 55 m. After that, there are two main falls in measured RSSIs at 60 m and 70 m due to the sharp corners of the curvatures. On the right side of the graph, the decline in RSSIs trend continues gradually due to the field with lower mode energy in the far region of the source.

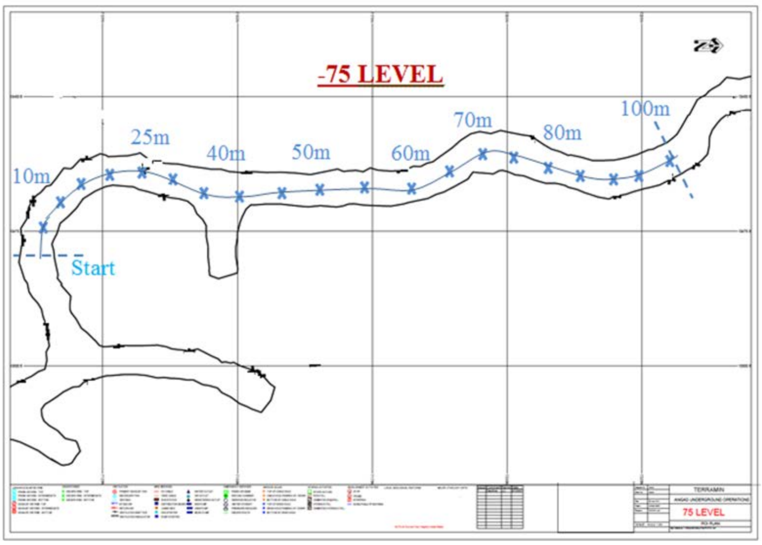


Figure 3-8 Layout of radio waves attenuation experiment in curved tunnel

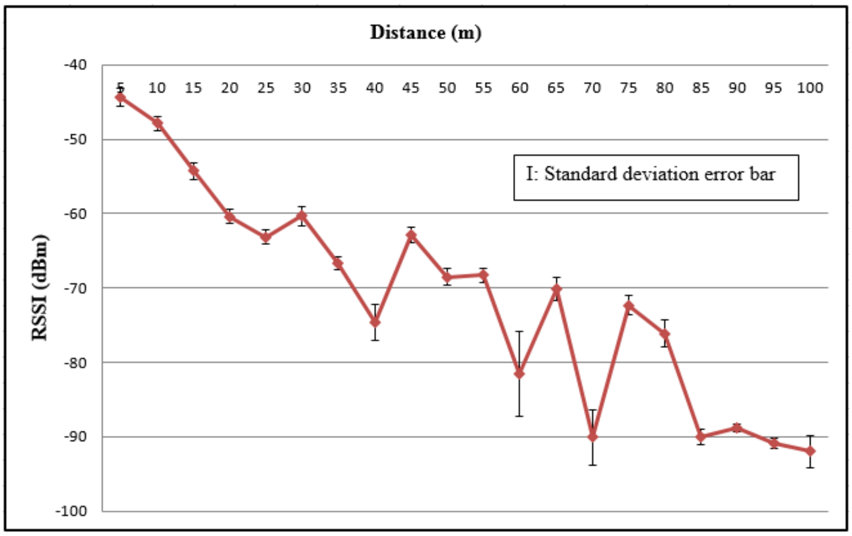


Figure 3-9 Results of radio waves attenuation experiment in curved tunnel at 2.4 GHz.

3.4 Radio waves propagation simulations in tunnels

The experimental measurements for Angas Zinc Mine tunnels were simulated by radio waves propagation model based on the multimode waveguide model. To this end, the excitation plane of GO model was used to analyse radio waves attenuation at the junctions, curvatures, and different fields (near and far regions from the transmitter). The principles of the model are given in section 3.2.

Figure 3-10 illustrates the models geometry and radio waves attenuation in the Angas Zinc Mine for both straight and curved tunnels. The details of the simulation is provided in Appendix A. The parameters for both tunnels are set according to the experiments conditions. The tunnel cross sections of the models are assumed rectangles with a height of 5.5 m and a width of 5.5 m. The tunnel walls, ceiling and floor are made of the same material and have permittivity of ε = 4ε_0 and conductivity of σ = 0.01 S/m. The tunnel interior is filled with air (ε_a =ε_0, σ_a= 0 S/m). The transmitting power is 3 dBm at the central frequency band of 2.4 GHz. The transmitting and receiving antennae are vertically polarized dipoles of the same height. Both antennae of the transmitter and receiver in the model are defined approximately at the centre of the tunnel width, and the walls of the mine tunnels are presumed smooth. Then, an electromagnetic simulation program of REMCOM was used to calculate the RSSI values based on the received power from the summation of rays' reflections on the walls' surface and the source. To decrease significantly the runtime of the calculation, the study area boundary was assumed adjusting the tunnel walls. The SBR method was employed to trace ray paths through tunnel geometry solving Maxwell's equations for consideration of the boundary conditions.

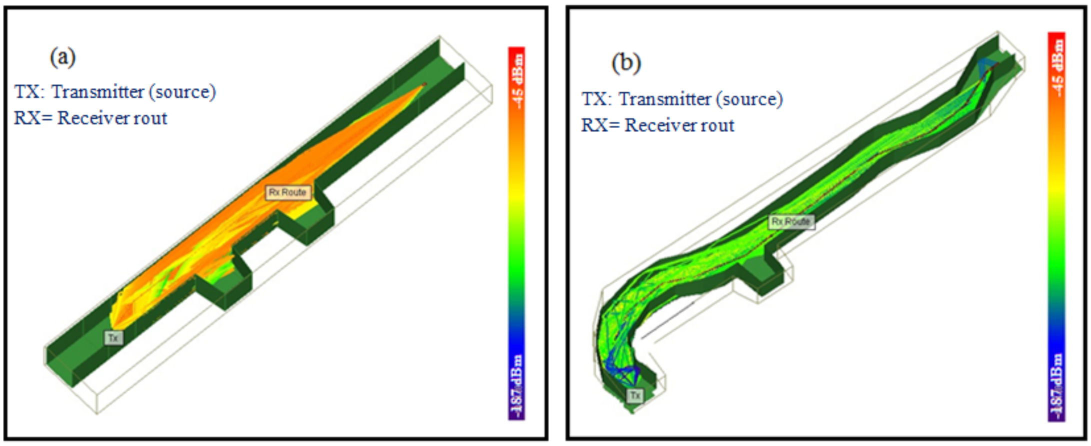


Figure 3-10 Model geometry and radio waves attenuation in the Angas Zinc Mine tunnels. (a) Model for straight tunnel and (b) model for curved tunnel

3.5 Discussion

3.5.1 *Comparison between experiments and simulations*

The experimental measurements are validated by simulation results for both experiments. The comparisons of the results confirm that the junctions of the branches and the curvatures have a major impact on radio signal propagation. The extra loss of RSSI values in the junctions occurs because of the sudden fluctuation and polarization changes in the waves caused by the larger cross section in tunnel dimension and sharp edges. The tunnel curvatures affect the radio waves propagation by preventing direct visibility between the transmitter and receiver and increasing multi-path components. The comparison of the experimental and simulation results for straight and curved tunnels is illustrated in Figure 3-11.

The curves of the RSSI results could be separated into two parts: the region near the source with fast attenuation of the signals and the region far from the source with gradual attenuation. In the former case, fast attenuation may have occurred because of the congested multiple modes in the near source. Therefore, the attenuation of higher-order modes would quickly attenuate as distance increases. In the latter case, lower-order modes are coming to the receiver with lower attenuation differences in the region far from the source. It is observed from Figure 3-11 that there is reasonable agreement for RSSI values between experimental and simulation results by the curves comparison. Differences between the measurements and simulations in RSSI values may have resulted from affective parameters which have not been considered in the equations and calculations. Some of these parameters could be comprised of roughness on the walls surface and wet areas caused by underground water inflow in some parts of tunnels.

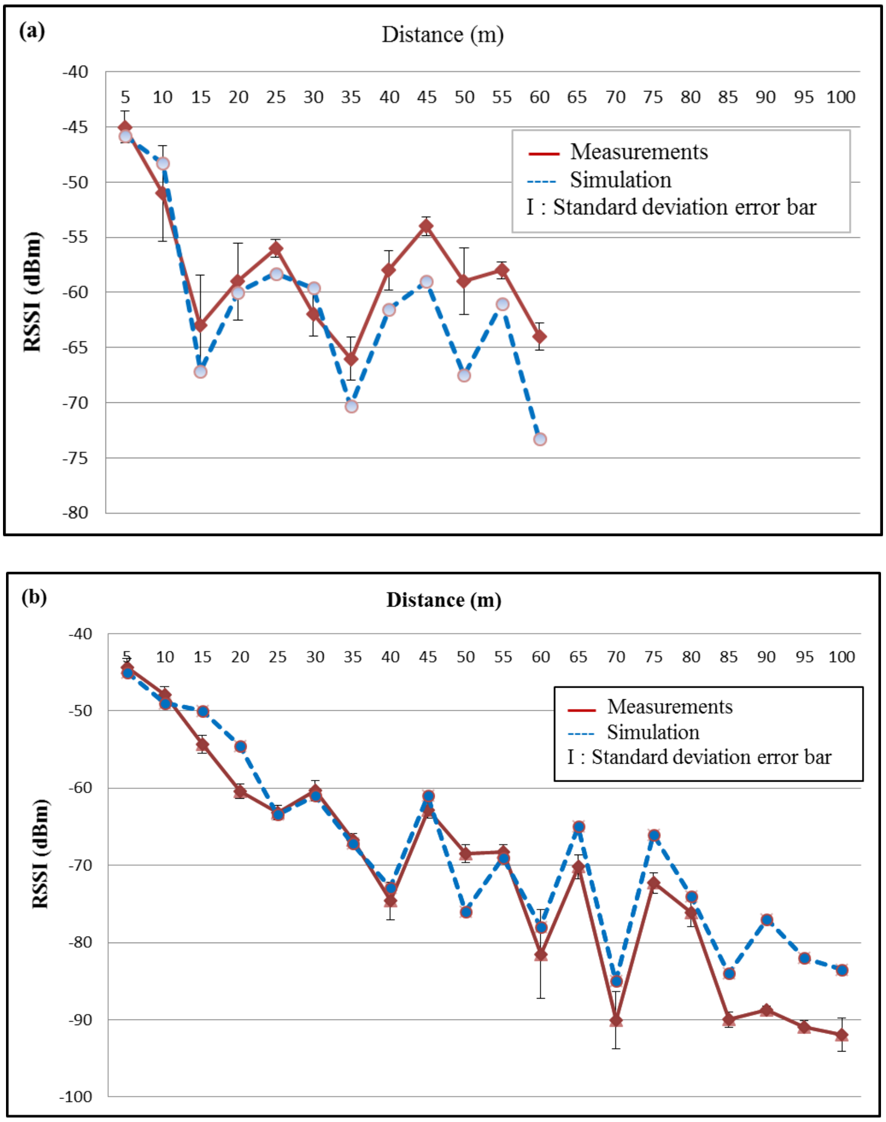


Figure 3-11 Experimental and simulation results of the RSSI values at 2.4 GHz. (a) For the straight tunnel and (b) for the curved tunnel

3.5.2 *Comparison of the measured results*

The experimental measurements in straight and curved tunnels are compared to analysis curves trends for the investigation of stable communication between wireless nodes. The comparison of the measurements obtained from the experiments in both tunnels based on the logarithmic trend lines of the RSSI values via distance are illustrated in Figure 3-12. In these trend lines, a gradual reduction of RSSI values as a function of distance in both tunnels is concluded. However, in the curved tunnel the RSSI values are reduced more sharply than in the straight tunnel as caused mainly by curvatures. According to the trend line equations, the radio waves attenuation in the curved tunnel is 3.1 times more than in the straight tunnel.

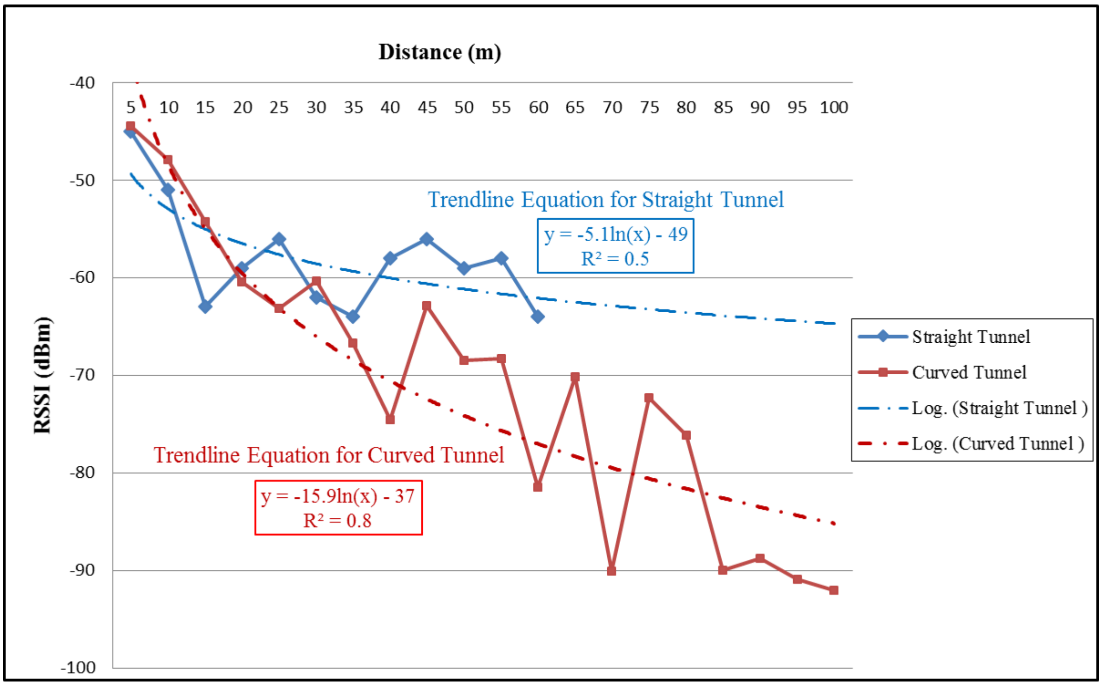


Figure 3-12 Comparison between RSSI measurements in straight and curved tunnels

According to the RSSI measurements as shown in Figure 3-12, A stable communication distance between ZigBee nodes is calculated in the underground mine tunnels. It is desirable to have RSSI values over -80 dBm for a stable wireless communication with the GSR. Based on this information and the trend lines, the stable wireless communication distances between developed ZigBee nodes by our group research are determined up to 100 m along straight tunnels and 70 m in the curved tunnels. These approaches are verified with the calculation of RSSI values at -80 dBm for the longest distance between GSRs shown in Figure 3-12. Therefore, a stable communication distance for packet delivery as one of the proposed system proofs based on ZigBee network was verified. Also, it is concluded that 104 GSRs are required to create stable wireless network for covering the whole levels in Angas Zinc Mine according to the excavated straight and curved tunnels and decline.

3.6 CONCLUSION

Underground wireless sensor networks could significantly improve the efficiency of environmental monitoring, workers and equipment locations, operational readings and communication system. In this research was shown that ZigBee is more suitable for underground wireless monitoring and communication system than the other underground mine WSNs. The stable communication distance between ZigBee nodes in underground mine based on the attenuation of radio waves was analysed. To this end, RSSI experiments in straight and curved tunnels at Angas Zinc Mine were performed and the results were compared with the simulations of radio waves attenuation in the tunnels. Evaluation of the experimental and theoretical results confirmed that the junctions of the branches and the curvatures of the tunnels have major effects on radio waves propagation. However, in the curved tunnel the RSSI measurements declined sharply than in the straight tunnel, caused mainly by curvatures. Regions of the experiments divided into the field near the source with fast attenuation of the signals due to the congested multiple modes in the near source and the field far from the source with the gradual attenuation due to the arrived lower-order modes to the receiver. Finally, the results showed the stable communication distances between developed ZigBee nodes up to 100 m and 70 m in straight and curved tunnels, respectively. Consequently, the experiments in this study prove a stable communication of packet deliveries between ZigBee nodes for underground monitoring and communication system.

CHAPTER 4. PERFORMANCE ANALYSIS OF ZIGBEE NETWORK IN UNDERGROUND MINES

4.1 INTRODUCTION

Wireless sensor networks (WSNs) have recently been proposed for underground mine monitoring and communication to enhance safety and productivity and so as to reduce operational costs. Typically, the underground WSNs consist of a few to several hundred nodes between a surface gateway and specified sensor nodes in the underground levels. Each node can connect to one or more nodes in order to transmit data. In particular, the placement of the sensing nodes plays a very important role to allow for efficient transmission as well as providing maximum security through the network. It is inevitable for underground WSNs to perform at a high level of network efficiency with lower energy-consumption and the most cost-effective establishment and maintenance. Despite the progress of WSNs technologies, they still rely on infrastructure such as so-called sinks to transfer data from underground sensors to the management server at the surface.

According to the experiments of developed ZigBee nodes (Moridi, 2015), the study focuses on the reliability of multi-hop data transmission between nodes in underground mines. In the following, PAN is technically defined as a low rate-wireless personal area network (LR-WPAN) in an ad-hoc and self-organising network designed to serve a variety of applications especially in WSNs. ZigBee, based on IEEE 802.15.4 standard (Chandane et al., 2012), is comprised of PAN Coordinator, coordinator (full-function device) and end-device. A ZigBee PAN Coordinator forms the only root of the network. First, it creates the network, and then waits for automatic joining connections of other nodes. It enables all nodes to communicate within the network and stores data. Due to a limited communication distance, intermediate coordinator nodes (full-function devices) are involved to transfer data between sensor nodes (the actual end-device) and the PAN Coordinator through multi-hop routing. As it is shown in Figure 2-10 the network architecture of different ZigBee topologies. A full-function device can sense the environment, as well as communicate with the other nodes. An end-device is only capable of sensing and sending data to the PAN Coordinator or nearest coordinator node. The PAN Coordinator is usually AC powered, while routers and end-devices are typically battery powered.

ZigBee based on the IEEE 802.15.4 standard has three main types of network topology for data transmission (the star, the cluster-tree and the peer-to-peer mesh) as illustrated in Figure 2-10. As seen, end-device nodes may be more beneficial in the cluster-tree topologies considering energy saving during sleep times, while more full-function devices have to be employed in mesh topologies as they need to relay the data of nearby nodes.

A key factor to evaluate the efficiency of the WSNs performance is the routing protocol. The protocol provides routes for each node (Bhat.M. Subramanya et al., 2011). Routing is the process of selecting paths within a network to send data from one node to the nearby nodes.

This chapter aims to evaluate ZigBee network performance and security in underground mines based on the link quality indication (LQI) for each received signal or packet using QualNet® 7.3 [1]. For this purpose, we investigate an optimal arrangement of ZigBee nodes by creating various scenarios of mesh and cluster-tree configurations, and LQI-related metrics evaluation in mine tunnels. In the scenarios, all nodes including the Pan Coordinator, the full-function devices and the end-devices are assumed to remain stationary. The procedure and methodology of an optimum arrangement of ZigBee nodes for underground mines is illustrated in Figure 4-1. We analyse the simulations of the mesh and cluster-tree topologies based on the network performance metrics of throughput, packet delivery ratio, end-to-end delay, energy consumption and network security.

4.2 Background

ZigBee network performance in the perspective of nodes positioning design has theoretically been developed by numerous research solutions (Chatterjee et al., 2013;

[1] QualNet®: http://web.scalable-networks.com/content/qualnet (last accessed 7 September 2015)

Guinard et al., 2011; Singh et al., 2007; Tian et al., 2012) and proposed algorithms (Medhat et al., 2012; Xu, 2012). These solutions and algorithms improved the results and network performance of the WSNs. Since real tests within industry environments are faced with performance difficulty as well as being costly and time consuming, simulation is a common way to study new and optimising routing protocols and topologies.

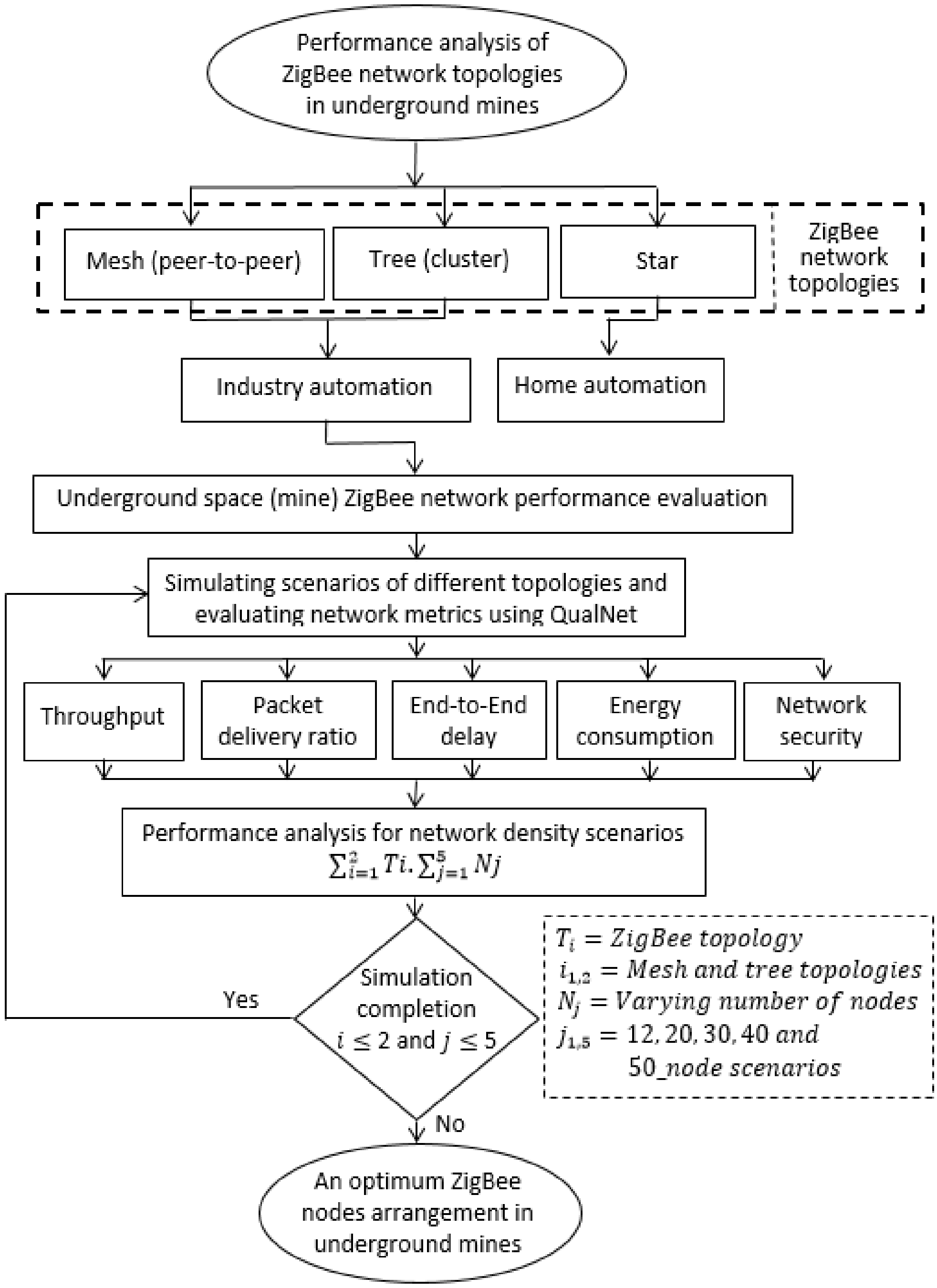


Figure 4-1 Procedure of optimum arrangement of ZigBee nodes for underground mines.

The routing protocols simulation is analysed for the improvement of ZigBee network performance and applications to select optimal paths to transfer data to the destination (Narmada & Sudhakara Rao, 2011; Roberts et al., 2013; Sharma & Kumar, 2012; Bhat.M Subramanya et al., 2011; Zen et al., 2008). Routing evaluation is an important task in ad-hoc networks that do not rely on a pre-existing infrastructure where the nodes are mobile through the environment. Other studies simulated different topologies to optimise ZigBee network performance for industrial systems using stationary nodes (Chandane, 2012; Khan et al., 2013; LAVRIC et al., 2013; Moridi, 2015; Ullo, 2010; Yasin et al., 2013). Reliable and cost-effective networks of ZigBee topologies require an analysis of quality of services (QoS) metrics such as throughput, packet delivery ratio, end-to-end delay, energy consumption and network security.

However, even though there are some performance evaluations of ZigBee networks in underground mines (Bo et al., 2012; Chehri, 2011), the simulation of node positioning comparing different topologies in such environments is hardly investigated. In this work ZigBee nodes arrangement considering the mesh and cluster-tree topologies in underground spaces is analysed based on the analysis of QoS metrics.

4.3 ZIGBEE NETWORK PERFORMANCE METRICS

ZigBee network topologies for the analysis study of optimum nodes arrangement including the mesh (Peer-to-Peer) and cluster-tree which are challenged in industry applications are evaluated. Typically, the performance of network topologies are assessed on the basis of metrics that mainly consist of throughput, packet delivery ratio, end-to-end delay and energy consumption. In particular any topology involved with higher throughput and packet delivery ratio, and lower end-to-end delay and energy consumption is more adequate for ZigBee applications. In these concepts, a packet is defined as a formatted unit of data carried along a communication channel, and each packet carries the information that will help it get to its destination. In the following, we define the basic metrics:

I) Throughput: It is defined as the ability of data packets successfully sent from source node to destination node in the unit time. In our study, the throughput (bits per second) is generated by the ZigBee application within scenario simulation times and is calculated as Eq. 4-1:

$$T = \frac{Tps \times 8}{Tlps - Tfps} \qquad \text{Eq. 4-1}$$

where the total packet sent, the time last packet sent and the time first packet sent are denoted as T, Tlps and Tfps, respectively.

II) Packet delivery ratio: The ratio between the packet number received at the destination node and the packet number sent by the source node is defined as packet delivery ratio (PDR).

III) End-to-End delay: Delay or latency through wireless networks is time taken by the packets to propagate from the source to the destination. The end-to-end packet delay is comprised of the summation of route discovery (source-processing delay), queuing (network delay), propagation and transfer time (destination delay). The end-to-end delay is one of the most critical and fundamental issues for WSNs. Many applications of sensor networks require an end-to-end delay guarantee for time sensitive data.

The average end-to-end delay of ZigBee applications for different scenarios is computed based on the Eqs. 4-2 and 3:

$$AD = \frac{Tt}{Npr} \qquad \text{Eq. 4-2}$$

where the average end-to-end delay, the total of transmission delay of all received packets and the number of packets received are denoted as AD, Tt and Npr, respectively.

$$Tdp = Tpr - Tpt \qquad \text{Eq. 4-3}$$

where the transmission delay of a packet, the time packet received at destination node and the time packet transmitted at source node are denoted as Tdp, Tpr and Tpt, respectively.

IV) Energy consumption: Energy efficiency is another critical aspect in the QoS of WSNs, because nodes are powered by batteries and require time and costs in recharging once they deployed. Energy consumption of a node in any network depends on four modes: transmit (TX), receive (RX), idle, and sleep modes. When nodes are in a sleep period the energy consumption in idle mode decreases because there are no packets to be sent nor received in the running time. However, when nodes become active and are ready to send data, they all reactivate and forward data at the same time which causes the transmit mode energy consumption to increase. Thus, when the duty cycle for nodes is 100%, that is, nodes are sending packets for the entire duration of the simulation, the overall average energy consumption is less than that of when node duty cycle is 50% or 25% (Yasin, 2013).

In the simulation, the total energy consumed in milliwatt-hour (mWh =1/1000 Wh) is calculated from Eq. 4-4:

$$TEc = T + R + I + S \qquad \text{Eq. 4-4}$$

where the total energy consumed (in mWh), the transmission mode (in mWh), the reception mode (in mWh), the idle mode (in mWh) and the sleep mode (in mWh) are denoted as Tec, T, R, I, S, respectively.

4.4 UNDERGROUND ZIGBEE NETWORK SETUP AND DESIGN

In this study, two ZigBee topologies under protocol IEEE 802.15.4 for varying traffic loads are evaluated to find optimum nodes arrangement using QualNet®7.3. This is one of the network simulators that mimic the behaviour of a real network. A network simulation is a cost-effective method for developing the early stages of network centric systems. QualNet allows us to evaluate the basic behaviour of WSNs and test combinations of network features that are likely to work. It also provides a comprehensive environment for creating and replaying network scenarios, and for analysing their performance to improve their design, operation and management. Scalability is one of the key features of the selected simulator that enables for creating a virtual network in underground environments to model large networks with adequate reliability. A brief overview of QualNet is presented in Appendix B.

In the scenarios, an underground mine with a vertical shaft and connected horizontal tunnels are modelled, which these then use for different mesh (peer-to-peer) and cluster-tree network evaluations. The network models have one surfaced PAN

Coordinator and 12, 20, 30, 40 and 50 nodes located in the shaft and tunnels. The nodes are selected as coordinator (router) or end device depending on the required use in the network topology. These scenarios are to simulate a real underground mine, covering an area of 1000m length and 1000m depth. The remaining simulation parameters are listed in Table 4-1.

Table 4-1 Simulation parameters and node configurations

Parameter	**Details**
Node placement	Stationary
Number of nodes	12, 20, 30, 40 and 50
Network topology	Mesh and Cluster-tree
Area of simulation	1000m*1000m
Channel frequency and data rate	2.4GHz and 250kbps
Physical and MAC models	802.15.4 radio
Energy model	MicaZ
Battery model	Simple linear,1200 mAh
Transmission Power	3 dBm
Antenna model	Omnidirectional
Modulation scheme	O-QPSK
Routing protocol	AODV
Path loss model	Two Ray model
Traffic	ZigBee application
No. of items and Payload Size	100 and 127bytes
Simulation time	10mins

In the scenarios, the MicaZ model (QualNet7.3, 2014) for the radio interface is employed. All the nodes in the scenarios are battery-operated devices, and we use a simple linear battery model for the comparison of the scenarios. Therefore energy is consumed by those interfaces according to the energy specification of MicaZ model shown in Table 4-2.

Table 4-2 Specifications of MicaZ energy model

Mode	Radio mode	Power @ 3V (mW)
Active	TX	48.0
Active	RX	56.5
Active	Idle	10.79
Sleep	Sleep	1.50

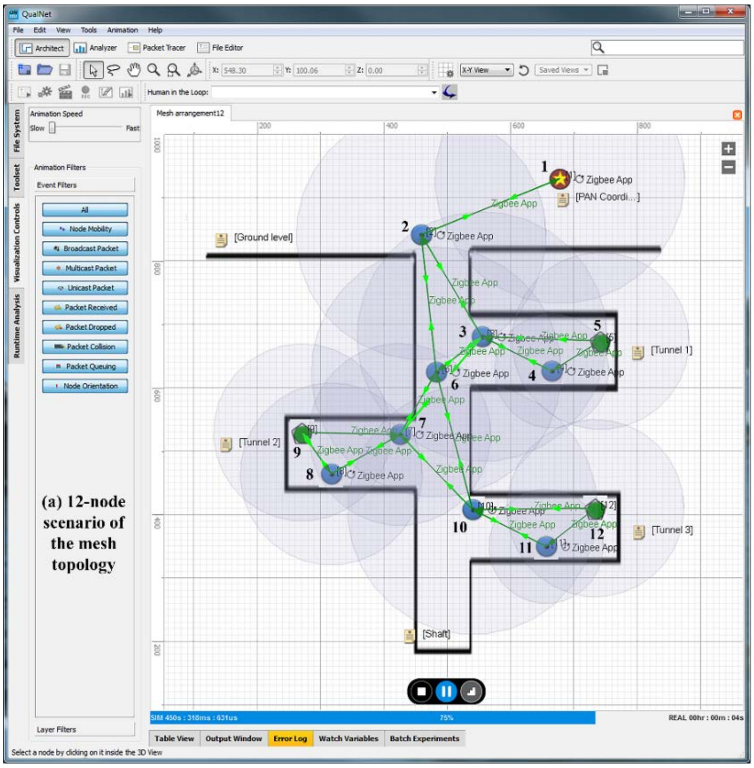
Only one PAN co-ordinator is considered as a final sink server to communicate with other source nodes for data processing and delivery in this multi-hop system. In other words, a wireless network between the surface PAN coordinator and the underground sensor are created. The PAN Coordinator and other sensor nodes including the full function and end devices remain stationary.

Scenarios are separately designed for the mesh and cluster-tree topologies associated with the different network size including the densities of 12, 20, 30, 40 and 50 nodes given in Table 4-3.

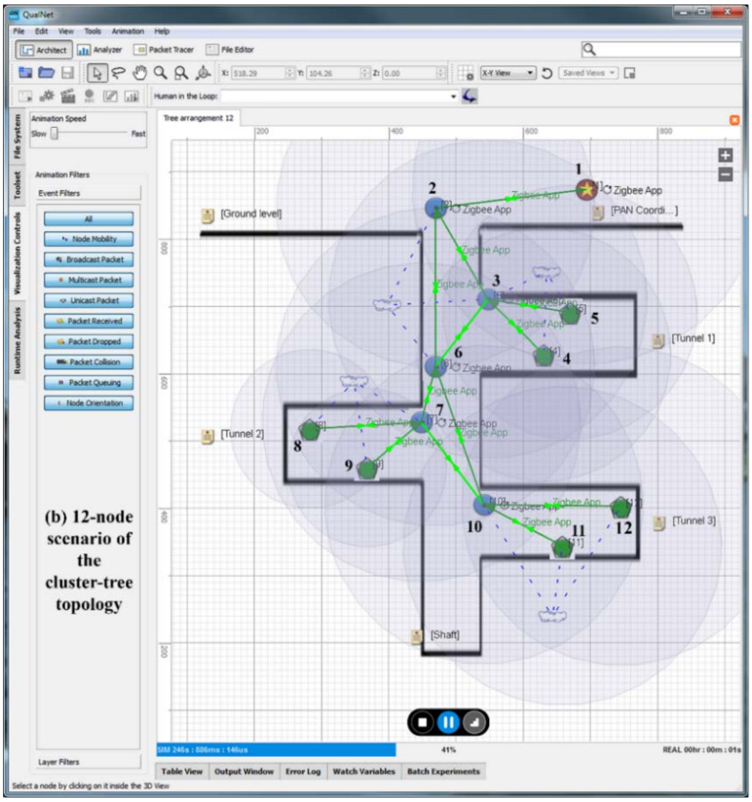
Table 4-3 Simulation scenarios of ZigBee topologies with different network size

Topology	Network size (nodes)
	12
	20
Mesh	30
	40
	50
	12
	20
Cluster-tree	30
	40
	50

Screenshots from the QualNet simulator on 12-node scenarios of the mesh and cluster-tree topologies are illustrated in Figure 4-2. In these topologies, full-function devices act as routers to transfer (or relay) data for next source nodes and as a sensor node to also sense the surrounding environment. An end-device only senses and sends to nearby nodes. The nodes in the scenarios are manually arranged based on the previous underground experiments. ZigBee applications defined in the software are used to evaluate traffic loads between nodes pair with the capability of sending 100 packets, each packet size having 512 bytes which are active during simulation time.



(a) 12-node scenario of the mesh topology



(b) 12-node scenario of the Cluster-tree topology

Figure 4-2 Arrangement view of ZigBee nodes in an underground mine. (a) Mesh topology, (b) Cluster-tree topology

4.5 Results and data analysis

The simulation results can be evaluated through various performance metrics in both the mesh and cluster-tree topologies. By using similar traffic loads, an optimum ZigBee node arrangement is found for different underground mines. As mentioned above, the results are analysed based on the performance network metrics of throughput, packet delivery ratio, end-to-end delay and energy consumption (see Section 4.3 for the definitions).

I) Throughput

The throughputs between nodes in 12-node scenarios are illustrated in Figure 4-3. The throughput between source node (SN) and destination node (DN) of (2,1), (3,2), (4,3), (5,3) in either the mesh or cluster-tree topology is a maximum of 4137 bits/s, with significant reductions in throughput in the cluster-tree topology compared to the mesh topology. This is due to simultaneous increase in receiving packets at the destination nodes (Yasin, 2013). WSNs based on the IEEE 802.15.4 standard commonly act as displays from sharp throughput drops at higher loads.

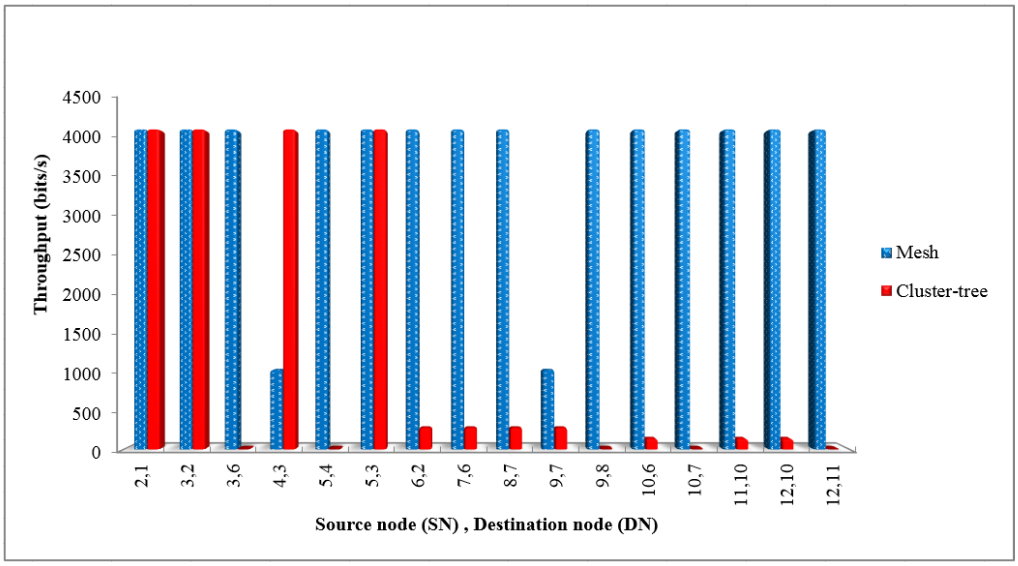


Figure 4-3 Throughput versus 12-node scenarios of the mesh and cluster-tree topologies

The comparison of changes in the number of nodes at the scenarios of 12, 20, 30, 40, and 50-node with the average throughputs are illustrated in Figure 4-4. The figure shows that average throughputs of 3866 and 2079 bits/s are moderately reduced as the number of nodes increases, with a minimum of 2918 and 1178 bits/s for the mesh and cluster-tree topologies, respectively. It is also observed that there is an acceptable throughput within the network for both topologies, however, the mesh topology performs a better throughput from SNs to DNs due to its path finding techniques. A drop of throughputs after 12-node scenarios among the mesh topology has occurred because of rising congestion of packets delivery in full function devices (coordinators) and because of an increase in the choices of links to nearby nodes and thus paths through the network.

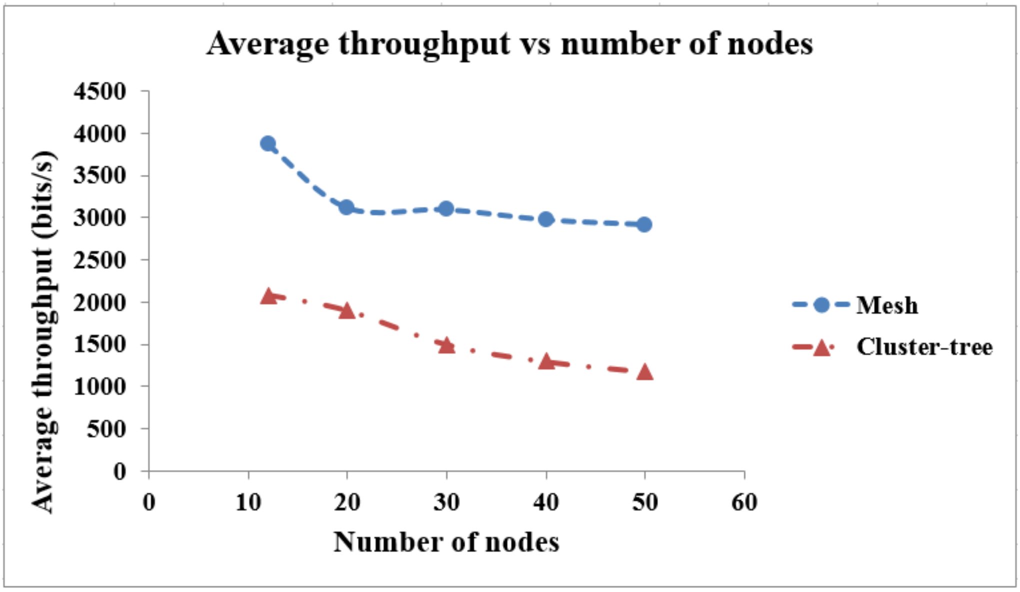


Figure 4-4 Average throughputs versus varying nodes numbers for the mesh and cluster-tree topologies

II) Packet delivery ratio

The packet delivery ratios (PDRs) are computed based on a percentage denotes a ratio between total packets received by DNs and total packets sent from SNs. The PDRs results for the varying numbers of nodes of the mesh and cluster-tree topologies are illustrated in Figure 4-5. The PDR in the mesh topology changes slightly from 81.8% for the 12-node scenario to 77.2% for the 50-node scenario, but it drops considerably in the cluster-tree topology from 64.5% for the 12-node scenario to 23.4% for the 50-node scenario. A higher PDR value shows better performance within the network. Therefore, a visual comparison of the results indicates that the mesh topology has a higher network performance at the same traffic loads for the ZigBee applications.

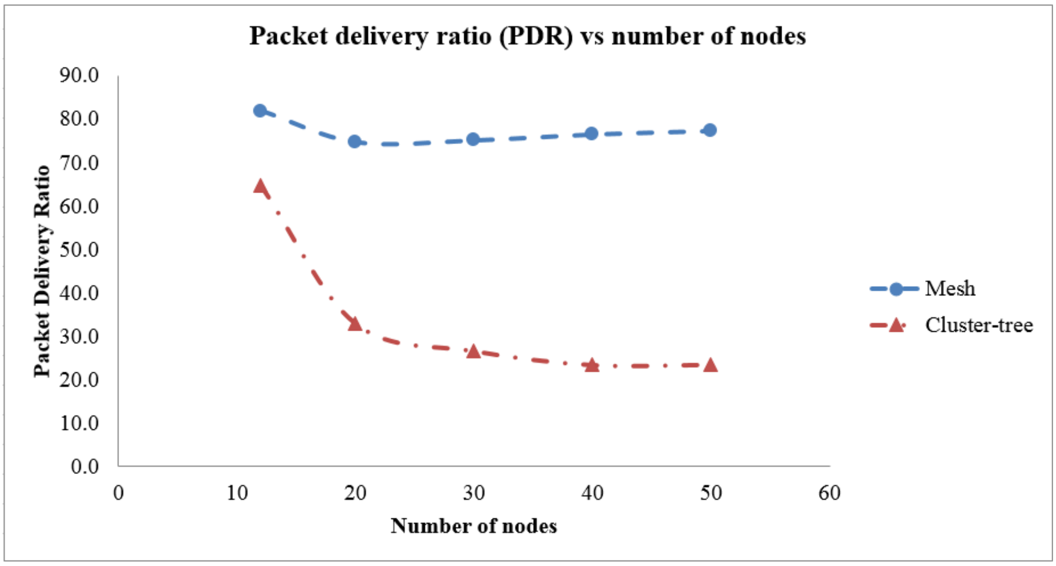


Figure 4-5 Packet delivery ratios versus varying nodes numbers for the mesh and cluster-tree topologies

III) End-to-End delay

The average end-to-end delays at each destination node for 12-node scenarios are illustrated in Figure 4-6. In these bar charts, the node IDs are those as specified in Figure 4-3. The charts show that end-to-end delays occur at nine destination nodes in the mesh topology, while it reduces to seven destination nodes in the cluster-tree topology with the same traffic load. It therefore causes a greater data latency through the network as a result of the increase in the number of hops, which results in queuing, channel access delays and transmission delays. As seen in Figure 4-6, there is no delay for node IDs 5, 9 and 12 in the 12-node scenario of the mesh topology, while it also does not occur for node IDs of 4, 5, 8, 9 and 12 in the 12-node scenario of the cluster-tree topology. In fact, the amount of the total delay is reduced with the increasing number of end-devices through the network.

The tendency of total end-to-end delay of the mesh and cluster-tree network topologies versus varying number of nodes is illustrated in Figure 4-7. The curves clearly show that the tendency of end-to-end delay is enhanced with increasing node

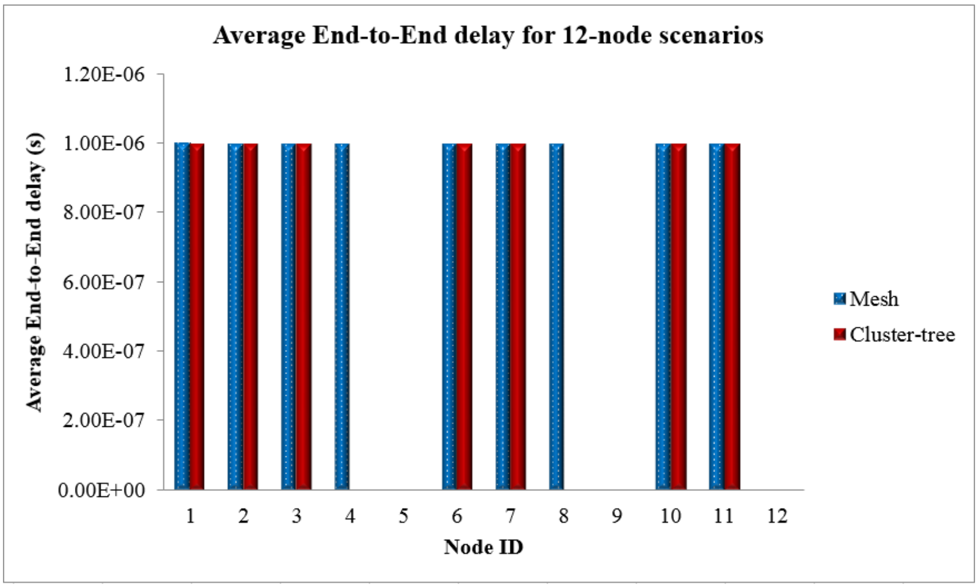


Figure 4-6 Average end-to-end delays at each destination node for the mesh and cluster-tree topologies

density in the networks. According to the mesh topology architecture, the rise in the number of full-function nodes, which are providing multi-hop routes, results in significant data latency in the network. From the graph in Figure 4-7 is observed that the total end-to-end delays for 12-node scenarios are 9s and 6s, whereas these reach to 32s and 13s for 50-node scenarios in the topologies of the mesh and cluster-tree, respectively. Consequently, the cluster-tree topology supports a more reliable network in the case of data latency compared to the mesh topology.

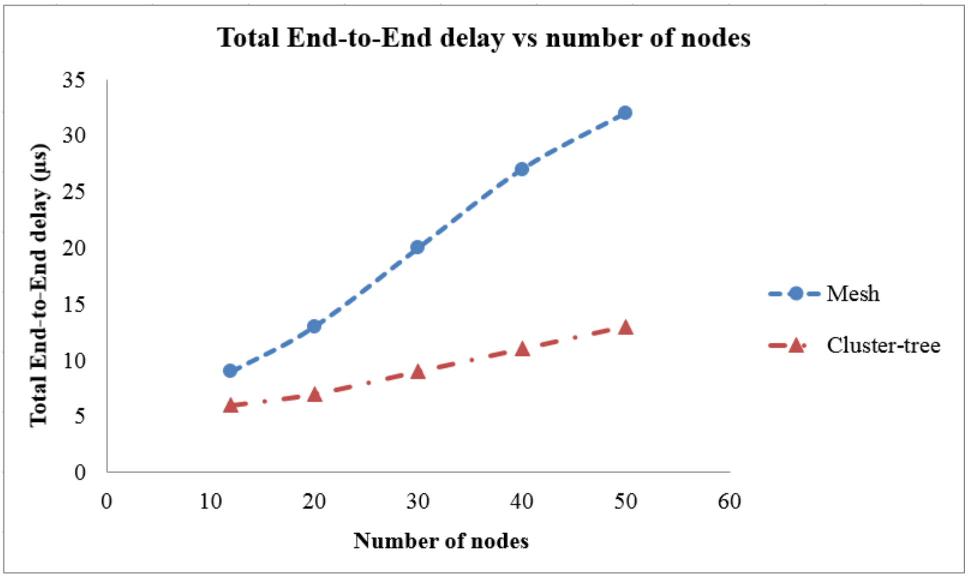


Figure 4-7 End-to-End delays versus varying nodes numbers for the mesh and cluster-tree topologies

IV) Energy consumption

Next step is evaluating the efficiency of the network by measuring the energy consumption. Figure 4-8 illustrates the total energy consumption for the mesh and cluster-tree topologies of ZigBee network versus varying number of nodes. The trends of the curves in the graph show an increase in energy consumed for more dense networks. It is also observed that total the energy consumed of 18.4 mWh for 12-node scenario increases to 99.44 mWh for 50-node scenario in the mesh topology, and it climbs from 15.7mWh for 12-node scenario to 64.2 mWh for 50-node scenario in the cluster-tree topology. Thus, the cluster-tree topology is more energy efficient than the mesh topology. This is due to the fact that more end-devices remaining in sleep mode in the cluster-tree topology. On the other hand, a considerable number of full-function destination nodes are more engaged in the mesh topology, which causes higher energy overall consumption. First, such destination nodes have to be largely in idle mode in order to communicate with nearby nodes. Secondly, the number of nodes predicted to receive data (receive mode) within a network of the mesh topology is more necessary than those in the cluster-tree topology.

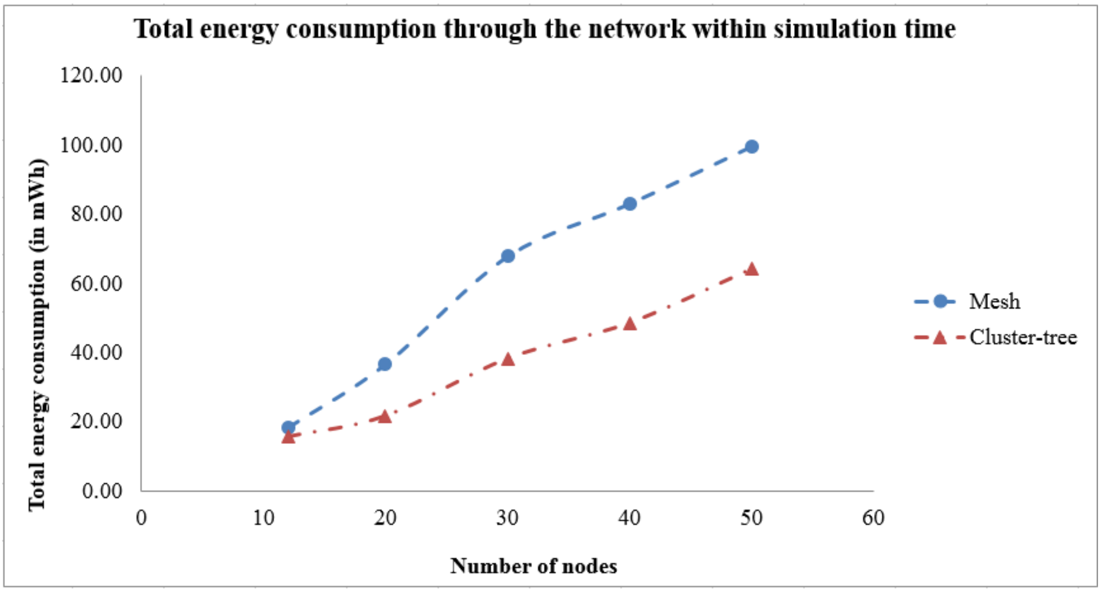


Figure 4-8 Energy consumption versus varying nodes numbers for the mesh and cluster-tree topologies

V) Network security

In a network with mesh (peer-to-peer) topology, all the devices that participate in relaying the messages are usually full-function devices because end-devices cannot be as a router and support bilateral communication. The PAN Coordinator might often be mains powered, while the devices will most likely be battery powered. Multiple hop communication of the mesh topology with a variety of routing alternative between nodes provides a higher network security for data delivery within the network. Underground mine applications such as environment attributes monitoring and bilateral communication under emergency condition are beneficial from a higher security of such network topology.

4.6 Discussion

The performance investigations of different ZigBee topologies in underground spaces (mines) are summarised in Table 4-4. The simulation results show that the mesh (peer-to-peer) topology provides more reliable networking for the arrangement of ZigBee nodes in underground mine tunnels. This network topology has higher throughput, packet delivery ratio and network security. Although the cluster-tree topology is involved with lower end-to-end delay and energy consumption through the network, such benefits do not play significant roles for underground ZigBee network communication.

Table 4-4 Comparison of the simulation results of ZigBee topologies reliability in underground spaces

Metric	The reliability of ZigBee network topologies	
	Mesh	Cluster-tree
Throughput	✓	✗
Packet delivery ratio	✓	✗
End-to-end delay	✗	✓
Energy consumption	✗	✓
Network security	✓	✗

As seen in Figure 4-7, the delay time of packet deliveries from the source nodes to the destination nodes for 12, 20, 30, 40 and 50-node scenarios in the mesh topology are 3, 6, 11, 16, 19 µs longer than the similar scenarios with the same conditions created with the cluster-tree topology, respectively. For actual underground operations, such a small increase in the end-to-end delay of the mesh topology would not be a major. In addition, the greater energy consumed through the network will not be as bad a negative aspect for the mesh topologies, as ZigBee nodes that are currently in development will be able to switch between battery power and mine power.

4.7 CONCLUSION

The selection of an appropriate network topology is crucial for the nodes arrangement of the industrial wireless WSNs. In this chapter, the performance of different network topologies for ZigBee-based WSNs are analysed for underground mine applications. Then scenarios of the ZigBee mesh and cluster-tree topologies under the IEEE 802.15.4 standard are investigated in the light of most important network metrics. Throughput, packet delivery ratio, end-to-end delay, and energy consumption are evaluated during simulations for varying nodes number including 12, 20, 30, 40 and 50-node scenarios.

In many sensitive industrial applications, the arrangement of wireless sensor nodes mostly depends on achieving higher throughput, packet delivery ratio and network security as well as lower latency data and energy consumption. While the cluster-tree topology meets advantages of lower latency data and energy consumption, the benefits of the mesh topology are higher throughput, packet delivery ratio and network security, which are the most significant features for the underground ZigBee node arrangements. The larger data latency and the slight increase in energy consumption through the network are no major concerns for underground mines projects, as the delay increases by only a few µs and future ZigBee nodes will be able to switch power between battery and mine power. Thus, it is concluded that the mesh topology enables ZigBee nodes to create an underground space wireless network that is more secure and delivers a higher quality of service than cluster-tree topology networks.

CHAPTER 5. UNDERGROUND COMMUNICATION SYSTEM INTEGRATION

5.1 INTRODUCTION

Underground mine safety and health remain challenging issues in the mining industry. Death toll statistics in China's coal mines have gradually reduced from 5798 to 2631 between 2000 and 2009 (Wu, 2011) but fatality still occurs. The number of occupational mining fatalities in the United States' underground metal mines has fluctuated from 40 to 46 during the years 2001 to 2010. Most importantly, 33.8% of the deaths have resulted from ignitions and explosions of gas or dust (CDC, 2012), in underground mining. In April 2014, two men were killed when a wall collapsed in an underground coal mine in New South Wales, Australia. Human errors were concluded from reports as the most significant reasons for mining fatalities. Thus, safety is always a significant concern in mining operation. Some studies have recently focused on improving the health for underground miners. Laney and Attfield (2010) have drawn attention to the fact that the prevalence of coal workers' pneumoconiosis or progressive massive fibrosis increased from 1990 to 2000 among United States underground miners. Therefore, specific consideration of both safety and health issues deserves priority in mine operation management and engineering designs to provide and maintain a safe and healthy workplace. In response to these challenges, mine automation by new technologies such as wireless sensor network (WSN) assisted with geographic information system (GIS) has been widely utilised in underground mines to enhance safety and health, productivity and reduce operational costs (Bhattacharjee, 2012; Chehri, 2009).

To this end, an integration system is developed to mitigate underground safety and health concerns. This system based on the development of ZigBee nodes is introduced to sense the underground mine environment, to regulate ventilation system and to communicate between surface offices and miners. Thus, reduced power consumption, near real-time monitoring of the environment and bilateral communicating between surface and underground personnel are achieved. Experimental tests were carried out to verify network reliability and security of the packet delivery in underground mines. The architecture of underground monitoring and communication for the system integration is illustrated in Figure 5-1. Temporal ZigBee data including messages, operation orders, and environmental attribute readings such as temperature, humidity and gases concentration are transferred to GIS management server in the surface control centre. The transmitted data is received and stored by ZigBee program then provided for manipulation in the control centre. Risk situations are immediately identified and responded through a logical process of data analysis in the GIS management server before reaching dangerous (unsafe) levels and accidents occurring. The ventilation system management is also used for the workplace health and safety compliance and the optimisation of mine site power usage.

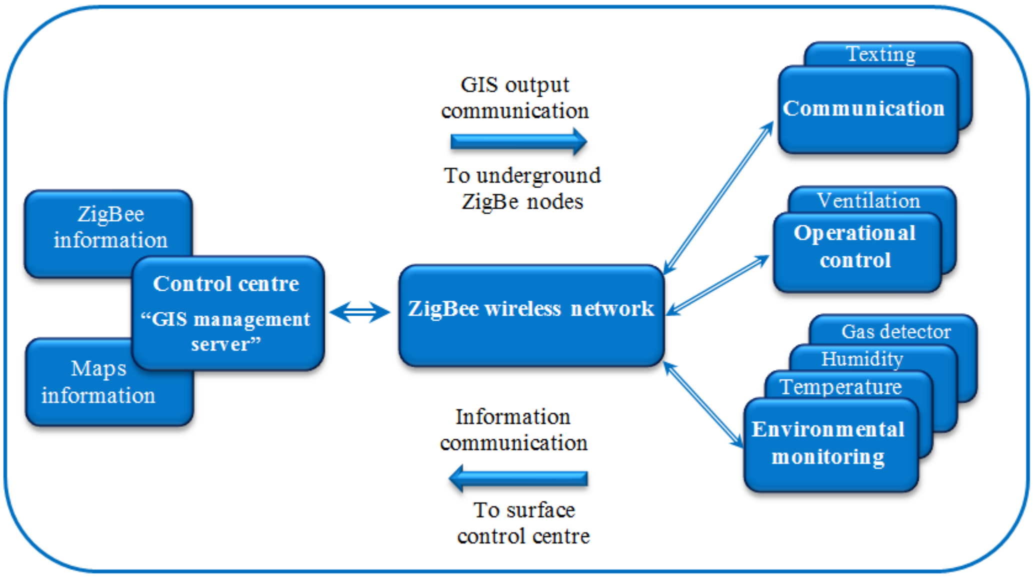


Figure 5-1 Architecture of monitoring and communication system in underground mines

The remainder of the chapter is organised as follows. The fundamental knowledge of ZigBee technology and GIS are first described. Then, the implementation and structure of system integration are demonstrated. Finally, the strategic process of combining ZigBee data and map information through the GIS management server is modelled for monitoring, communication and controlling the environmental attributes in an underground mine. In this chapter, the applications and functions of the underground mine monitoring and communication systems are considered based on the capability of developed ZigBee nodes.

5.2 BACKGROUND

The underground WSNs consist of a few to several hundred nodes between a surface gateway and specified sensor nodes at underground levels (Karl & Willig, 2005). ZigBee based on IEEE 802.15.4 protocol is a new wireless sensor technology which has more benefits than other WSNs for underground monitoring and communication systems (Chen et al., 2012). Even though ZigBee technology provides only a low data rate, its benefits are low power consumption, very cost-effective nodes, network installation and maintenance (Shu-guang, 2011). It is also capable of providing networking applications for data transmission between nodes (node to node relays) with high performance based on many wireless hops. It does not require any access point or central node to transmit data between clusters. Significance of ZigBee in underground mines compared to other WSNs was evaluated in the recent publication of authors (Moridi et al., 2014).

GIS is new technology used for spatial data analysis in order to capture, store, analyse, manage, and present data that is linked to locations (ESRI, 2012). GIS allows users to view, understand, question, interpret, and visualize data in many ways that reveal relationships, patterns, and trends in the form of maps, globes, reports, and charts. Web-GIS is an inevitable trend which helps solve the problems of spatial information integration and sharing in technical aspect of web media (Ghorbani, 2012; Huang et al., 2010). Recently, researchers have technically focused on the GIS supports for the management of emergency and unsafe conditions (Kawamura, 2013; Salap, 2009; Sharifzadeh et al., 2008).

5.3 USE OF GIS IN UNDERGROUND MINES

GIS is based on computer programs used for storage, modelling, retrieval, mapping and analysis of geographic data. In this system, spatial features of a specified environment are stored and manipulated in a coordinate system, which refers to a specific place. GIS merges multi-layers of required geographic and spatial data for the user evaluation, and helps determine the locations and times of possible incidents in advance. Figure 5-2 illustrates a cycle of GIS to process data and layers for the purpose of risk assessment in underground mine sites. GIS server is capable of managing and processing data for a substantial number of attributes coming from different sources. It also is able to distribute and share data between users based on internet or intranet, and data could be saved, manipulated or informed by other users. Therefore, GIS can decrease the time and cost of sharing geographic data and its attributes.

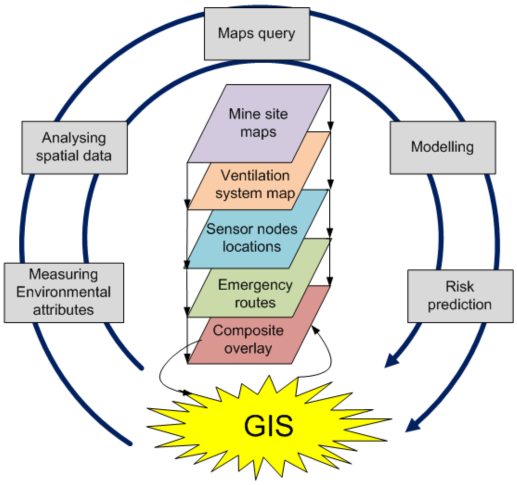


Figure 5-2 GIS data process cycle and geographic layers in an underground mine

5.4 ZIGBEE AND GIS SYSTEM INTEGRATION

In the challenging environment and changing topology of a mine, reliable and simplified communication is a high-stake issue with the objectives of safe and efficient mining operations. Automation of remote and automatic systems has improved workplace safety and health for miners, yielded cost-effectiveness, management improvement of technical problems, energy savings, real-time response to incidents. In response to these challenges, integration of technologies has a significant role in underground mining automation. According to WSNs' specific features of high reliability and multi-hop networking, ZigBee can create an integrated wireless network between nodes in the underground mine tunnels and the surface gateway. In this study, ZigBee's capability of monitoring underground environmental attributes is combined with geographic information to provide potential applications in communication, operational and environmental monitoring systems of underground mining.

In order to achieve such smart underground mine system, integrating maps information and spatio-temporal data from ZigBee nodes into a database at a control centre is required. Figure 5-3 illustrates data processing and results management in the surface control centre.

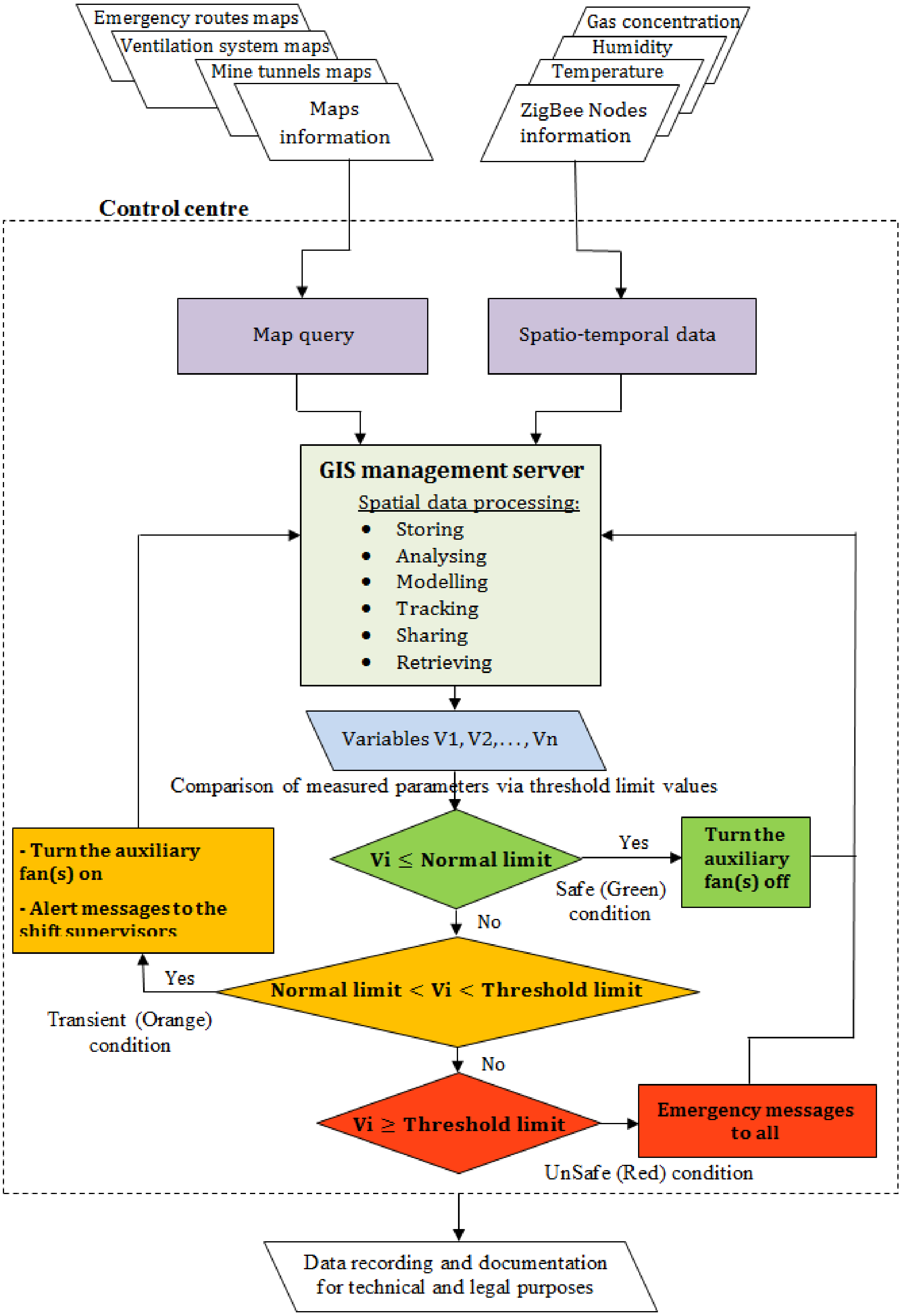


Figure 5-3 Flow chart of data processing and result management

The network demanded in an underground mine must be capable of providing bilateral communications between the surface control centre and all underground wireless nodes interactively. According to the threshold limit values for the different variable parameters (V1, V2, …, Vn) of underground mine environment, the conditions of safe, transient and unsafe were set. Thus, the remote or automatic countermeasures in a GIS management server were arranged in order to control ventilation fans and send alert or alarm messages to relevant authorities. Additionally, immediate texting messages are bilaterally communicated between underground personnel and the surface operator in emergency conditions.

Based on this system, near real-time monitoring data, remote and automatic controls, and communication by texting messages have achieved the required safety and health outcomes and improving underground mining operations. Such achievements are more efficient for emergency management when system configuration enables control, monitoring and communication between users in various places connected by internet medium access.

5.5 SYSTEM STRUCTURE

5.5.1 *Wireless network setup*

The entire system of the tested underground WSN is composed of different ZigBee nodes such as coordinator, routers and end devices. These products were developed in collaboration with Tokyo Cosmos Electric Co., Ltd. The JN5148-EK010 kit (Jennic) stacks were employed to create ZigBee network. The wireless network initially is created by coordinator (gateway) to join other nodes. A ZigBee coordinator connected to laptop (PC) using in the experiments is illustrated in Figure 5-4. Bilateral communication was provided between the coordinator and end devices to send and receive messages and readings instantaneously taken by their sensors. Routers with the ability of sensing the environment were employed to relay communication through the network. In addition, sending and receiving messages and remote control of ventilation fans are enabled by the surface coordinator based on the designed software (Figure 5-4).

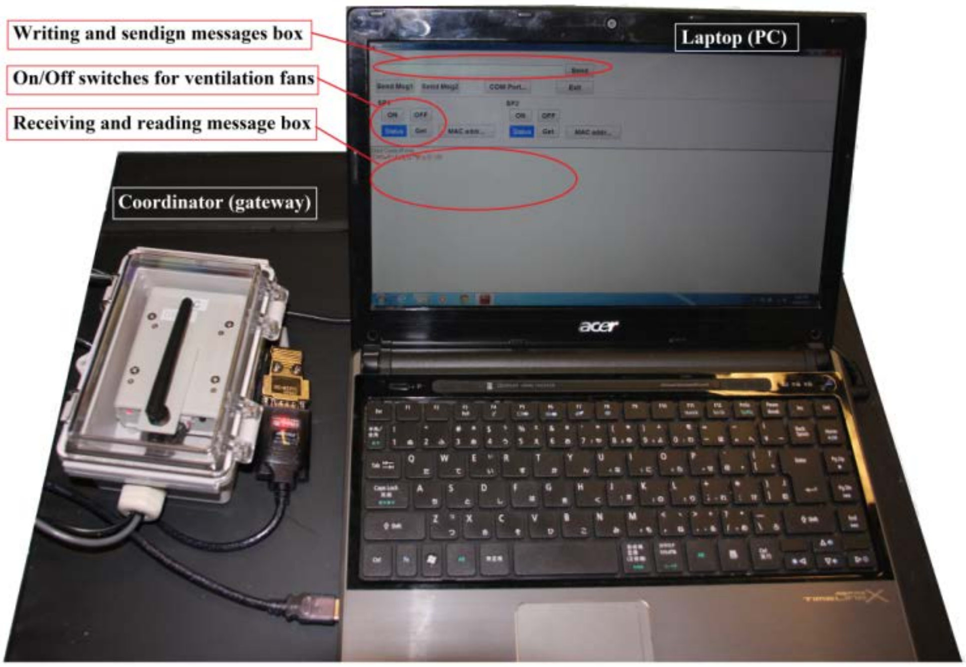


Figure 5-4 ZigBee coordinator connected to laptop (PC)

To setup WSNs, power consumption and high reliability of packet delivery are the most concerns. For the former case, ZigBee nodes are configured to transmit data in longer periods when the mine is in safe and transient conditions which it is caused to extend the life of batteries. In latter case, different time intervals are considered for data delivery of environment sensing to avoid network congestion and possibility of packets loss. The power usage of direct and alternating currents (DC/AC) for the ZigBee nodes (except the coordinator) were designed to operate under battery and mine site power supply, respectively. Thus, alternating currents power usage is resulted in the extension of battery life, and ZigBee nodes are enabled to continue long-time data telemetry during power outages at any accident. The ZigBee nodes can last a few days to several months depends on their data rate and applications.

5.5.2 *Sensing environment*

The safety and health of coal and metal/non-metal mining operations were raised considerably as the result of the wireless monitoring of environment attributes. Digital temperature-humidity compound sensor on-board of each JN5148 with advanced sensitivity and long-term stability for mine sites is utilised in the system. Methane, Oxygen, CO2, CO, NOX and SO2 concentration sensors (readers) are easily connected to ZigBee nodes to sense the environment. The sensors were configured the single-line communication to transmit real-time data to the nodes. The measurement of CO2 concentration in this study was considered to manage safety and health risks nearby coal strata in coal mines or fumes-filled spaces in metal/non-metal mines.

5.5.3 *Text messaging operators*

Developed ZigBee nodes are enabled to connect with laptops and mobile phones for sending and receiving text messages. Figure 5-5 illustrates portable radio stations to connect laptop (Tablet) which are designed to be placed in an underground refuge chamber and mobile phones for emergency purposes. The radio station is getting a significant role for wireless communication with surface operator during accidents particularly when cable damage or power outage occurs. Even though, its primary role is the remote control of ventilation fans. ZigBee nodes were placed in the boxes to minimise environmental effects on their operation.

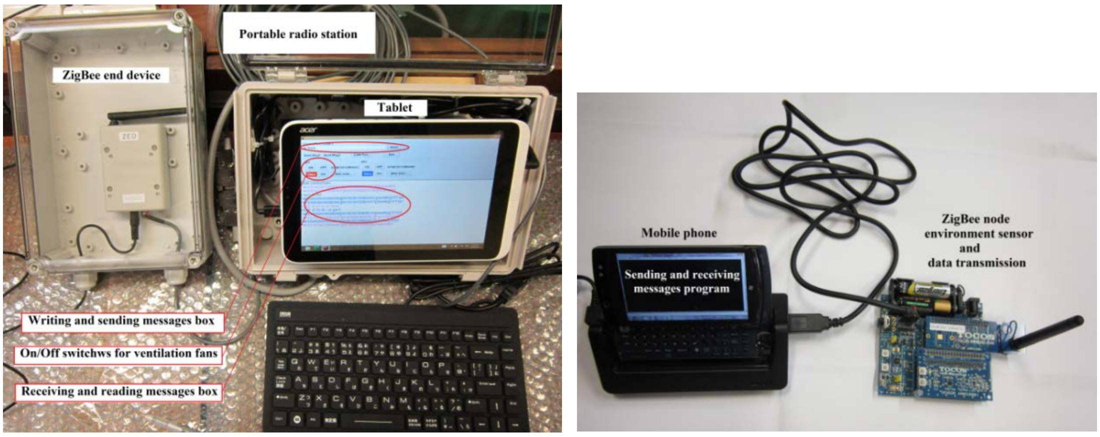


Figure 5-5 Portable ZigBee radio stations to communicate between laptop and mobile phones

5.5.4 *Ventilation control*

Air ventilation deficiency in underground mines is a critical issue to the occupational safety and health of mine personnel. Moreover, optimization of the fans power consumption to supply underground fresh air is considered on ventilation system design. Therefore, adding auxiliary fans to the ventilation system is economically required to improve air quality during hot seasons, blasting, any gas leakages and increase of exhaust fumes. In the proposed system, remote and automatic controls of auxiliary fans were programmed with the software installed on PCs locate at the surface office and refuge chamber. Figure 5-6 illustrates ZigBee node with the ability of wireless connection to the (auxiliary) fans. Special computer interface with ON/OFF switches and receiving/sending messages installed on PCs (laptop and tablet) is illustrated on Figure 5-7. In the computer interface, separate command icons were designed for each auxiliary fan which gives the user the ability of the ventilation system control.

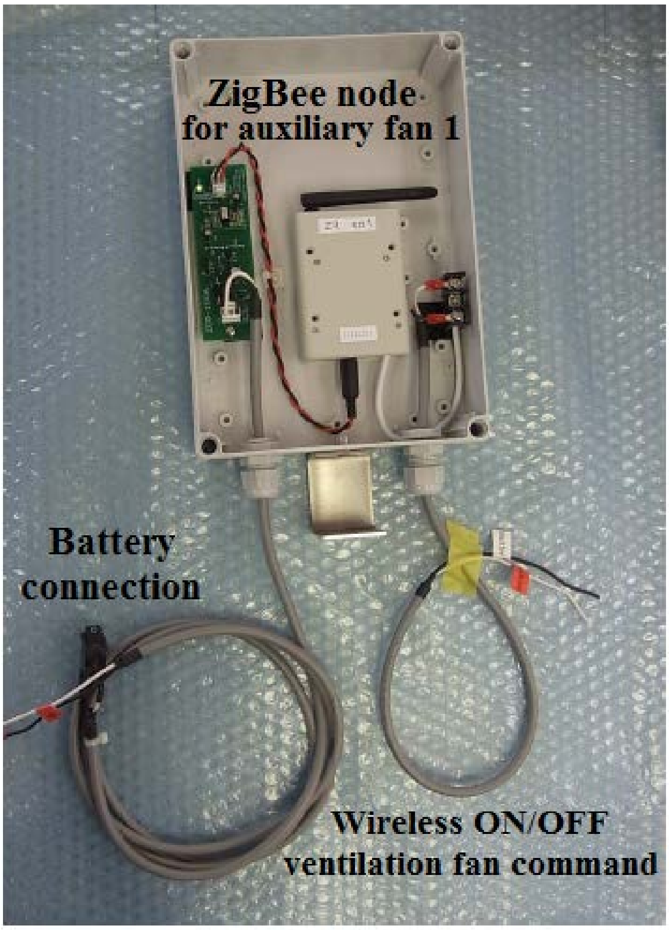


Figure 5-6 ZigBee node with the ability of wireless connection to the (auxiliary) fans

5.6 Data management server using GIS

The prototype model developed in this study relies on ZigBee data and geoprocessing data of GIS. Data management server was developed on ESRI's established ArcMap 3D software, part of the ArcGIS software package.

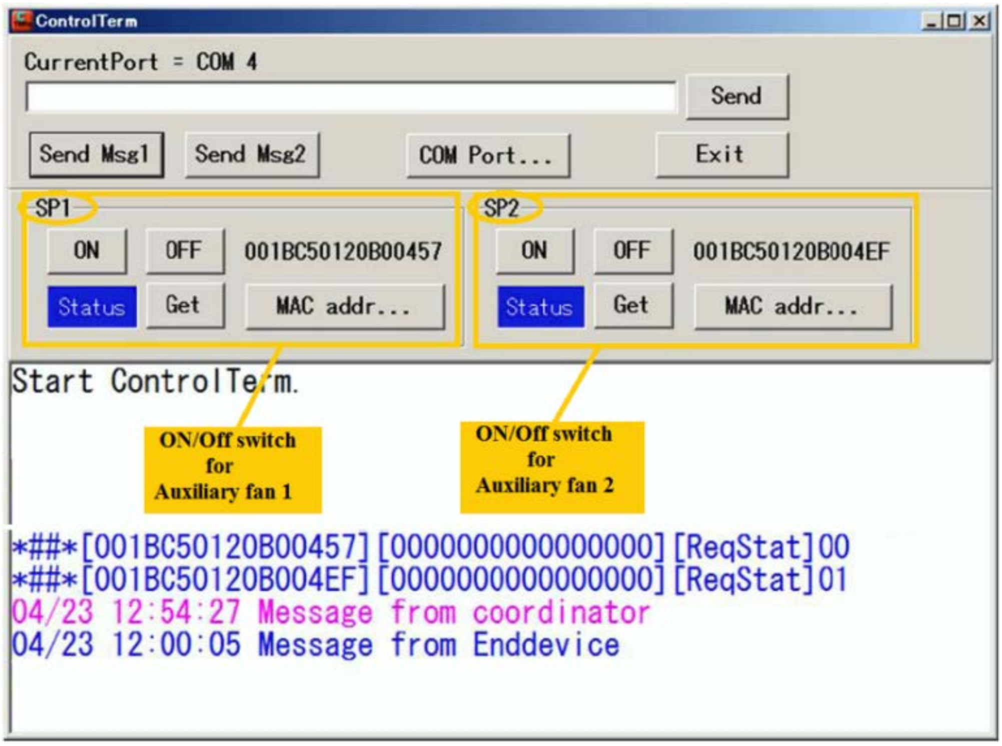


Figure 5-7 Designed computer interface to switch ON/OFF the (auxiliary) fans and receiving/sending messages

5.6.1 *Input data*

The first step of our designed management server is to communicate with the outside world to receive required information. Figure 5-8 illustrates data flow sheet and the variety of input data for the GIS management server. Input datasets in the database are comprised of map information, ZigBee nodes data, ZigBee text messages, ZigBee node positions, threshold limit values and contact details. Map query is primary process of map information to merge and display required features in GIS server to represent the fundamental layers of underground tunnels, geographically. These layers are revised according to the progress of underground mining activities. Then, other input data is analysed and located on the layers for further manipulation.

The quality of input dataset is considered to process and analyse at any particular database. Consequently, the quality of input data in our designed GIS management server is divided between long-term and short-term datasets. Maps, ZigBee node positions, threshold limit values and contact details are determined to be long-term input data into the database which may be periodically updated. These data are stored in attribute tables that are associated with ArcGIS geo-processing models. ZigBee node data which measured environmental properties of mine tunnels is derived as short-term (temporal) data. In this case, the datasets of environmental phenomena such as temperature, humidity and gas concentrations change from time to time or remain relatively continuous. Therefore, spatio-temporal data models, which show both spatial and temporal characteristics of environment, are considered as input data in the GIS management server. The spatio-temporal data is stored and manipulated in the ArcGIS geo-processing based on the related or joined table command to digital tables of data collection by ZigBee gateway software.

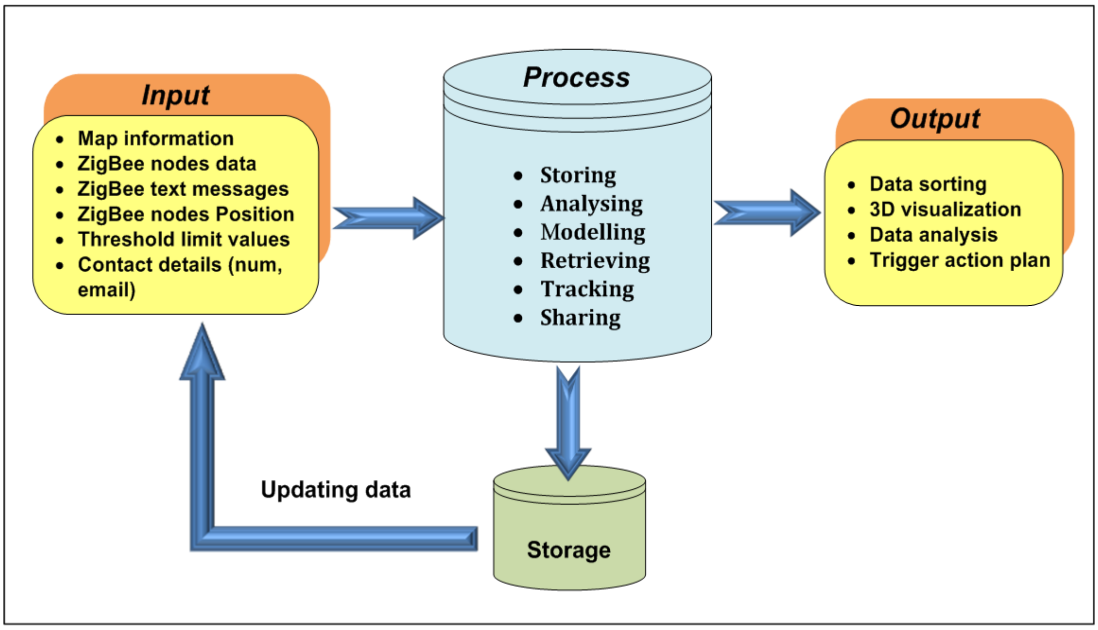


Figure 5-8 Data flow sheet of integrated system in GIS server

5.6.2 *Process strategy*

Real-time process strategy for safe working environments involves the combination of data models and programs in GIS management server to monitor and communicate underground mine automatically and remotely. A pattern of decision making in managing spatio-temporal data was modelled as a procedure to monitor the environment attributes of underground mine tunnels (Figure 5-3). To this end, near real-time and flexible scheduling strategy was planned to apply the performance of ZigBee network in an emergency status. An experiment was simulated on real maps of underground mine with developed ZigBee nodes to control ventilation fans

(ON/OFF) and text emergency messages from surface control office. A section view of an underground mine and ZigBee node positions in ArcGIS screen are illustrated in Figure 5-9. In this model a gateway was located in the surface control office to receive and transmit data through the underground network. The network is extended by ZigBee routers between the surface gateway and underground end devices based on optimised communication ranges. ZigBee End devices were divided to three groups in this experiment. One is connected to the auxiliary fans to switch them on or off automatically or remotely. Another is attached to a radio station which enables to write and read messages. The radio station can be portable or located in underground refuge room. Lastly, sensor nodes are mounted in working area which sense environment attributes such as temperature, humidity and gas concentration.

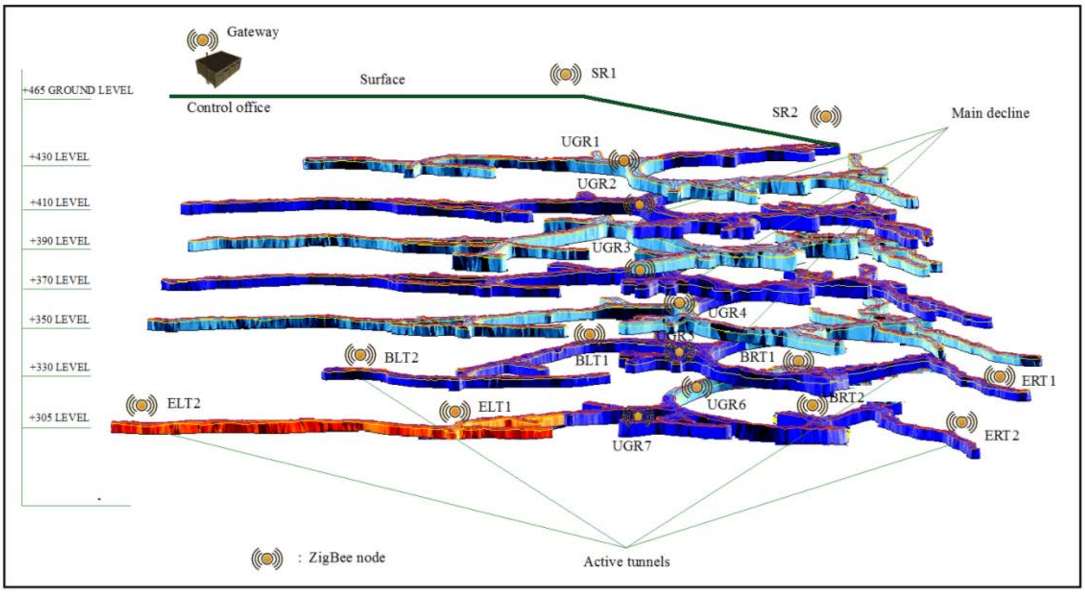


Figure 5-9 A thematic map of an underground mine and ZigBee node positions in ArcGIS

The transmitted data firstly is stored in the GIS management server located at control centre. The ability of the map visualisation on GIS (ArcGIS) allows the position and component of the attributes in underground mine environment to be visually displayed on the screen. Then, the spatio-temporal data tables stored by ZigBee software in the database were joined or related to the attribute tables of node geographic positions in the geo-processing services of GIS management server. A joining table of spatio-temporal data and geographic node position created in ArcGIS (ArcMap) is illustrated in Table 5-1. In other words, in this joining table each node position is connected to the related and measured variable parameters including temperature, humidity and gas concentration.

Table 5-1 Storage of transmitted data by ZigBee gateway

Table

ZigBee-nodes

FID	Shape *	Node	Position	OBJECTID *	ZigBeeNodes	Temperature_C_	Humidity___	GasConsantration__ppm
10	Point	1	SR1	1	Node 1	T1	H1	G1
8	Point	2	SR2	2	Node 2	T2	H2	G2
11	Point	3	UGR1	3	Node 3	T3	H3	G3
12	Point	4	UGR2	4	Node 4	T4	H4	G4
7	Point	5	URG3	5	Node 5	T5	H5	G5
13	Point	6	UGR4	6	Node 6	T6	H6	G6
14	Point	7	UGR5	7	Node 7	T7	H7	G7
15	Point	8	UGR6	8	Node 8	T8	H8	G8
17	Point	9	URG7	9	Node 9	T9	H9	G9
6	Point	10	BLT1	10	Node 10	T10	H10	G10
5	Point	11	ELT1	11	Node 11	T11	H11	G11
1	Point	12	BLT2	12	Node 12	T12	H12	G12
0	Point	13	ELT2	13	Node 13	T13	H13	G13
2	Point	14	BRT2	14	Node 14	T14	H14	G14
3	Point	15	ERT2	15	Node 15	T15	H15	G15
16	Point	16	BRT1	16	Node 16	T16	H16	G16
4	Point	17	ERT1	17	Node 17	T17	H17	G17

1 (0 out of 17 Selected)

ZigBee-nodes | Tempe | Humi | GasC

Following this, the spatio-temporal data was analysed, modelled and retrieved in the GIS management server. A geo-processing model based on Python (ArcPy) was designed to track and control the environmental attributes in different conditions. Normal and threshold limit values to assess environmental attributes according to underground mining standards were then derived. Normal and threshold limit values for the discrete conditions of safe and unsafe statues are presented in Table 5-2. According to the normal and threshold limit values, the status of working environment in underground mine were assessed in three conditions of safe (green), transient (orange) and unsafe (red).

Table 5-2 Threshold limit values for working environments in underground mine

Variables (V_i)	Event procedure conditions		
	Safe (Green)	Transient (Orange)	Unsafe (Red)
Temperature ($T_1, T_2, \ldots, T_n$), °C	Ti ≤28	28 < Ti < 40	Ti ≥40
Humidity ($H_1, H_2, \ldots, H_n$), %	Hi ≤75	75 < Hi < 85	Hi ≥85
Gas concentration for Co_2 ($G_1, G_2, \ldots, G_n$), ppm	Gi ≤2000	2000 <Gi< 5000	Gi ≥5000

Finally, a loop of conditional procedures and trigger actions were set. The measured parameters (spatio-temporal data) were stored while these data are less than or equal normal limit values (safe condition). The loop was periodically retrieved each 30 minutes in order to consume less power and to extend the battery life of ZigBee nodes and reduce congestion through the network. Otherwise, a trigger plan was set for the values mounted in the range of between normal and threshold limits (transient condition) or greater than threshold limit (unsafe condition). The trigger action plan applied in the GIS management server to respond the deviation of values from normality is presented in Table 5-3. In the transient (orange) condition, the auxiliary fans which had designed for emergency ventilation system would be automatically or remotely turned on. In this state, the model was also setup to send alert messages to shift supervisors. The periodic time of data reading in orange state is reduced to 15 min to ensure the safe and health conditions of underground environment in the shorter time possible. Emergency (alarm) messages in the event of unsafe (red) condition would be texted to surface authorise and to underground personnel for immediate evacuee from the hazardous places. The cycle time of data acquisition is minimised to 5 minutes in this situation.

Table 5-3 Trigger action response plan

<table>
<tr><th rowspan="2">Variables (V_i)</th><th colspan="3">Counter measure implements</th></tr>
<tr><th>Safe (Green)</th><th>Transient (Orange)</th><th>Unsafe (Red)</th></tr>
<tr><td>Reading time interval (min)</td><td>30</td><td>15</td><td>5</td></tr>
<tr><td>Temperature ($T_1, T_2, \ldots, T_n$)</td><td rowspan="3">• Next reading</td><td rowspan="3">• Turn the auxiliary fan(s) on
• Text message to the shift supervisors
• Next reading</td><td rowspan="3">• Text message to all to evacuate from unsafe place(s)
• Next reading</td></tr>
<tr><td>Humidity ($H_1, H_2, \ldots, H_n$)</td></tr>
<tr><td>Gas concentration ($G_1, G_2, \ldots, G_n$)</td></tr>
</table>

5.6.3 *Output*

Mine safety and health were improved by intelligent maps supporting spatio–temporal data and coordinate of ZigBee nodes in this experiment. The schematic representation of integrated system outputs for underground monitoring and communication is illustrated in Figure 5-10. The final outputs of GIS management server are comprised of 3D visualization monitoring of underground mine tunnels and messages texting for alert and alarm conditions. The web-GIS is another application supporting the GIS management server to promote the underground monitoring and communication system.

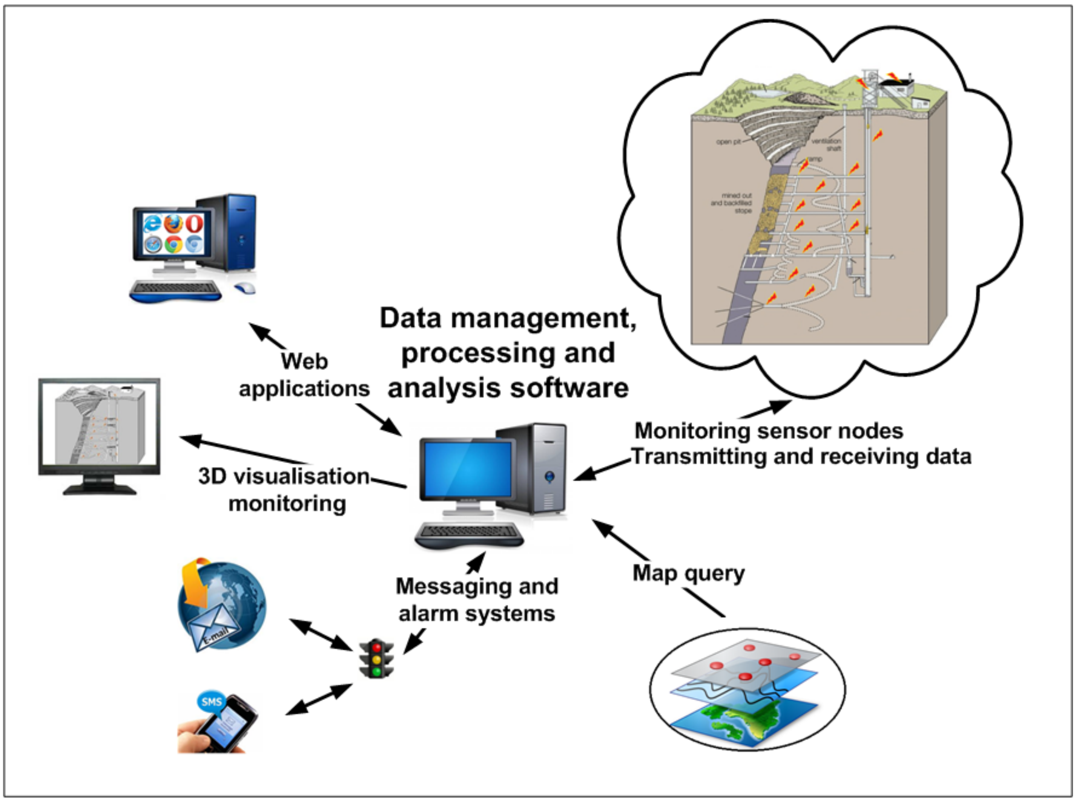


Figure 5-10 Schematic representation of integrated system outputs for underground monitoring and communication

5.6.4 *Data storage*

Data storage and management in the central data repository of server is an essential part of the integrated system. In fact, all geographic and spatial data are stored and managed in ArcMap's geodatabase which accesses to the database at any time over the long-term. In the geodatabase, organisational structure for storing datasets and creating relationships between datasets were also provided for further analysis and interpretation. In addition, a multi-user access is enabled to work and command orders from different mine site offices.

An integrated data management and documentation to generate geospatial metadata was another approach of geodatabase automation. Metadata can create geospatial data document to investigate any genuine or non-genuine claims.

5.7 CONCLUSION

An integrated system based on the WSNs and GIS was introduced to automate underground mine monitoring and communication. The proposed system enhances safety and health, operational management and reduces capital costs. Considering the capability of ZigBee network and ArcGIS, the applications of real-time underground monitoring (temperature, humidity and gas concentration), ventilation system control and communication in emergency conditions by surface user would be achievable. The system is equipped with automatic or remote triggers action plans for measured environmental attributes. The measured data were classified to three categorises consisting of normal (green), transient (orange) and unsafe (red) conditions based on their values compared to normal and threshold limit values. At normal (green) condition, the measured attributes are below the normal value limits. The mining operation is continuing as it was and readings are recorded with 30 minute intervals. At the transient (orange) condition, the measurements are between normal and threshold value limits. In this state, trigger actions are become automatically active to switch the auxiliary fan on and texting message to shift supervisors. In addition, reading's intervals are reduced to 15 minutes in this situation. At unsafe (red) condition, the measurements are getting greater than threshold value limits and the system texts messages to all underground personnel for immediate evacuee from the hazardous places. Reading's intervals are reduced to 5 minutes. Furthermore, the system provides multi-users surface operation and 3D visualization for realistic understanding of underground environment and miners' conditions, and it could be a useful approach for high-tech underground mining.

CHAPTER 6. ZIGBEE NETWORK MODEL GENERALISATION FOR UNDERGROUND MINES

6.1 INTRODUCTION

The development of a generalised ZigBee network model is hugely beneficial for the design of a wireless underground mine monitoring and communication systems. This is owing to the large variety of networking variables, the rapid technological advancement of ZigBee nodes, and considerable changes in environmental parameters from one mine site to another one.

Thus, the recognition of entire variables is a key component for the evaluation of the reliability of the ZigBee functions and applications in an underground mine. In fact, a system design and a model of ZigBee network are proposed for the verification of the reliability of required underground functions and applications. Ben Maissa et al. (2013) emphasised the necessity of investing WSNs' performance, based on model analysis and validation, before handling critical functions by such systems. Stanley-Marbell et al. (2008) observed the influences of the WSNs' operation considering the variables of the hardware, software and physical limits. They focused on the importance of the recognition of the uncontrollable parameters of the environment and run-time parameters alike to develop a more realistic model and evaluate the performance of WSNs under a system model. These works attempted to provide models of WSNs to predict system properties and challenges associated with cost and time effectiveness on a real project. This chapter will demonstrate that practical investigations to confirm and calibrate the results of such system models, in order to sensibly evaluate controllable and uncontrollable parameters, are crucial in a heterogeneous environment such as underground excavations.

Having selected and simulated ZigBee networks for monitoring and communication systems in underground environments, Moridi, Kawamura, Sharifzadeh, Chanda, and Jang (2014) concluded that recognising and assessing the effective parameters is crucial in designing a ZigBee network. The efforts of (Zarei et al., 2013) posit a method for assessing the principal parameters of tunnels water inflow. Accordingly, the controllable and uncontrollable parameters of a ZigBee network and the surrounding environment are illustrated in Figure 6-1.

There are a considerable number of and localization of nodes and the metrics of the network, are adjustable for better data telemetry in underground mines. The uncontrollable parameters are the number of hops, network congestion and infrequent failures in the reception of data packets. It might be possible to render these parameters controllable within confined spaces. There are also environmental variables of tunnels that are uncontrollable in ZigBee network design as opposed to the known or controllable parameters of tunnel geometry, layout and employed system support. Such uncontrollable parameters include the rate of water inflow fluctuation, the degree of wall surface distortion and roughness, the radio frequency interferences of operating and communication systems, obstacles like dump trucks, boggers, and air compressors, as well as the variation rate of permeability, dielectric constants, and conductivity in the surrounding rock mass along openings.

Therefore, a ZigBee network can efficiently be established after determining the underground effective parameters influencing ZigBee communication signals, and finding the maximum reliable communication distance between nodes in different underground openings with all variables. Thus, quantifying all of the above parameters is a prerequisite for the design of a reliable ZigBee network for underground openings.

The purpose of this chapter is to generalise a ZigBee network model with a more comprehensive and realistic representation of a communication and monitoring system in underground mines. First, the procedure for the establishment of a ZigBee network in an underground mine is described. Then, a system design and model is developed based on the classification of results from an experiment undertaken at an underground mine in Western Australia (an analytical study). After that, another experiment was designed to physically verify the reliability of the proposed ZigBee network model in the underground mine.

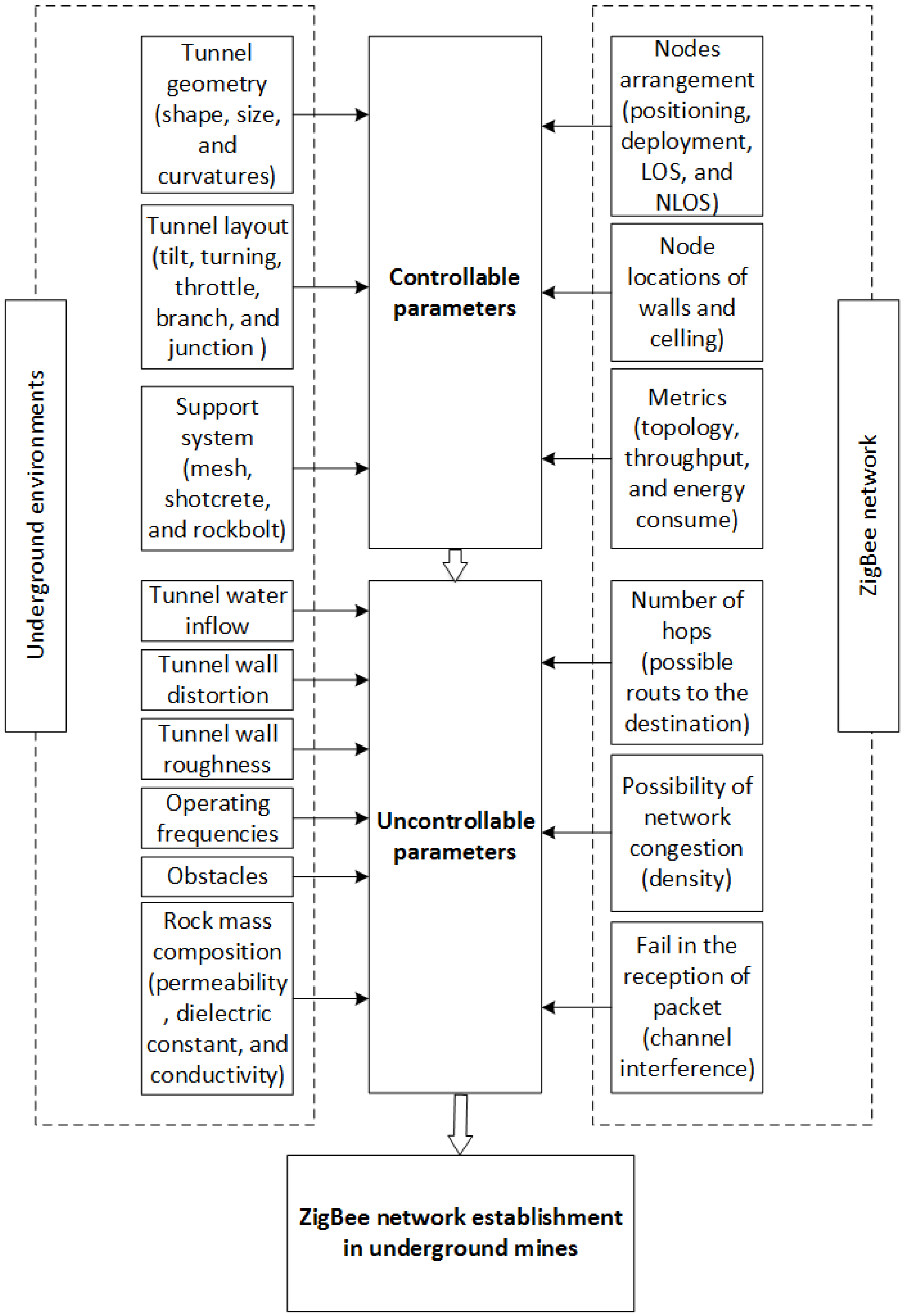


Figure 6-1 Principal steps for assessing a ZigBee network establishment in underground mines

This was be done by the testing system's functions and applications, for example, messages texting and controlling ventilation fan operations as a model testing. Finally, the results of the analytical study and verified experiments are discussed with a subsequent.

6.2 ZIGBEE NETWORK MODELLING IN UNDERGROUND MINES

In order to implement an underground monitoring and communication system, building a model, considering the determination of required functions and applications and the recognition of the variables of network metrics and environmental variables, is necessary for the assessment of technical and economic evaluations.

6.2.1 *System design and modelling*

In order to design

Input, process and output for an underground monitoring and communication system design and model are illustrated in Figure 6-2. Access to basic information including utilising ZigBee nodes technology, desired applications (such as environmental monitoring, ventilation management, or type of communication) as well as mine site details is mandatory for system design and modelling. Normally, for the verification of a system design, system modelling is utilised (Robinson, 2012). Therefore, a pilot experiment must be conducted to operationalise the principles governing the system design and modelling of an underground ZigBee network. The output of the model will lead to a reliable outcome for the required functions and applications.

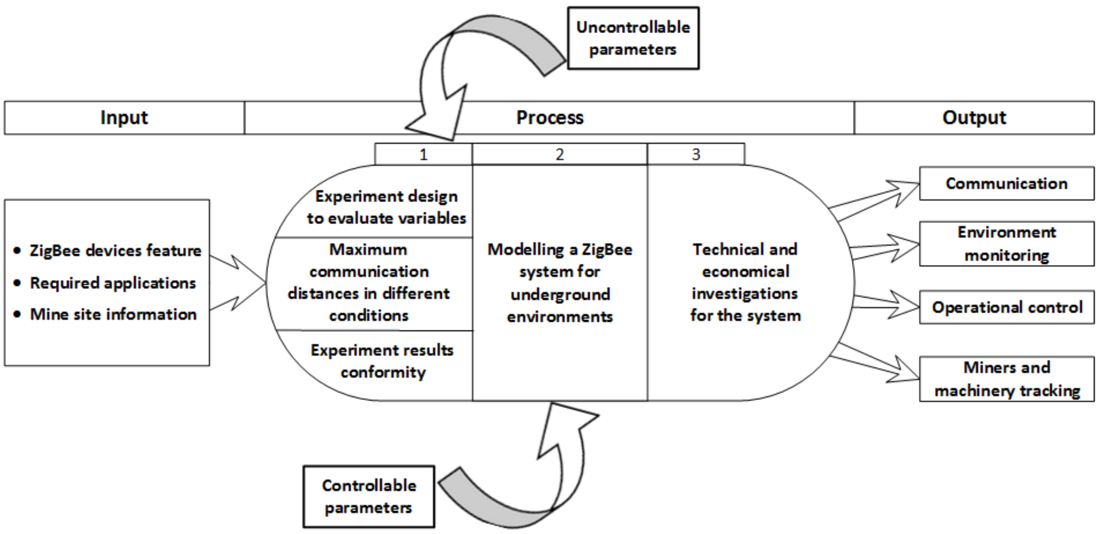


Figure 6-2 Diagram of system design and model of an underground mine monitoring and communication system

6.2.2 *Generalising a model*

The aim of generalising the ZigBee model in underground mines is to be able to implement a systematic feasibility study of technical and economic evaluations, based on the system design and modelled results. This procedure is illustrated in Figure 6-3. Investigations of the ZigBee network model applied in underground spaces are empirically verified. Numerous runs and adjustment ZigBee functions and applications may be required before an adequate and reliable system design is achieved. Results documentation of the process would undoubtedly be valuable for the investment justification and to convince mine managers of the benefits of such an innovative system.

6.3 An underground environment experiment for system design

An experiment is designed to investigate the reliability of a wireless underground mine monitoring and communication system. To this end, the maximum distance of radio communication is evaluated in different conditions of underground environments and ZigBee nodes arrangement and location. After analysis of the measurements and classification of results, the system design for a reliable ZigBee network can be developed for an underground concept.

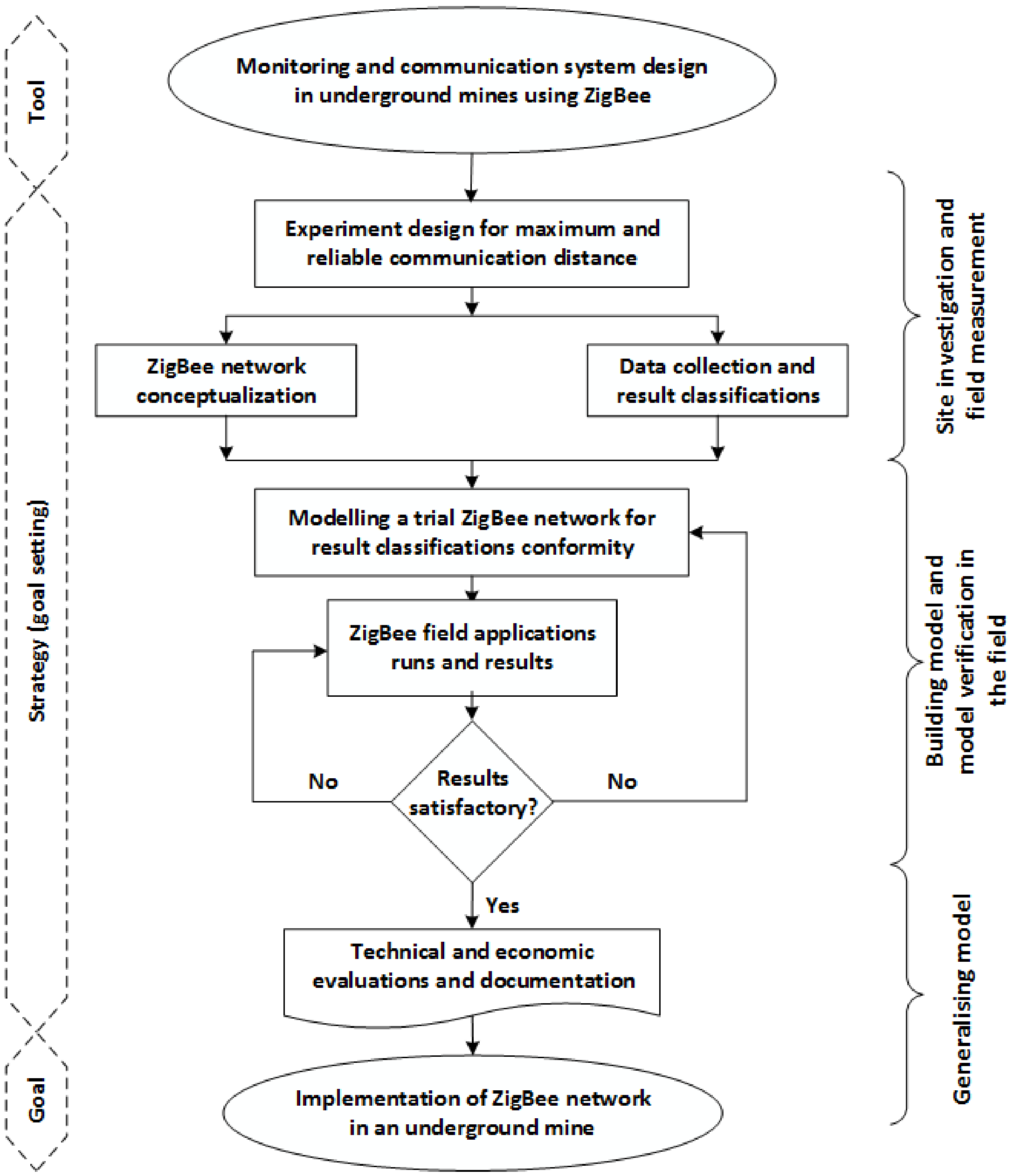


Figure 6-3 Procedure of generalising ZigBee network in an underground mine

6.3.1 *Experiment locations*

An experiment was conducted in Tunnel 11 at level 9415 of a nickel underground mine in Western Australia at a depth of approximately 1000 metres. A layout of the test location in this level is illustrated in Figure 6-4. The test lines in the experiment were conducted in two accesses (415 and 390) of this tunnel. Access 415 is a straight opening whereas access of 390 is a curved opening.

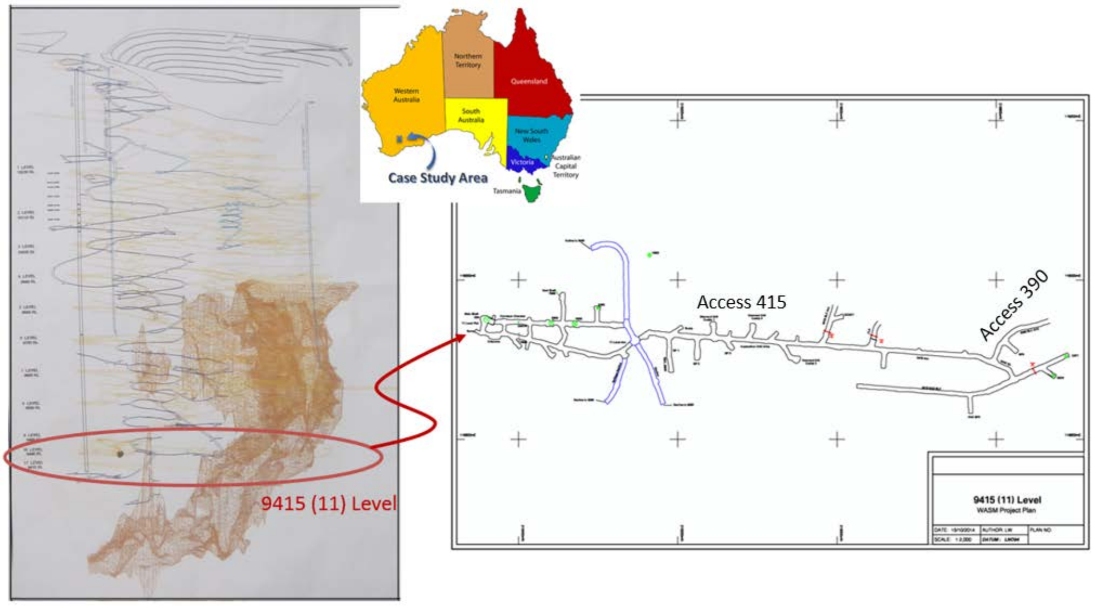


Figure 6-4 Layout of test location in tunnel 11at level 9415m

6.3.2 *Experiment apparatus*

In this experiment, IEEE 802.15.4 standard and ZigBee evaluation development kit (EDK) based on TOCOS engine were employed. One ZigBee Coordinator described as TWE-EK-002-LCD-SIP, two ZigBee routers described as TWE-EK-002-NLC-SIP, one laptop with software development environment (SDK) and TOCOS-TagViewer, two tripods, and one measurement tape was used. The type of ZigBee router (node) used enables measurement of signal strength (LQI) and sensing of environment attributes such as temperature, humidity and luminance. Information recorded by TOCOS-TagViewer is presented in Table 6-1.

Table 6-1 Recorded information by TOCOS-TagViewer

MAC address of Transmitted side: 001BC501 : 20B0075C									
Date	**Time**	**LQI**	**Sequence Number**	**Transmitter ID**	**Transmitter Voltage**	**SHT21 temperature (100 times,**	**SHT21 humidity**	**BH1715 luminance**	**ADC1 (mV)**
11/11/2014	2:05:01 PM	156	15	0b0075c	3070	2917	6428	0	742
11/11/2014	2:05:06 PM	153	16	0b0075c	3070	2917	6423	0	741
11/11/2014	2:05:11 PM	162	17	0b0075c	3070	2917	6423	0	740

6.3.3 *Experiment setup*

The underground attenuation of ZigBee nodes was considered in this experiment. The measurement of WSN's communication distance is attained based on the acceptable radio signal strength of a received data packet in terms of the LQI value. Ha et al. (2013) held that although RSSI provides a traditional metric for radio transceivers, LQI is an effective metric which has become more common in the latest ZigBee transceivers such as Chipcon's CC2420. LQI values indicate that they are more reliable for link quality estimation and have a higher correlation with the distance between two ZigBee nodes compared with RSSI values. The LQI is an integer in the range 0-255 where 255 represents the strongest signal. The relationship between the LQI value and the detected power, P, in dBm for the ZigBee node in this experiment (JN5148), is approximately given by Eq. 6-1.

$$P = \frac{7 \times LQI - 1970}{20} \qquad \text{Eq. 6-1}$$

Eq. 6-1 is valid for 0 < LQI < 255. According to the preceding approach described in 3.5.2, reliable LQI for certain data transmission between ZigBee nodes is assumed to be greater than 50 (-80 dBm). Therefore, the recorded information in this experiment would be analysed on this basis.

6.3.4 *Experiment methodology*

The experiment investigated the attenuation tendency of radio wave intensity. This includes the estimation method of the maximum distance between ZigBee nodes in the different underground conditions based on appropriate LQI for being cognisant of identifiable variables. To this purpose, the test lines were designed where the distance between the two ZigBee nodes increases continuously at certain intervals until the LQI drops lower than the specified limit.

The procedure for LQI measurements in Tunnel 11 of the nickel mine are illustrated in Figure 6-5. In this procedure, the coordinator was connected to the laptop (PC) for recording data while the ZigBee nodes were mounted on tripods to gauge signal strength. For consistency of the results, the measurements were repeated at least 5 times for each interval.

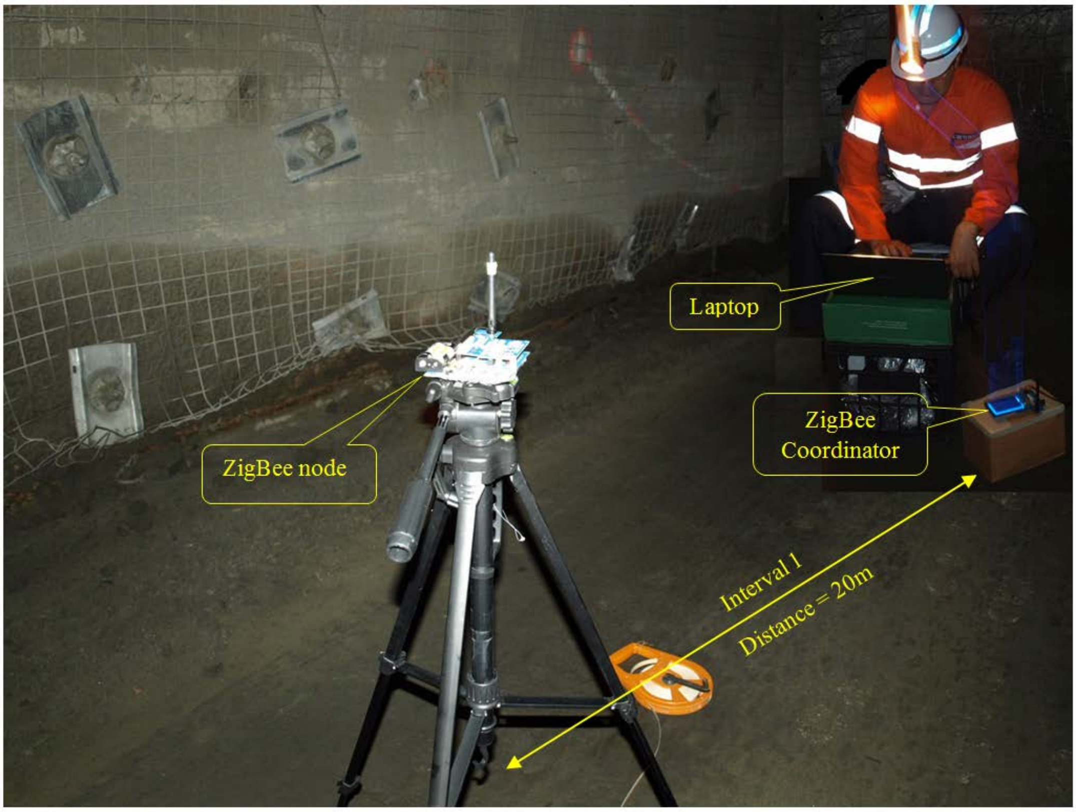


Figure 6-5 Procedure of LQI measurements along the tunnel

6.3.5 *Experiment measurements and results*

The experiment measurements were carried out in five tests lines described below in different conditions at level 11.

I) Test 1

In this test, the ZigBee coordinator was located in the middle of the tunnel at level 11/ 415 access. The ZigBee node was placed on a tripod at a 1.5m height to minimise the signal propagation because of signal's scatter caused by floor's surface and located in the middle of the tunnel at 20m intervals. The test line was then placed in the middle of tunnel isolated from the side effects of the walls and floor. The layout of the tunnel and the position of ZigBee node at each interval are illustrated in Figure 6-6. The fluctuation of the signal strength based on the LQI versus distance increase is also illustrated in Figure 6-7.

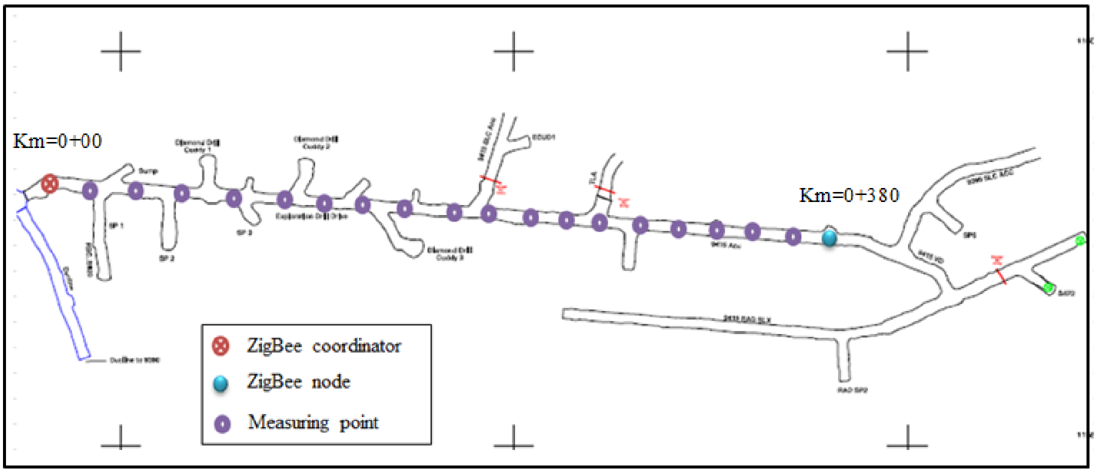


Figure 6-6 Position of the ZigBee node and coordinator at the specified intervals in Test 1

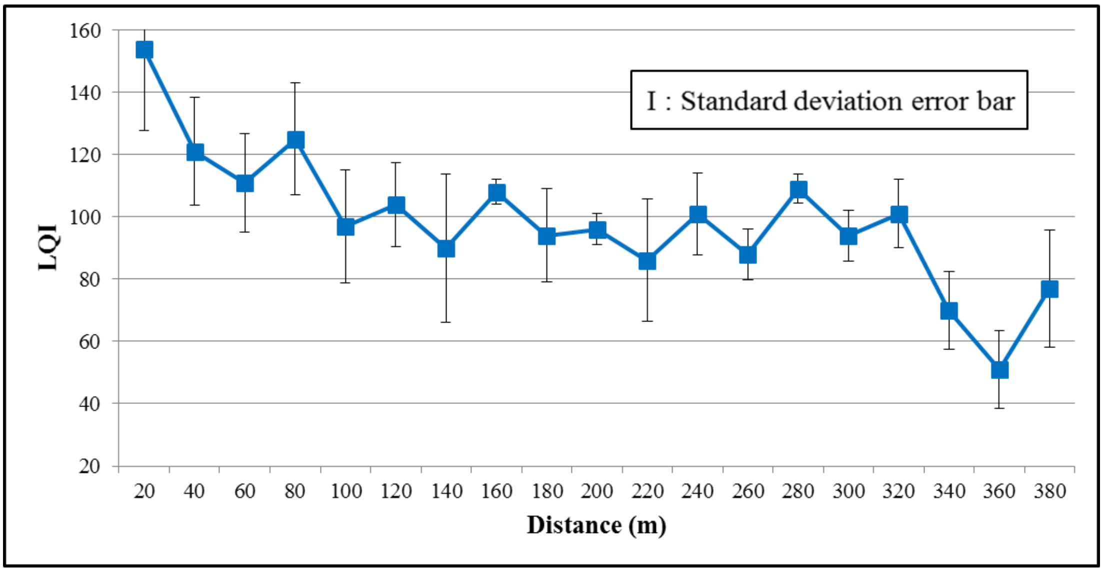


Figure 6-7 Signal strength based on the LQI versus distance increase in Test 1

II) Test 2

The test was performed at the level 11/ 415 access and a ZigBee node was placed on the tripod located close to the tunnel wall at 30m intervals. The coordinator was also close to the wall. The test line was straight and located nearby the tunnel wall. Figure 6-8 shows the position of the ZigBee node at increasing distance remote from the coordinator with the specified interval. The signal strength based on the LQI versus distance increased is also illustrated in Figure 6-9.

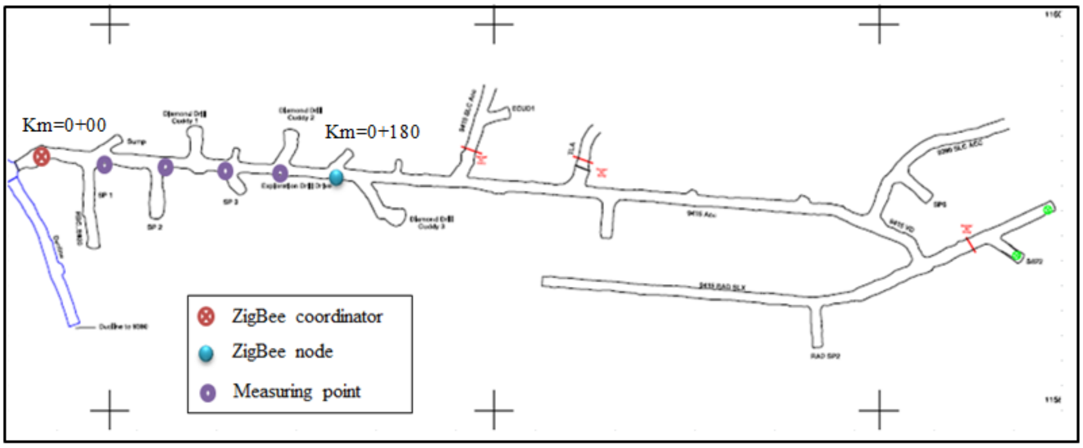


Figure 6-8 Position of the ZigBee node and coordinator at the specified intervals in Test 2

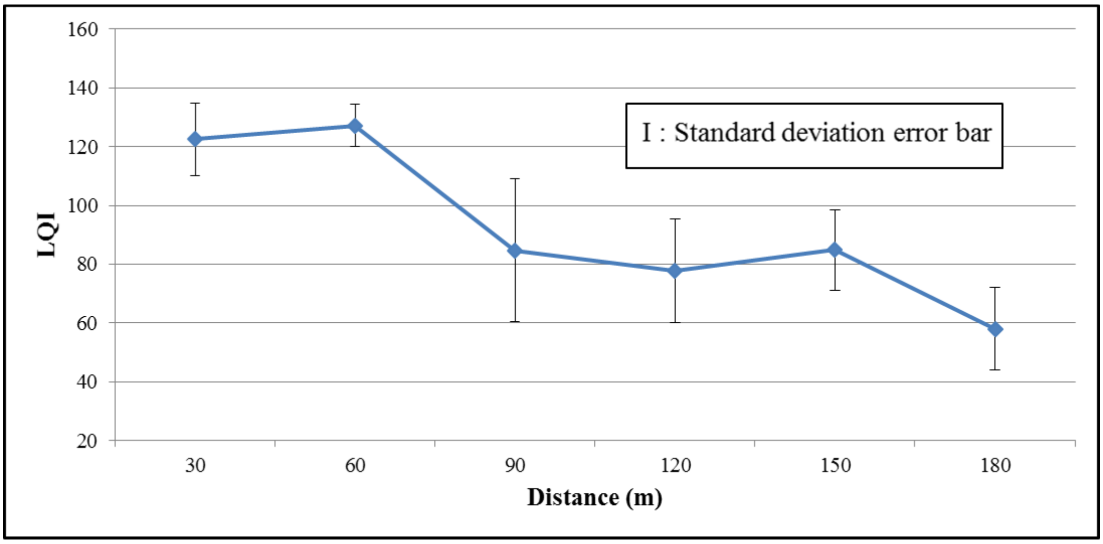


Figure 6-9 Signal strength based on the LQI versus distance increase in Test 2

III) Test 3

The test was performed at the level 11/ 415 access. The ZigBee node was placed on the floor located in the middle of the tunnel at 20m intervals. The test line was situated in the middle of the tunnel located on the floor without tripods. Figure 6-10 shows the position of ZigBee node which is at increasing distance remote from the coordinator with the specified interval. The signal strength based on the LQI versus distance increase is illustrated in Figure 6-11.

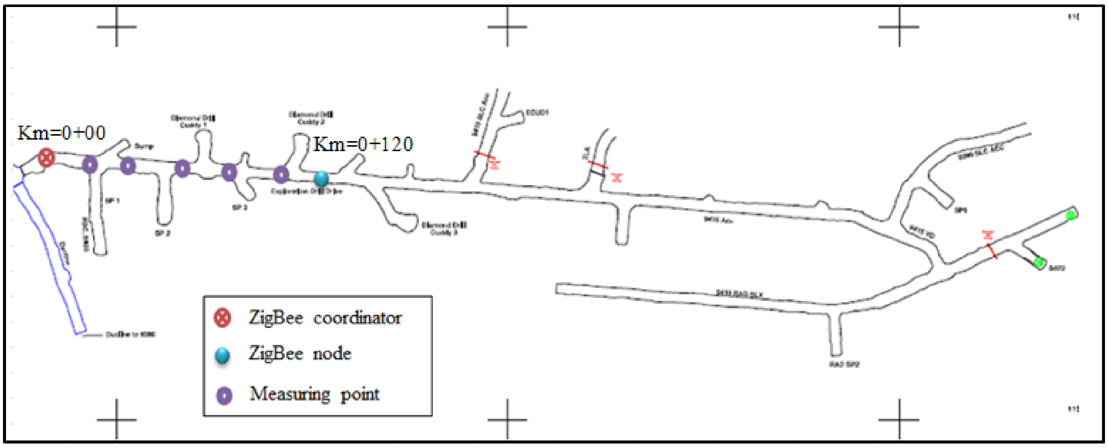


Figure 6-10 Position of the ZigBee node and coordinator at the specified intervals in Test 3

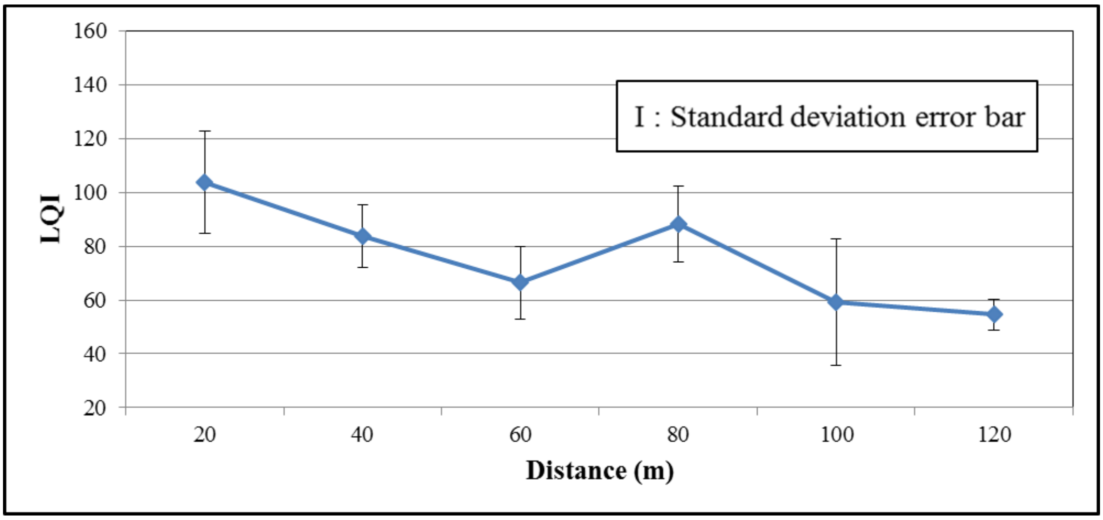


Figure 6-11 Signal strength based on the LQI versus distance increase in Test 3

IV) Test 4

The test was performed at the level 11/ 415 access. The ZigBee node was placed on the tripod located close to the tunnel wall with 20m intervals. The coordinator was on the opposite side to the node position (non-line of sight). Figure 6-12 shows the position of ZigBee node which is at increasing distance remote from the coordinator with the specified interval. The signal strength based on the LQI versus distance increase is illustrated in Figure 6-13.

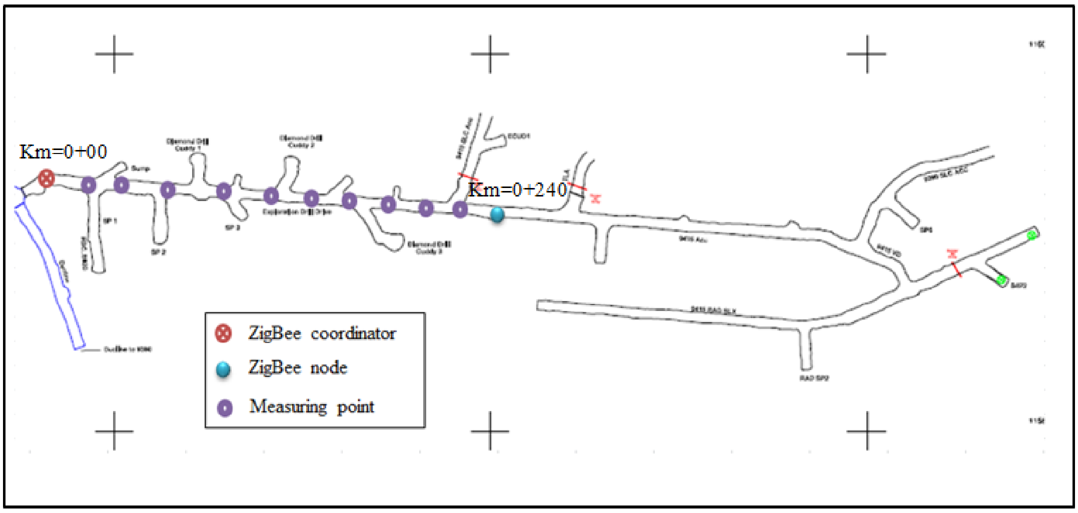


Figure 6-12 Position of the ZigBee node and coordinator at the specified intervals in Test 4

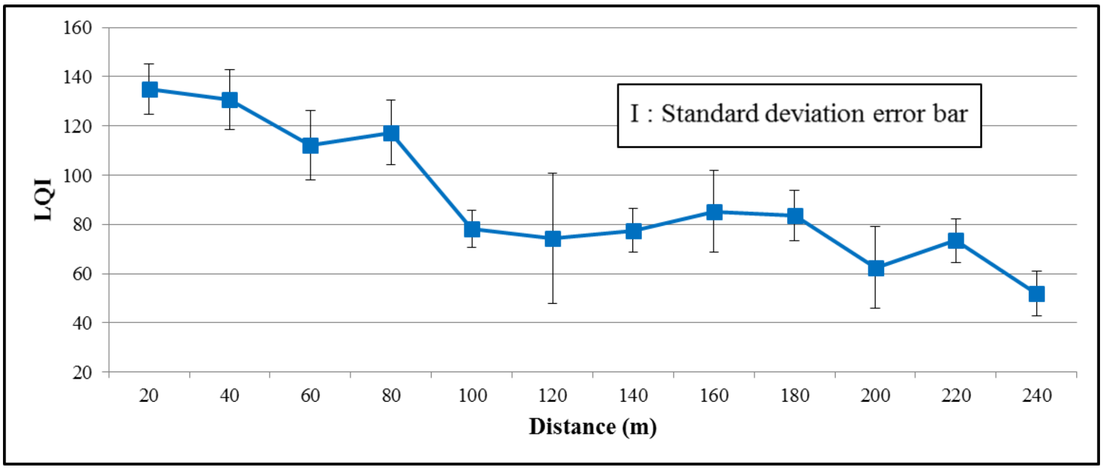


Figure 6-13 Signal strength based on the LQI versus distance increase in Test 4

V) Test 5

The test was performed in a curvature at the level 11/390 access. The ZigBee node was placed on the tripod located in the middle of the tunnel at 20m intervals (non-line of sight) ad at a high dip angle. The test line was located in the middle and far from the walls and floor of the tunnel. Figure 6-14 shows the position of ZigBee node which is at increasing distance remote from the coordinator with the specified interval. The signal strength based on the LQI versus distance increase is illustrated in Figure 6-15.

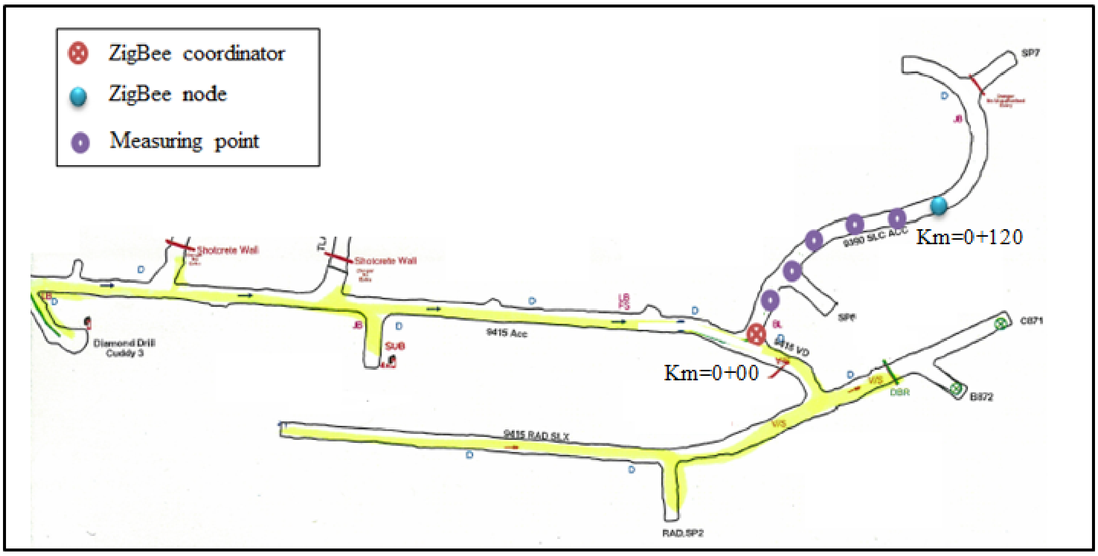


Figure 6-14 Position of the ZigBee node and coordinator at the specified intervals in Test 5

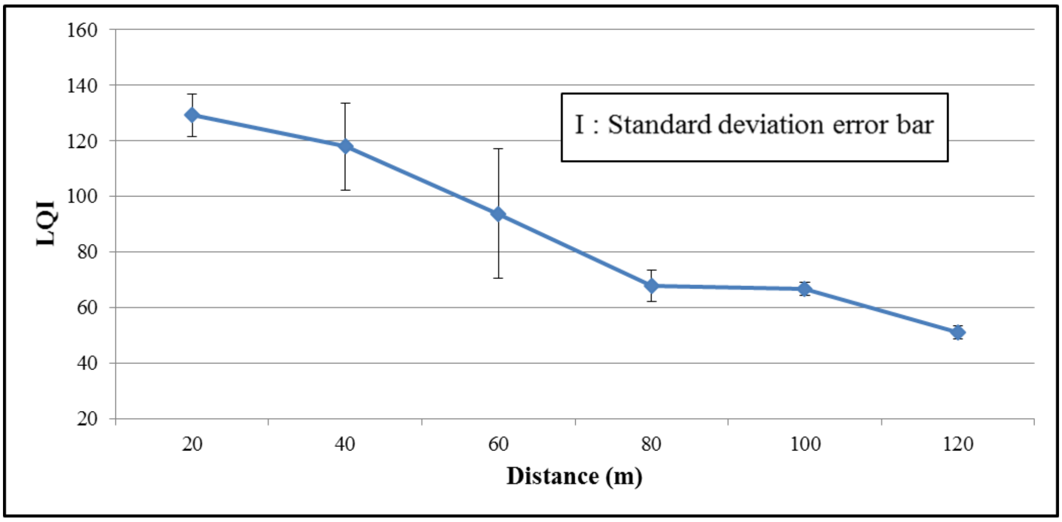
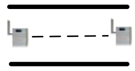
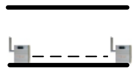
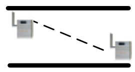
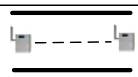
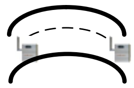


Figure 6-15 Signal strength based on the LQI versus distance increase in Test 5

6.3.6 *Results analysis*

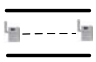
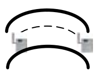
Tests results are briefly summarised in Table 6-2 considering the directional line of sight and non-line of sight and the position of the nodes. The position of nodes in the tests represents the location of the test line from tunnel walls and floor to determine the factors affecting the maximum communication distance. As seen in Table 6-2, the parameters such as the walls roughness and distortion, the floor and the curvature of the tunnel and the arrangement of nodes could substantially impact the signal attenuation and reduced communication distance between ZigBee nodes. That is why an experiment is required to design a wireless monitoring and communication system in every underground environment considering the unique nature and circumstance of each.

Table 6-2 Experiment results - Summary of the maximum communication distance between ZigBee nodes under different conditions

Descriptions		Communication distance (m)	Tunnel plan view Test line
Test line	**Node positions**		
Straight line	in the tunnel axis	380	
Straight line	on the tunnel wall	180	
Diagonal straight line	on the opposite tunnel walls	240	
Straight line	on the floor of tunnel	120	
Curved line	in the middle of curved tunnel	120	

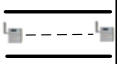
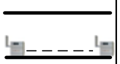
The results are analysed and classified to develop a more rigorous system design of a ZigBee network taking into account relevant factors in the underground openings. The effect of tunnel curvature on communication distance is indicated in Table 6-3. Communication distance leads to a dramatic drop from 380m in a line of sight of radio propagation compared with 120m in a non-line of sight under the similar conditions with respect to support system, test line position from the walls and the floor and the level of the ZigBee nodes. However, tunnel water inflow caused greater attenuation in the line of sight test.

Table 6-3 Classification of results based on the passageway effect

Test line view	Radio propagation regions	Tunnel layout	Support system	Test line position	Node level	Water conditions	Communication distance (m)
	line of sight (LOS)	straight	mesh shotcrete rock bolt	in the tunnel axis	1.5m height	water inflow through a ditch	380
	non-line of sight (NLOS)	curved and inclined	mesh shotcrete rock bolt	in the tunnel axis	1.5m height	dry	120

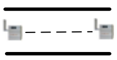
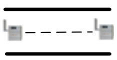
Classification of results based on the tunnel walls effect is indicated in Table 6-4. The communication distance between two ZigBee nodes in a straight tunnel falls rapidly from 380 m to 180 m where the test line changes the location from the middle of the tunnel to nearby the walls. This occurred when the tests were performed where there were similar conditions of tunnel layout, support system, ZigBee node height, and water inflow through a ditch.

Table 6-4 Classification of results based on the tunnel walls effect

Test line view	Test line position	Tunnel layout	Support system	Node level	Water conditions	Communication distance (m)
	in the tunnel axis	straight tunnel	mesh shotcrete rock bolt	1.5m height	water inflow through a ditch	380
	on the tunnel wall	straight tunnel	mesh shotcrete rock bolt	1.5m height	water flow through a ditch	180

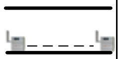
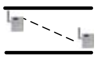
Results classified according to the evaluation of ZigBee nodes level- height effect is indicated in Table 6-5. ZigBee communication distance in this test reduced significantly from 380m to 120m mainly because of nodes placed in close proximity to the floor. In addition to the effect of floor unevenness (increases attenuation), the tunnel floor has an inclination of 0.3%. For this reason, any line of sight tests where the distance between ZigBee nodes was greater than 100 m may have been considered as a non-line of sight test. This explains why the height of nodes placement becomes an important factor in the system design of a ZigBee network in underground excavations.

Table 6-5 Classification of results based on the ZigBee nodes level - height effect

Test line view	Node level	Test line position	Tunnel layout	Support system	Water conditions	Communication distance (m)
	1.5m heigh t	in the tunnel axis	straight tunnel	mesh shotcrete rock bolt	water inflow through a ditch	380
	on the floor	in the tunnel axis	straight tunnel	mesh shotcrete rock bolt	water flow through a ditch	120

Results classified from the evaluation of ZigBee nodes arrangement is indicated in Table 6-6. The communication distance increases from 180m to 240 m provided that the test line changes from a straight to a diagonal one. This derives from conducting tests in similar conditions and ZigBee node levels. Thus, the relative positioning of ZigBee nodes to each other could certainly be a definitive item in optimising an underground system design in terms of cost and energy efficiency.

Table 6-6 Classification of results based on the nodes arrangement effect

Test line view	**Nodes arrangement**	**Tunnel layout**	**Test line position**	**node level**	**Support system**	**Water conditions**	**Communication distance (m)**
	straight line	straight tunnel	on the tunnel wall	1.5m height	mesh shotcrete rock bolt	water flow through a ditch	180
	diagonal line	straight tunnel	on the opposite tunnel walls	1.5m height	mesh shotcrete rock bolt	Water inflow through a ditch	240

Therefore, it is confirmed that factors such as the passageway, the walls and the floor of a tunnel and the level and arrangement of ZigBee nodes have major impacts on radio wave attenuation and consequently on the distance of communication. On the basis of such experiment results, the design of a ZigBee network becomes more sensible taking into account a variety of parameters in an underground context.

6.4 An underground environment experiment for verifying the system design

The purpose of this experiment is to verify the system design of a ZigBee network that has been based on the classified results obtained from the communication distance experiment. This experiment also includes an investigation into the reliability of ZigBee functions and applications, specifically those involving the ZigBee nodes developed by our research group for bilateral underground mine communication (via message texting) as well as remote control of ventilation system. The ZigBee nodes applicable to this experiment are illustrated in Figure 6-16.

6.4.1 *Experiment apparatus*

The system tested is composed entirely of different ZigBee nodes such as coordinator, routers and end nodes. These products were developed in collaboration with Tokyo Cosmos Electric Co., Ltd. The JN5148-EK010 kit (Jennic) stacks were employed to create the ZigBee network. The wireless network is initially generated by the coordinator (gateway) which invites other nodes to join the network. A ZigBee coordinator (gateway) connected to the laptop (PC) used in the experiments is illustrated in Figure 6-16. The coordinator would normally be located in the surface office to allow users to monitor the underground mine, but was located in the tunnel for this experiment. Sending and receiving messages and remote control of ventilation fans are also normally enabled by the surface coordinator.

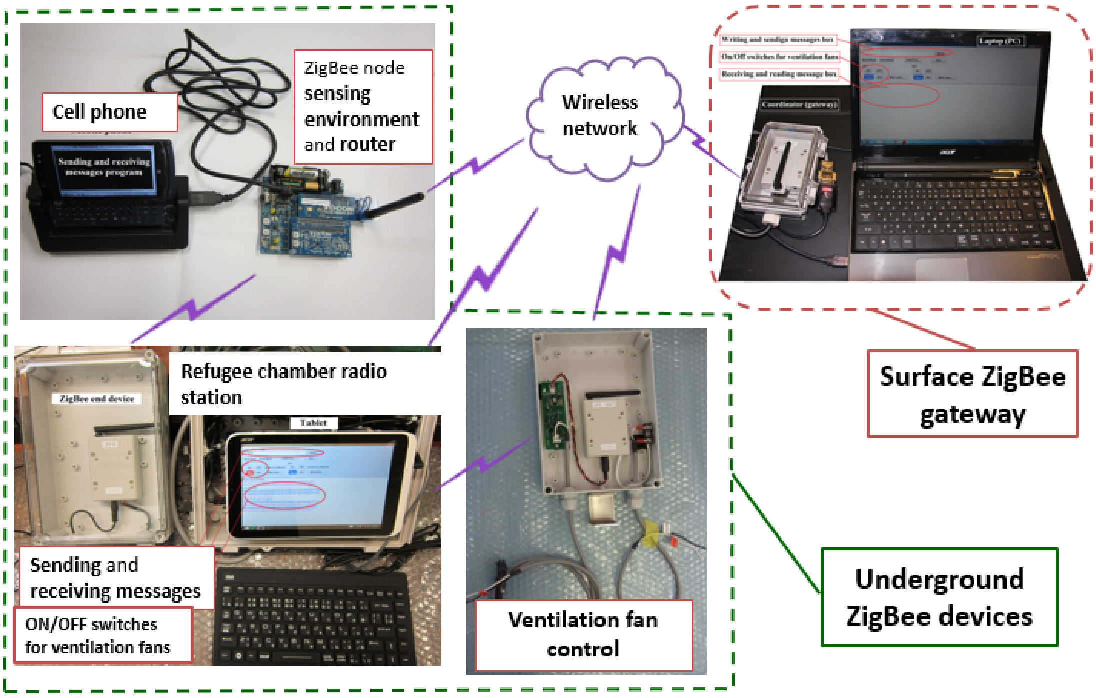


Figure 6-16 Applicable ZigBee nodes for underground environments

Bilateral communication provides wireless connections between the coordinator and a radio station (end device) to send and receive messages and data readings taken and delivered by sensors. It is advantageous to locate the radio station including a ZigBee node and a tablet in a refugee chamber in the event of an emergency, particularly where there is a failure of primary communication systems such as telephones or leaky feeders. The extended capability of the ZigBee node connection to a cell phone is another communication support option between miners and refugee chambers or surface operators.

Ventilation fan control is also provided by the ZigBee node using the ability to wirelessly connect to the fans. A screenshot of the designed program showing on PCs (laptop and tablet) with ON/OFF switches and receiving/sending messages is illustrated in Figure 6-18. There are separate command icons for each auxiliary fan in the program. Routers are manufactured with the ability of real-time sensing of the environment as well as relaying communication signals throughout the network. A digital temperature, humidity and luminance compound sensor on board of each JN5148, with advanced sensitivity and continued stability, were utilised for the experiment. ZigBee nodes were placed in the boxes to minimise adverse environmental effects on their operation.

Alternating current (AC) power was required for the ZigBee coordinator and radio station (end-device). Therefore, the test line to establish the ZigBee network selected based on the availability of power points on level 11. Routers were used which were compatible with direct current (DC) power between 9 and 32 volts. In this experiment, a 12-volt battery was used.

6.4.2 *Experiment setup*

To set up the experiment, the coordinator was first turned on and connected to the laptop to save and monitor data and also to establish an automatic wireless network to join routers and end devices to the network. The applicable ZigBee nodes were arranged at level 11 based on the classification of results of the last experiment to verify the design of the system. This is illustrated in Figure 6-17. Also, the coordinator was located in refugee chamber connecting to the power point which was supplied with 220 volts. The first router's preferred location is in a line of sight from the coordinator at the specified maximum distance. Otherwise, an imbalance in the number of nodes in the system design will affect network performance negatively. For example, if a ZigBee network with a high density of nodes is used, the ability to control traffic congestion will be affected as well as impact overall economic costs. On the other hand, if there are fewer nodes over a greater communication distance, the reliability of communication would be the main concern for network performance. As a result, an accurate appraisal of optimally arranged nodes for the ZigBee network, as was done during the system design experiment, must include consideration of the controllable and uncontrollable parameters. The ZigBee network was constructed in accordance with the outcomes that appraisal the total length of the ZigBee network was 365 m and had a total of 5 nodes through the level 11 as shown in Figure 6-17.

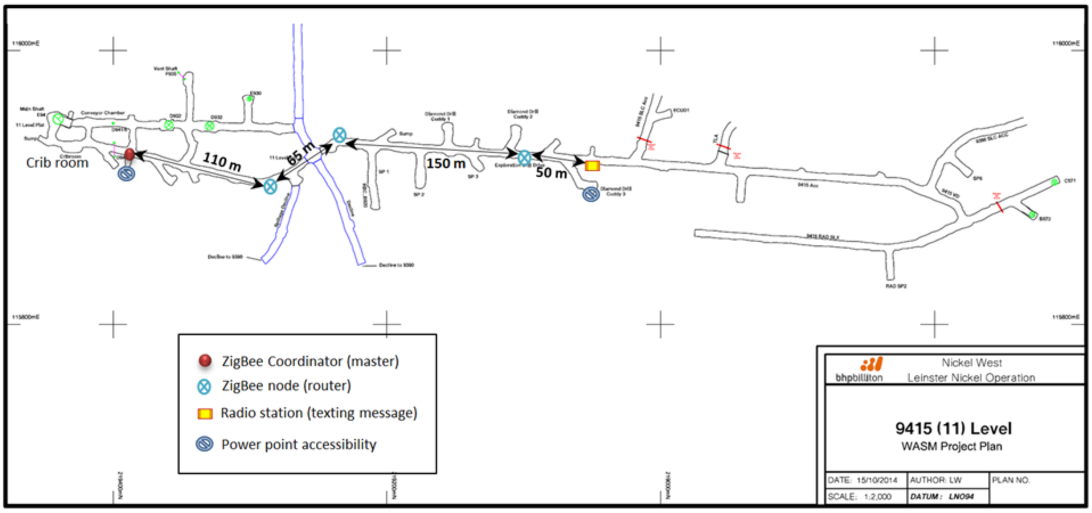


Figure 6-17 Arrangement of ZigBee nodes for the verification of the system design

6.4.3 *Experiment results*

The radio station was mounted at the end of the test line to communicate with the coordinator through the other nodes. Successful communication between coordinator and radio station is illustrated in Figure 6-18 where the messages sent (as red) and received (as blue) were transmitted from the coordinator to the radio station. As shown in Figure 6-18, the ControlTerm program was configured both on the laptop which was connected to the coordinator as well as the tablet connected to the radio station.

In summary, these experiments demonstrated that wireless sensor networks can significantly improve the efficiency of underground monitoring regarding personnel, plant, and equipment location, operational readings, and communications. They also verified that ZigBee network performance of a carefully designed system is reliable for underground wireless monitoring and communication systems.

The results show that stable communication distances for ZigBee nodes are sustainable up to 360 m and up to 120 m in straight and curved tunnels, respectively. Additionally, the following outcomes were successfully achieved: the real-time monitoring of underground spaces in terms of temperature, humidity and illumination and the control of ventilation system by a master node (coordinator) as well as communication between nodes.

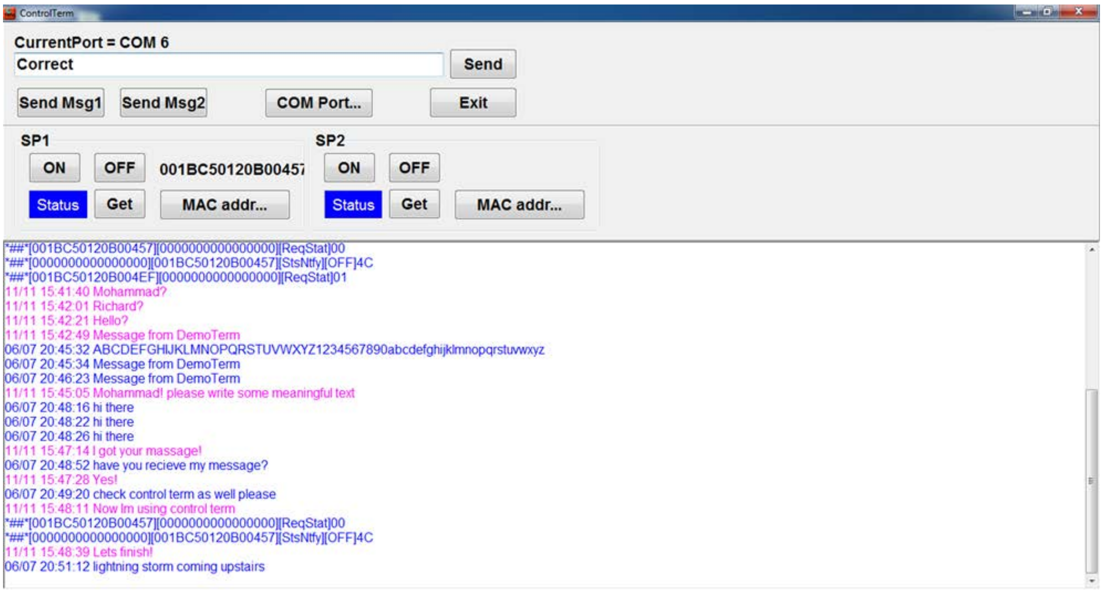


Figure 6-18 ControlTerm program to send (red) and receive (blue) messages from the coordinator to the radio station

6.5 CONCLUSION

In this chapter, a procedure for a system design of ZigBee networks for underground mines was generalised. It shows the implementation of ZigBee networks is initially based on the system design specifications. These specifications themselves are determined from the investigation of reliable and maximum communication distances under different conditions. Specifications may not be applicable unless the effects of all controllable and uncontrollable parameters are appraised and assessed at maximum distances. Since every underground mine site has varying controllable and uncontrollable parameters, experiments have to be individually designed when developing a functional model. Furthermore, technical and economic evaluations can be undertaken using this model.

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CHAPTER 7. CONCLUSIONS AND FUTURE WORK

The study set out to explore a reliable monitoring and communication system for underground mines. The reasons were to make a contribution to mining automation so as to improve mining safety and health as well as operational management in such adverse environments. To this end, an integrated system considering new technologies of wireless sensor networks (WSNs) and GIS was proposed. The main findings of the thesis and connections across the chapters are illustrated in Figure 7-1. These findings can be classified as theoretical and empirical discoveries. Theoretical findings on WSNs in underground environments in the second and third chapters were illustrated where the selection of an adequate networking through reviewing the literature and investigating the radio wave propagation and attenuation in underground openings were performed. The empirical findings of the performance evaluation, system integration design, and generalising model for ZigBee networks were examined and analysed in the fourth, fifth and sixth chapters respectively.

The aim of the second chapter of the study clearly sought to answer two questions. First, what is the history of WSNs in underground mines? As ZigBee network is one technology of WSNs, it is crucial to review past work utilising other technologies in underground mines. The evaluation of sensors' ability for underground mining in the literature strengthened the importance of this study on the subject. The services of WSNs were classified in monitoring environmental features, communication, and target tracking which enable mitigating significant concerns in underground mines. Second, how ZigBee technology was proposed and how it significantly benefits the improvement of monitoring and communication systems for underground mines. It also attempted to analyse the applications, stack, routeing protocols, topologies, reliability, and the security of ZigBee network. Then, the strengths and weaknesses of ZigBee network to establish such system in underground spaces were examined.

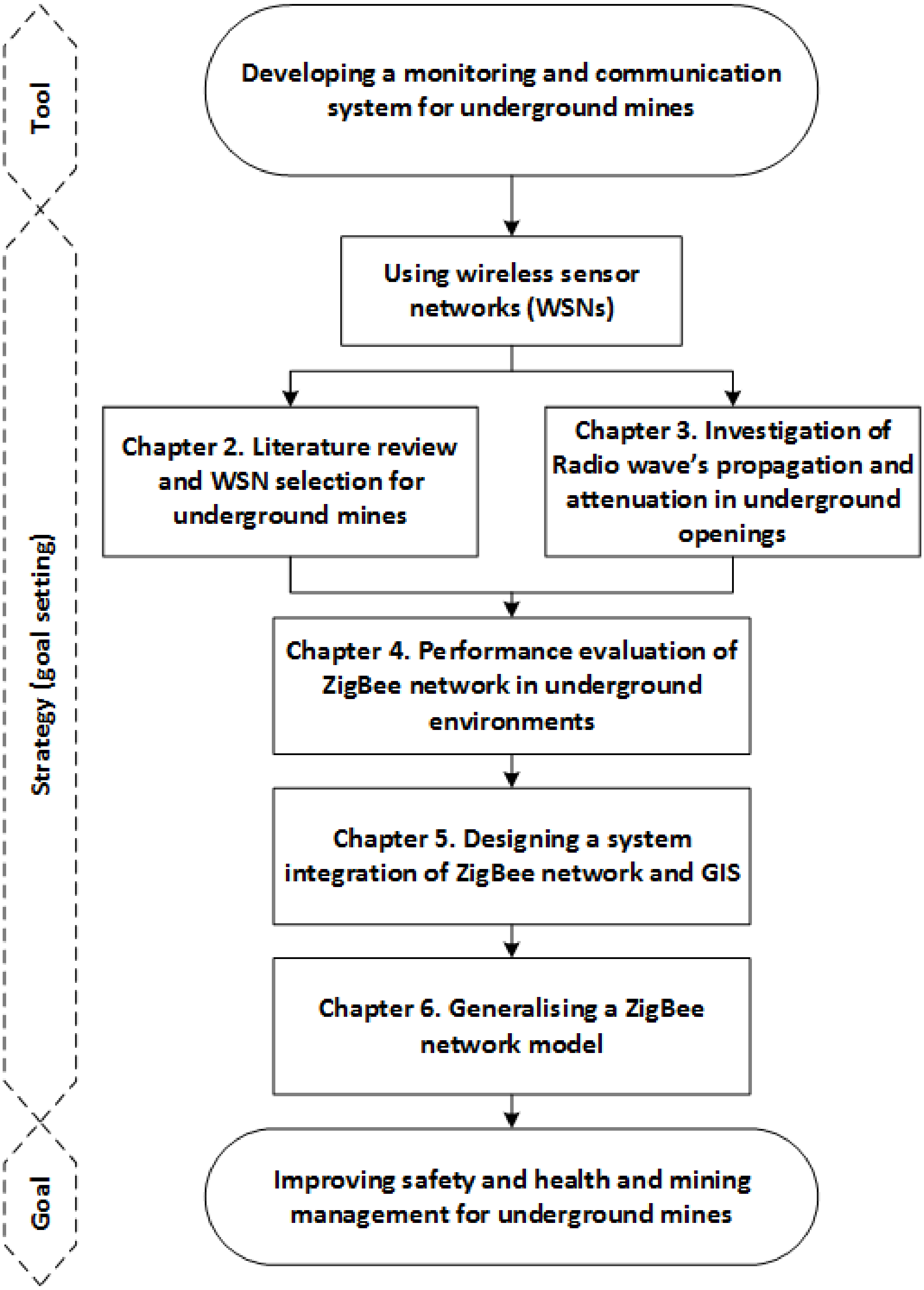

Figure 7-1 Main findings of the thesis and links across to the chapters

It is logical that an investigation of radio wave propagation in confined spaces is fundamentally mandatory to develop a ZigBee network covering all the levels of an underground mine. A gold mine in South Australia was utilised for testing. Therefore, chapter three examines the current models of radio wave propagation in tunnels, and experiments and simulations were set out to answer the following questions: how some factors of underground environments affect the behaviour of radio waves and what is the methodology and simulation of investigating a stable communication distance in tunnels. Although certain ZigBee nodes that were used in the experiments with a limited number of tunnels, they did show a certain distance of a stable communication and the consistency of experimental and simulation results supports the validity of radio wave equations for underground mine environments.

The evaluation of network performance and security is another attempt that has to become a precedent in developing a monitoring and communication system in underground mines. Chapter four covered the answers of which network topology makes the ZigBee system more secure with appropriate network metrics for the purpose of underground mine operations. The simulation results showed that mesh topology is a better option for greater throughput, packet delivery ratio and network security with lower latency data and energy consumption. The approaches represent the optimal arrangement of nodes in terms of the economic and technical assessments for underground mine monitoring and communication systems.

An information system for data collection and a process is required to quickly respond to underground events when ZigBee network is transferring data. Thus, the ZigBee network integrated with GIS was proposed in chapter five. It explains how the system integration utilising ZigBee and GIS for underground mine monitoring and communication operates. Additionally, automatic and remote trigger action plans for measured environmental attributes to control mining operations are developed. Multi-users surface operation and 3D visualisation for the realistic understanding of the underground environment and miners' conditions could also have other obvious implications of this system integration.

To this point, all experimental and simulation results that propose an underground mine monitoring and communication system were analysed based on the data collection limited to the certain types of ZigBee nodes for the certain underground mines. In other words, every underground mine site has its own environmental and operational parameters which affect radio wave propagation. Also, the progress of technology in ZigBee node's features is significant. Therefore, chapter six generalises a model for monitoring and communication systems at any underground environment using ZigBee networks. This model was then verified by conducting experiments in an underground nickel mine in Western Australia. The first experiment was carried out to find maximum and stable communication distance between ZigBee nodes in the presence of the surrounding parameters. This was the basis in designing the monitoring and communication system for that underground mine. The second experiment was performed to evaluate specified ZigBee functions and applications in the levels of that underground mine in order to verify the system design in the first experiment. Finally, the generalisation of the model was approved the reliability of establishment of ZigBee networks in underground mines through achieving the successful experimental findings.

The future work for the establishment of a reliable monitoring and communication system must interact between surface and underground operators so it covers all mobile and fixed functions and applications based on the ZigBee technology. The prospect of a proposed ZigBee communications system is illustrated in Figure 7-2.

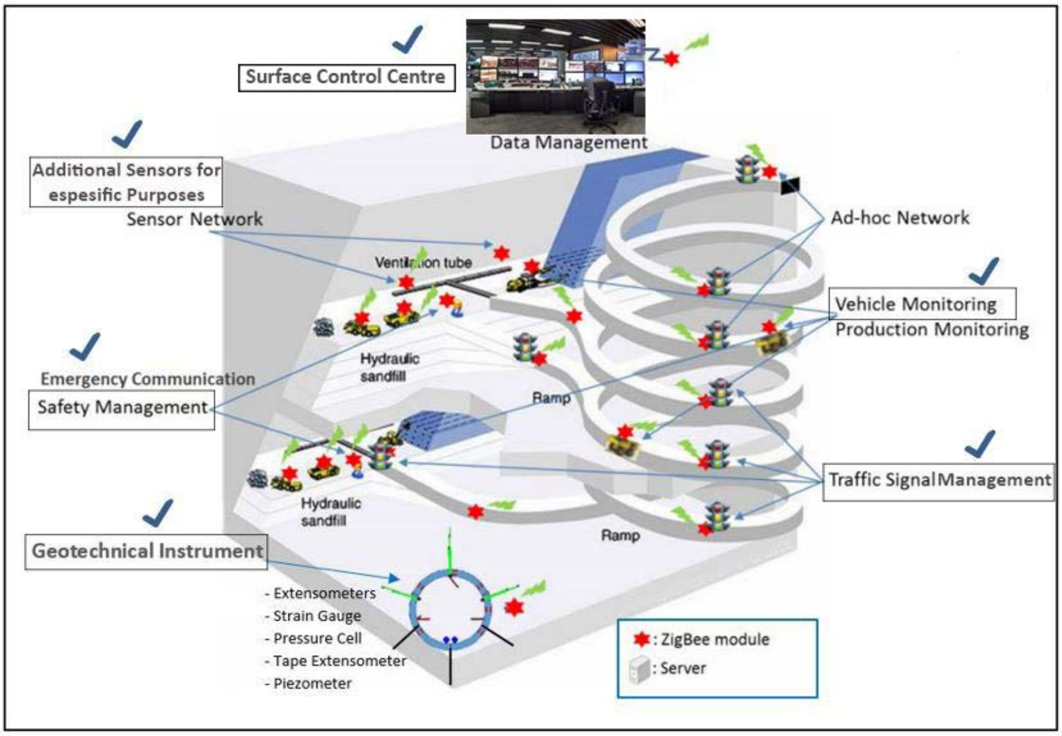

Figure 7-2 Prospect of proposed communications system in underground mine site

This system enables for real-time monitoring and communication between surface operators and the functions and applications of underground mines. That is, it is able to join all stationary and mobile sensors with different duties such as data-reading of the geotechnical instrument, tracking of the miners and the plant machinery, controlling the ventilation system, and managing the traffic signals from the surface. It is an essential tool for underground mine automation to improve project management in the era of safety, health, economic, cost and operations. These approaches consider the sensor node's abilities and the applications requirement, and are generally classified as follows:

(a) Safety and health approaches

- Air quality and quantity measurements
- Determination of workers' locations
- Emergency and safety communications
- Gas detector and fire alarm
- Geotechnical instrumentation

(b) Operations management and control

- Real-time monitoring of underground mining from a surface control centre
- Improving the underground operation cycles (scheduling)
- Traffic control (Signals)

As seen in Figure 7-2, some functions and applications which were not covered in this study are marked for further investigation. Furthermore, to establish such a robust and reliable monitoring and communication system on the basis of data telemetry using ZigBee nodes (without access points), there are still more concepts to be tested and verified. Particularly, there is a need to analyse the reliability and accuracy of the ZigBee network for tracking mobile nodes.

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APPENDIX A: SIMULATION PROGRAM OF REMCOM TO FIGURE OUT THE RSSI VALUES IN TUNNELS

A simulation program of REMCOM was used to calculate the RSSI values based on the received power of rays' reflections on the walls' surface of tunnels and the source. Wireless InSite 2.7.0 (June 2013) was utilised as an electromagnetic modelling tool for predicting the effects of buildings and terrain on the propagation of electromagnetic waves. It predicts how the locations of the transmitters and receivers within an urban area affect signal strength.

Wireless InSite is capable of modelling signal propagation for virtually any indoor environment. Floor plans may be read into Wireless InSite from CAD files, such as DXF, or they can be created from scratch using the Wireless InSite Floor Plan Editor. This editor allows the user to create a custom indoor environment by specifying wall locations, wall heights, ceilings, floors, windows, and doorways. The material properties of each of these structures can be changed to accurately reflect the real environment.

The calculations are made by shooting rays from the transmitters, and propagating them through the defined environment. These rays interact with environmental features and make their way to receivers. Interactions include reflections from feature faces, diffractions around objects, and transmissions through features. Wireless InSite uses advanced high-frequency electromagnetic methods to provide accurate results over a frequency range from approximately 50 MHz to 100 GHz. The effects of each interaction along a rays' path to the receiver are evaluated to determine the rays' electric field. At each receiver location, contributions from arriving ray paths are combined and evaluated to determine predicted quantities such as electric and magnetic field strength, received power, interference measures, path loss, delay spread, direction of arrival, impulse response, electric field vs. time, electric field vs. frequency, and power delay profile.

Radio wave propagation model in tunnel:

To simulate radio wave propagation in our cases (tunnels), Full 3D Model in REMCOM was selected because two ray tracing methods are available with the FULL 3D model including the Shooting and Bouncing Ray (SBR) method and the Eigenray method.

Ray tracing models based on a geometrical optics (GO) approach is investigated in this study for simulation results. The excitation plane is used in the GO model based on Sun (2010) study on the evaluation of EM field distribution. According to this method, the summation of all rays' powers receiving from all reflection points and the source are computed.

Tunnel environment model:

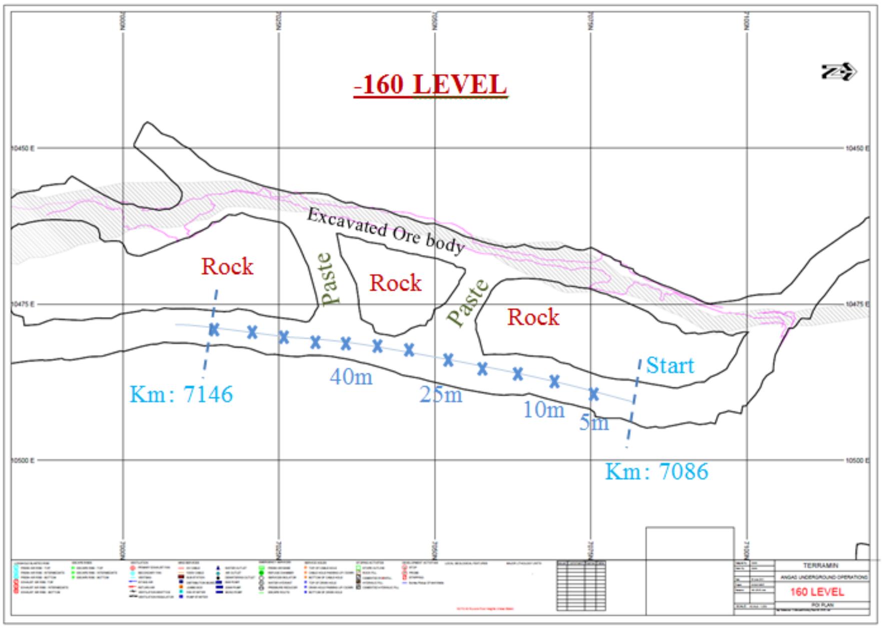
The tunnel cross section size is defined with a height of 5.5 m and a width of 5.5 m; the tunnel wall, ceiling, and floor are made of the same material with electrical parameters ε (permittivity) = $4\varepsilon_0$, σ (conductivity) = 0.01 S/m; the tunnel interior is filled with air (ε = ε_0, σ = 0 S/m). The transmitting power is 3 dBm with the central frequency of 2.4 GHz band. The transmitting and receiving antennas are horizontally polarized dipoles at the same height. Both antennas of the transmitter and receiver in the model are defined approximately at the centre of the tunnel width, and the walls of mine tunnels are presumed smooth.

Simulations:

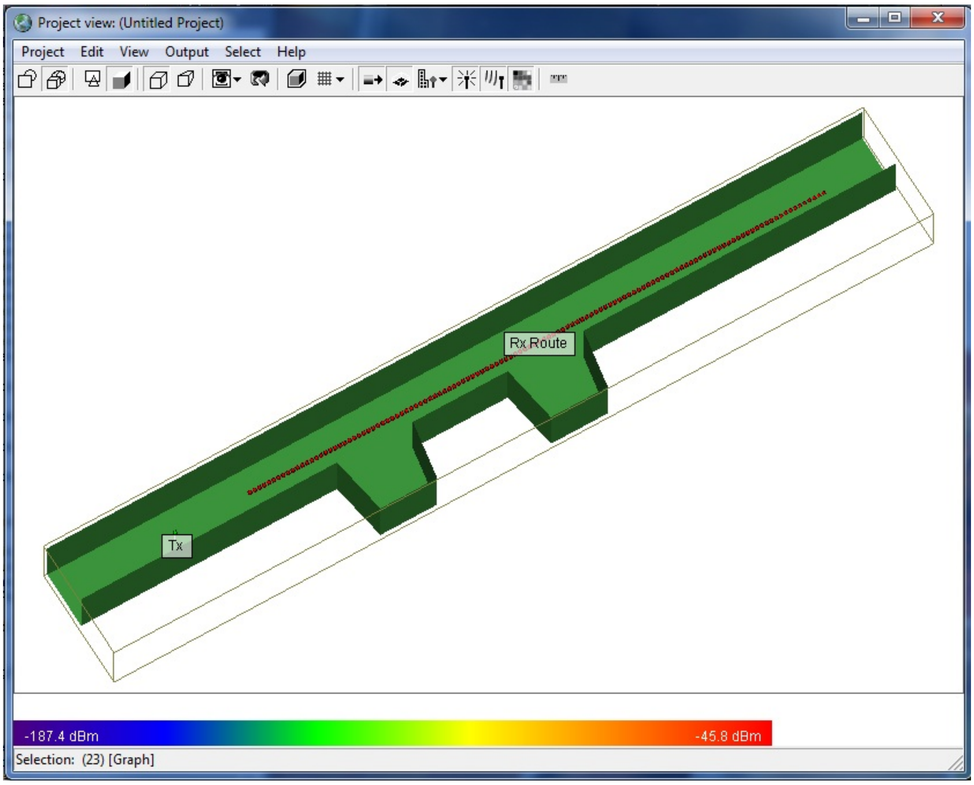
A. Straight tunnel

Indoor design is used for radio wave investigation for tunnel channel in Wireless InSite (REMCOM software). In the tunnel case, thickness of walls, floors and ceilings are assumed 100 m.

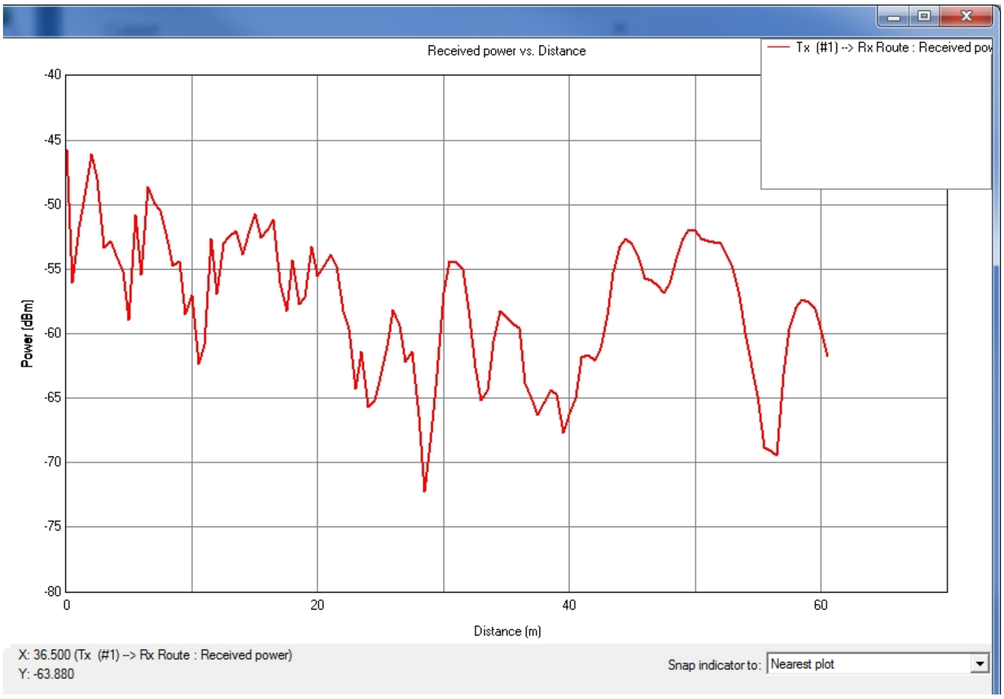
2.4 GHz narrowband Sinusoid waveform and a Half-wave dipole antenna are created in the project. Transmitter point and receiver routs are designed 1.5m above the floor.



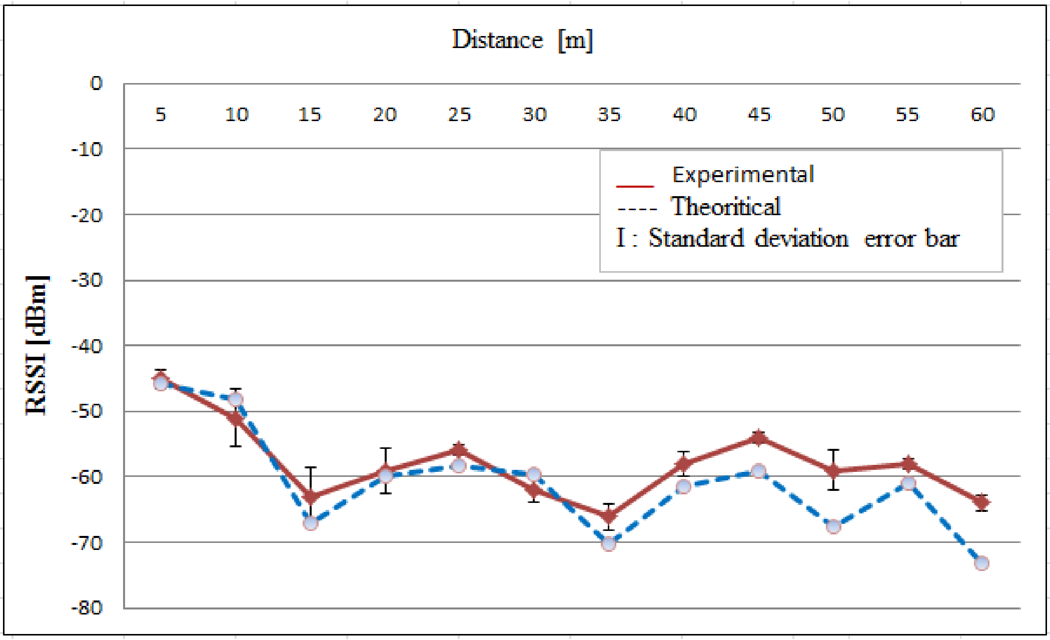
Tunnel at a 160 m depth



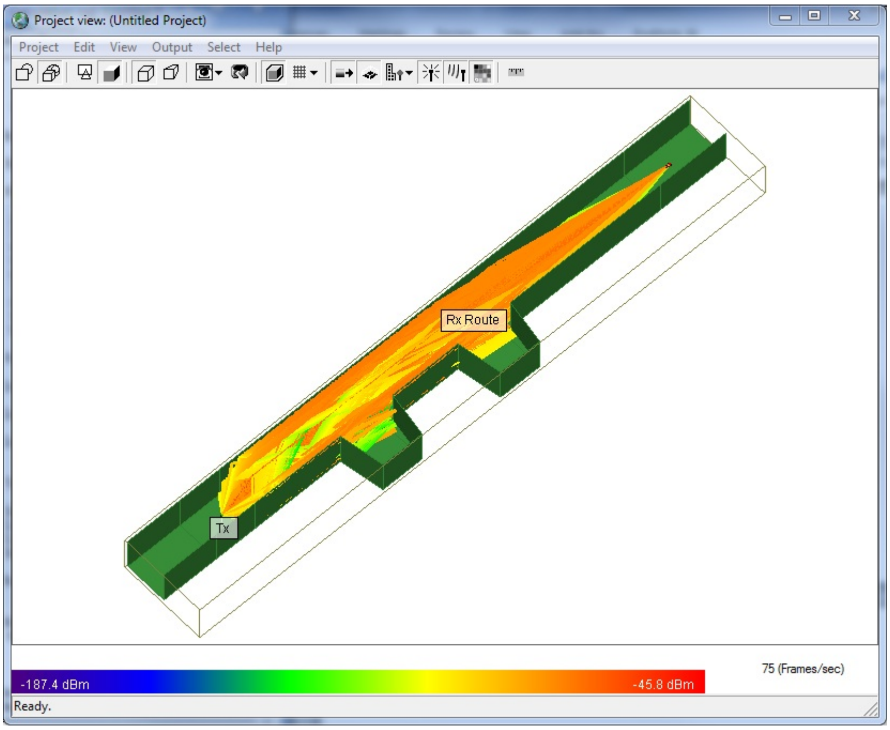
Model of straight tunnel



Received power via distance with 0.25 m interval of receivers



Experimental and theoretical received Power at 2.4 GHz in the straight tunnel

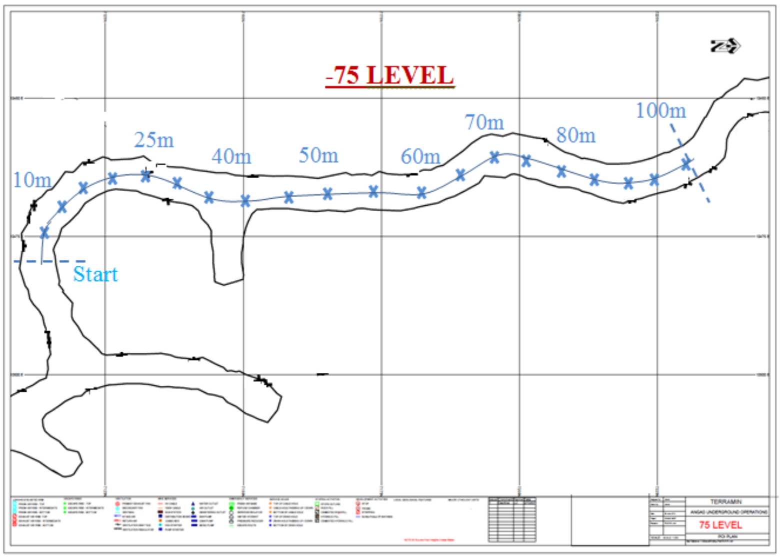


Viewing the propagation paths to the receiver point v in the straight tunnel

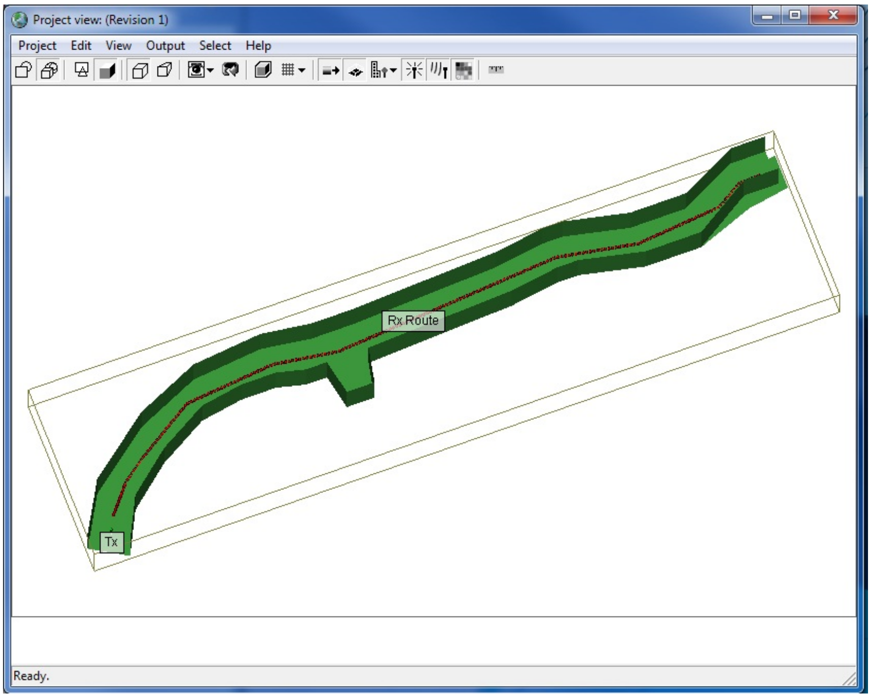
B. Curved tunnel

In the Curved tunnel case, the environmental properties and radio wave characteristics are set the same as straight tunnel parameters.

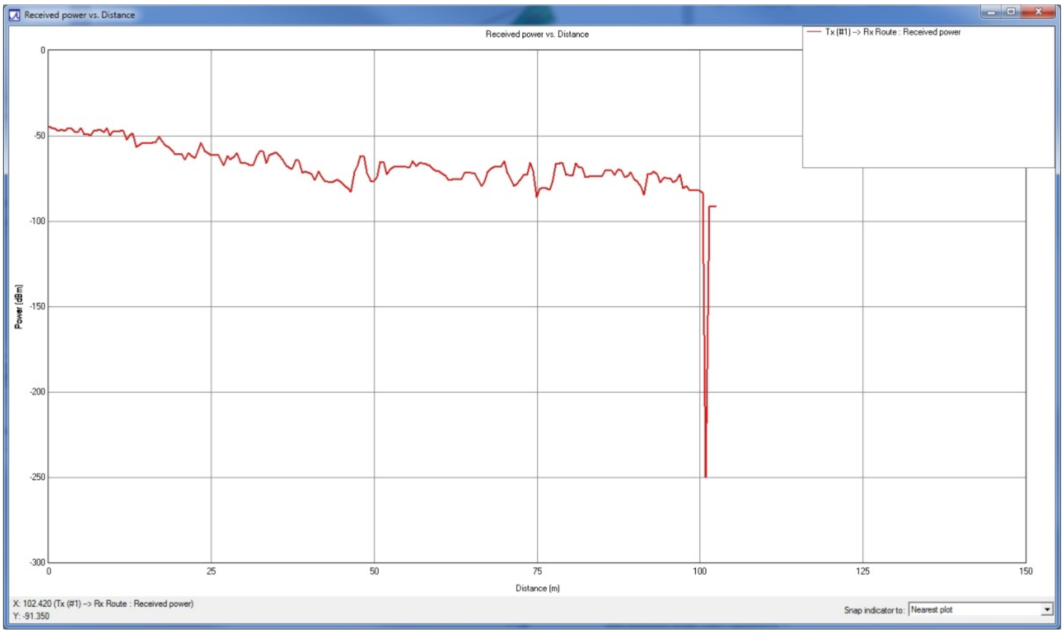
Design and comparison between theoretical and experimental results are shown in the figures below.



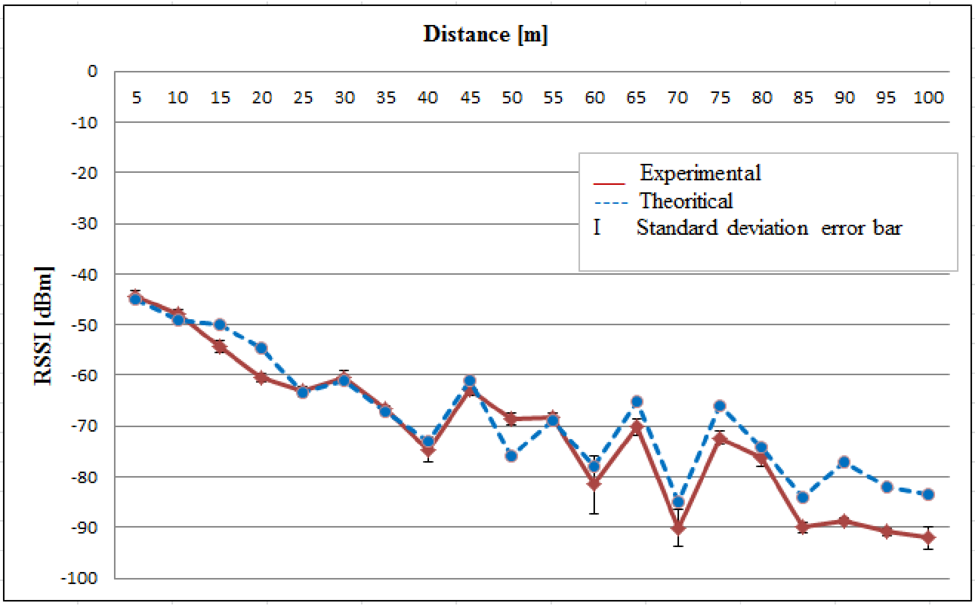
Tunnel at a 75 m depth



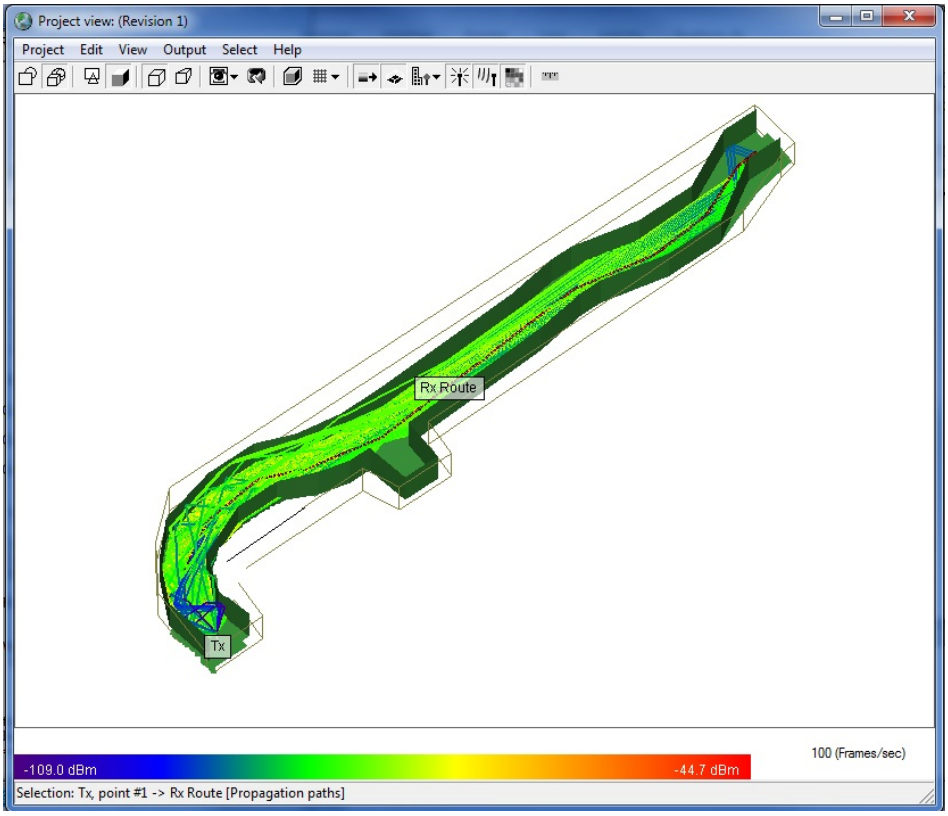
Model of curved tunnel



Received power via distance with 0.25 m interval of receivers



Experimental and theoretical received Power at 2.4 GHz in the curved tunnel



Viewing the propagation paths to the receiver point in the curved tunnel

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APPENDIX B: UNDERGROUND SCENARIO DESIGN USING QUALNET SIMULATOR

QualNet is one of the network simulators that mimic the behaviour of a real network. A network simulation is a cost-effective method for developing the early stages of network centric systems. Users can evaluate the basic behaviour of a wireless sensor network and test combinations of network features that are likely to work. QualNet provides a comprehensive environment for designing protocols, creating and animating network scenarios, and analysing their performance.

QualNet is composed of the following tools:

- QualNet Architect — A graphical experiment design and visualization tool. Architect has two modes: Design mode, for designing experiments, and Visualize mode, for running and visualizing experiments.

- QualNet Analyser — A graphical statistics analysing tool.
- QualNet Packet Tracer — A graphical tool to display and analyse packet traces.
- QualNet File Editor — A text editing tool.
- QualNet Command Line Interface — Command line access to the simulator.

I) QualNet Features and Benefits

QualNet is a comprehensive suite of tools for modelling large wired and wireless networks. It uses simulation to predict the behaviour and performance of networks to improve their design, operation and management [2].

QualNet enables users to:

- Design new protocol models.
- Optimize new and existing models.
- Design large wired and wireless networks using pre-configured or user-designed models.
- Analyse the performance of networks and perform what-if analysis to optimize them.

The key features of QualNet that enable creating a virtual network environment are:

- Speed

QualNet can support real-time speed to enable software-in-the-loop, network emulation, and hardware-in-the-loop modelling. Faster speed enables model developers and network designers to run multiple “what-if” analyses by varying model, network, and traffic parameters in a short time.

- Scalability

QualNet can model thousands of nodes by taking advantage of the latest hardware and parallel computing techniques. QualNet can run on cluster, multi-core, and multi-processor systems to model large networks with high fidelity.

- Model Fidelity

QualNet uses highly detailed standards-based implementation of protocol models. It also includes advanced models for the wireless environment to enable more accurate modelling of real-world networks.

- Portability

QualNet and its library of models run on a vast array of platforms, including Windows and Linux operating systems, distributed and cluster parallel architectures, and both 32- and 64-bit computing platforms. Users can now develop a protocol model or design a network in QualNet on their desktop or laptop Windows computer and then transfer it to a powerful multi-processor Linux server to run capacity, performance, and scalability analyses.

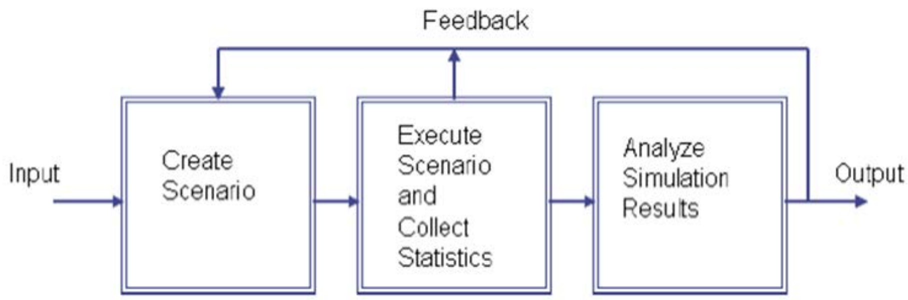
- Extensibility

QualNet can connect to other hardware and software applications, such as OTB, real networks, and third party visualization software, to greatly enhancing the value of the network model.

II) Scenario-based network simulation

In QualNet, a specific network topology is referred to as a scenario. A scenario allows the user to specify all the network components and conditions under which the network will operate. This includes: terrain details, channel propagation effects including path loss, fading, and shadowing, wired and wireless subnets, network devices such as switches, hubs and routers, the entire protocol stack of a variety of standard or user-configured network components, and applications running on the network. Most of these are optional; you can start with a basic network scenario and specify as much detail as necessary to improve the accuracy of your network model.

III) General Approach



Scenario-based simulation

Underground ZigBee network simulation

I) Simulation setup

The main objective of our study to analyse and compare two ZigBee topologies under protocol 802.15.4 for varying traffic loads and find an optimum nodes arrangement using QualNet. In a simulation model of underground mine consisting of a vertical shaft and connected by several horizontal tunnels , mesh (peer-to-peer) and tree (cluster) topologies are performed with one PAN Coordinator and different numbers of 12, 20, 30, 40 and 50 nodes. The nodes are selected coordinator (router) or end device depends on their applications in the network topology. These scenarios are simulated considering a real underground mine in an area of 1000m length and 1000m depth. Other simulation parameters are listed in the table followed.

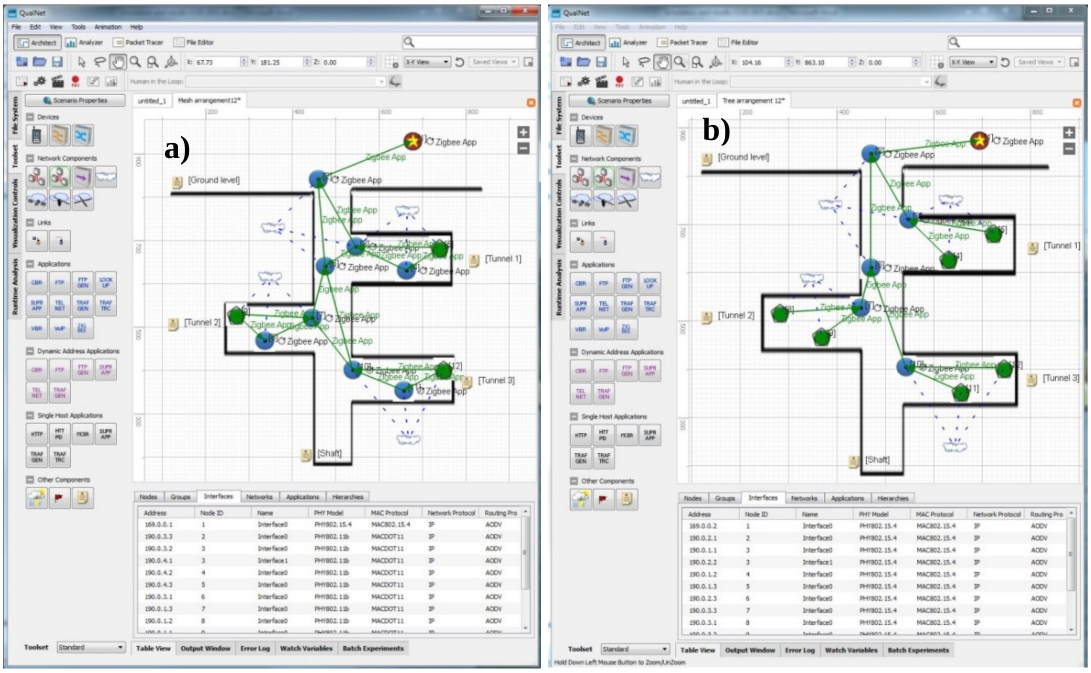
II) Underground scenario design

In the scenarios, only one PAN co-ordinator is considered as a final sink server for data processing and delivery to communicate with other source nodes in a multi-hop system. In other words, a wireless network between surface PAN co-ordinator and underground source nodes as full function devices including co-ordinators and end-devices is created. In our simulation scenarios all the nodes including Pan Coordinator, full function devices and end-devices are stationary.

Simulation parameters and node configurations

Parameter	Details
Node placement	Stationary
Number of nodes	12, 20, 30, 40 and 50
Network topology	Mesh and Tree
Area of simulation	1000m*1000m
Channel frequency and data rate	2.4GHz and 250kbps
Physical and MAC models	802.15.4 radio
Energy model	MicaZ
Battery model	Simple linear,1200 mAh
Transmission Power	3 dBm
Antenna model	Omnidirectional
Modulation scheme	O-QPSK
Routing protocol	AODV
Path loss model	Two Ray model
Traffic	ZigBee application
No. of items and Payload Size	100 and 127bytes
Simulation time	10mins

Scenarios are separately designed for mesh and tree topologies associated with the different number of 12, 20, 30, 40 and 50 nodes. Following figure illustrates 12-node scenarios of mesh and tree topologies, respectively. In these topologies, a full-function devices plays roles as a router to transfer (or relay) data for next source nodes and as a sensor node to sense environment around itself as well. While an end-device enables to sense and send data to the nearby nodes. ZigBee applications are used to evaluate traffic loads between pair of nodes with the property of sending 100 packets and each packet size including 512 bytes which are active during simulation time.



View arrangement of ZigBee nodes. a) Mesh topology, b) Tree topology

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