PERFORMANCE ANALYSIS OF WIRELESS MESH NETWORKS FOR UNDERGROUND MINES

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ABSTRACT

Underground mines are harsh environments that have unique challenges that limit wireless communication. To ensure the safety and efficiency of mining operations, communication systems play a vital role. Despite the major developments in communication technologies, underground mines are still challenging environments for wireless communication, however, the advent of wireless mesh networks offers a cutting-edge solution to the mining industry and understanding the performance of this technology is fundamental to its application in dynamic areas of underground mines. This research project aims at conducting a performance analysis of wireless mesh networks by developing a prototype system set up of wireless mesh transceivers to conduct a feasibility study of data transmission on the network in underground mines. The second aspect of this study investigates network parameters, such as latency, throughput, and signal-to-noise, as a function of increasing mesh nodes on the network and internode spacing of mesh nodes. By combining theoretical models with real-time performance of the mesh system, realistic conclusions and better recommendations can be given to mining companies with regards to deploying wireless mesh systems in their underground mines.

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LIST OF COMMONLY USED ABBREVIATIONS

ADC	Analog-to-Digital Converter
DAC	Digital-to-Analog Converter
DSP	Digital Signal Processor
FCC	Federal Communication Commission
GB/s	Gigabits Per Second
LD	Laser Diode
LED	Light Emitting Diode
M2M	Machine to Machine
MIMACS	Mine Wide Integrated Monitoring and Control System
MINERS	Magnetic Inductive Networked Rescue System
mmwave	millimetre-wave
MST	Mine Site Technology
PED	Personal Emergency Device
PLC	Power Line Communication
SDR	Software Defined Radio
TTE	Through the Earth
TVWS	TV White Space
TVWSD	TV White Space Devices
TVWSDB	TV White Space Data Base
TX	Transmitter
UWB	Ultra-Wide-Band
VLC	Visible Light Communication
WAP	Wireless Access Point
Wi-Fi	Wireless Fidelity
WRN	Wireless Repeater Node

CHAPTER ONE

1. INTRODUCTION

1.1 Scope

Communication is the art of transferring data signals from one location to another in order to relay information [1]. In all sectors of human influence, communication is key to improved productivity and efficiency. Proper communication infrastructure enables people to share information which then results in the growth and development of communities, businesses and industries.

Major developments in telecommunications (3G, 4G, 5G and Wi-Fi) have positively influenced the quality of life in the society, businesses and production rate in many industries [2]. However, despite these developments, the mining industry is one of the industries that is still lagging in the development of communication systems that are best suited for its harsh environments. During mine accidents (rock burst or fire), in some instances, the lack of proper communication systems has frustrated rescue operations and as a result, many lives of mine workers have been lost [3].

In South Africa, the mining industry has set to improve the efficient use of resources through automation of equipment and to improve the safety of mine workers through miner tracking systems [4]. This step requires the use of digital wireless communication systems that are reliable and capable of transmitting real-time data from underground mine workers and equipment to the surface mine operators in the control room. The advantages of having a good communication system for the mines are enormous, from improved mine production efficiency to improved safety of mine workers [5] [6].

There are several cutting-edge connectivity solutions that are applicable to the mining industry, and these leading technologies include wired Ethernet, optical fibre, power line communication, Wi-Fi, visible light communication and wireless mesh networks [6] [7]. Typical applications that can run on these networks range from basic network applications e.g. file transfer protocol (FTP), voice over internet protocol (VoIP) and video conferencing to telemetry applications.

Wired communication systems, such as the leaky feeder technology, a wired transceiver of radio signals, are common in underground mines today [8]. However, these wired systems impose serious challenges in laying out a wired network in every corner of the mine, firstly because wired networks are not easily scalable due to the limitation in rolling out a network cable in every corner of the mine, the cost implications associated with labour and the fact that it takes way too long to install a workable wired network, makes wired networks a challenge to work with.

Another major disadvantage associated with wired networks is that in the event of a mine accident, such as a roof slide, rock burst, flooding or fire, resulting in mineworkers being trapped, if enough infrastructures are damaged, these wired systems prove worthless and unreliable. In such catastrophic events, it is imperative that communication between trapped miners and mine operators is maintained so that a speedy rescue operation can be carried out.

Wireless mesh networks offer an alternative cutting-edge solution that makes use of simple low-cost wireless routers that can be installed strategically in underground mine tunnels without the need for any fixed wired infrastructure. Understanding the performance of wireless mesh networks in these environments is thus imperative and cannot simply be done by simulation or mathematical modelling because simulation and mathematical models fail to accurately model the real and physical mining environment [9]. As such, a proof of concept is a vital tool for researchers to accurately analyse the performance of a system and in the process, expose the gap between theoretical modelling done in simulation and the real-time performance of a system in a real and physical environment [9].

This research project focuses on building a proof of concept mesh network that will be used to analyse the performance of wireless mesh networks in an actual underground mine.

1.2 Motivation

Wireless mesh networks are one of the new technologies in telecommunication that has the potential to provide communication for both indoor or outdoor environments and the harsh environments, such as underground mine tunnels. However, there are still performance challenges associated with deploying wireless mesh networks in such environments and some of these challenges include transmission range and throughput, as well as the choice of routing protocols on mesh routers, among other challenges.

In addition, the available research work on wireless mesh networks is mainly based on simulation work and mathematical models and this is a problem mainly due to the huge gap between theoretical models and the real-time performance of the system [9]. Research work based on simulation only gives a rough estimate of the performance of the network and this is not 100% accurate.

Therefore, this research work focuses on building a wireless mesh network that will be used to conduct experiments in underground mines. The results obtained will then be used to analyse the performance of a wireless mesh network in an actual underground mine.

1.3 Objectives

This dissertation will focus on defining the mesh technology and constructing a proof of concept mesh system. The second objective is to analyse the performance of this technology in an actual underground mine. There are three main goals in this project:

- To determine the latest digital communication system for data, voice and video communication in underground mines.
- Constructing a proof of concept system to be deployed and tested in an actual underground mine.
- Analyse the performance of the communication system.

1.4 Contribution

There is very little publication on the deployment and performance analysis of wireless mesh networks in real harsh environments. This research work will contribute to the following:

- Summarized literature study of current communication technologies that are applicable to the mining industry, highlighting their advantages and disadvantages.
- This work will contribute to the understanding of the performance of wireless mesh networks that are deployed in underground mines.
- This work will assist many other researchers in understanding the challenges associated with building and deployment of wireless mesh networks in harsh mining environments.

1.5 Communication system requirements

System requirements as set by Schauenburg System state that the latest digital communication technology that can provide communication for underground mines must be defined using the latest digital technologies. The system test set up of transceivers must be developed to be tested in underground gold, lime and chrome mines. The transmission range of the transmitter (TX) must be at least 100m with a maximum transmission power of 500mW and a data rate of at least 1MBps. The transceivers are to be used in the stope of an underground mine and are thus required to be mobile and portable and should allow for at least 100 devices to be connected to them. Telemetry applications will be fundamental to the use of transceivers in the underground mines, however, if the transceivers can handle video, voice and text, the better.

1.6 Research question

This dissertation will aim to answer the following research question: What is the performance of wireless mesh networks in providing data, voice and video communication in underground mines? To answer the proposed research question, a good research methodology needs to be followed.

1.7 Research methodology

Figure 1 depicts an overview of the research methodology that will be used to achieve the main project objective. The methodology that has been selected for this project is an empirical quantitative approach of evaluating the performance of wireless mesh networks by way of practical experimental research. The first step is identifying and defining the problem to be solved. The second is conducting a literature review of various communication systems applicable to the mining environment in order to collect as much information as possible that will then be used to formulate engineering solutions. Once this is achieved, a suitable communication system will be chosen for implementation. A prototype of the chosen system will then be designed and developed to conduct the tests in different environments. Standard network parameters will be measured by varying the network topology and the results collected from the different testing environments will then be used to analyse the performance of the communication system. This approach will help to achieve the objective of this research, to know and understand the performance of wireless mesh networks in underground mines.

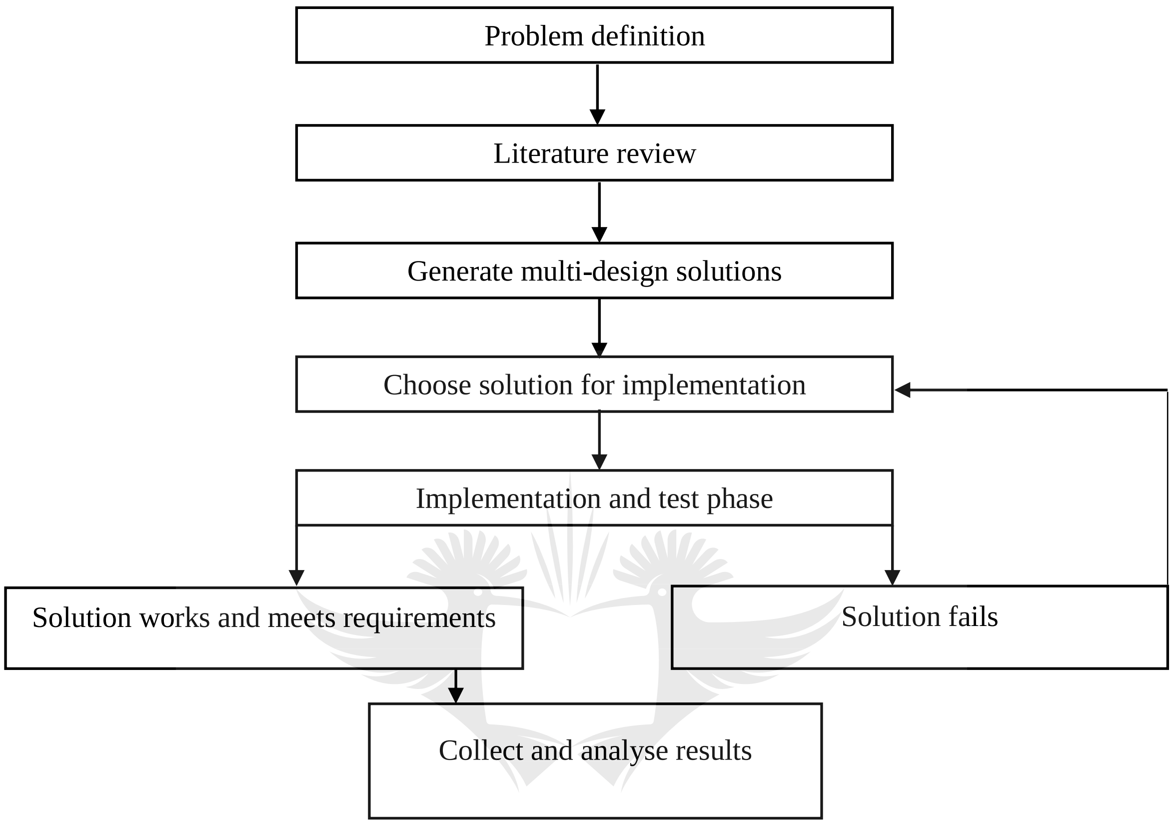

Figure 1: Research methodology overview

1.8 Structure of the dissertation

The structure of the rest of this dissertation is as follows:

- Chapter 2 presents a literature review of suggested wireless communication systems from research fields and existing implemented wireless communication systems that are applicable to underground mines.
- Chapter 3 presents a detailed literature study of a wireless mesh network, the chosen communication system to answer the research question.
- Chapter 4 discusses the mesh system design and the experimental design that will be used to conduct experimental tests.
- Chapter 5 discusses the physical construction of the proof of concept test system. The focus in this chapter is on the components that make up a mesh system and the associated cost implications of constructing such a proof of concept test system. Furthermore, the implementation of a mesh system and the associated challenges are also presented and discussed.

- Chapter 6 presents experimental results collected from the implementation phase. This chapter ends with the analysis of experimental results.
- Chapter 7 concludes the research project and presents recommendations for future related work.

CHAPTER TWO

2. LITERATURE STUDY

2.1 Introduction

This chapter focuses on discussing communication systems that are applicable to the mining industry. This chapter begins by discussing some of the already existing and implemented communication systems that are applicable to the mining industry. It then ends with a discussion on some of the viable communication systems from research fields, highlighting their application to the mining industry as well as their associated advantages and disadvantages in providing communication in the mining environment. The rest of this chapter is organized as shown in Figure 2.

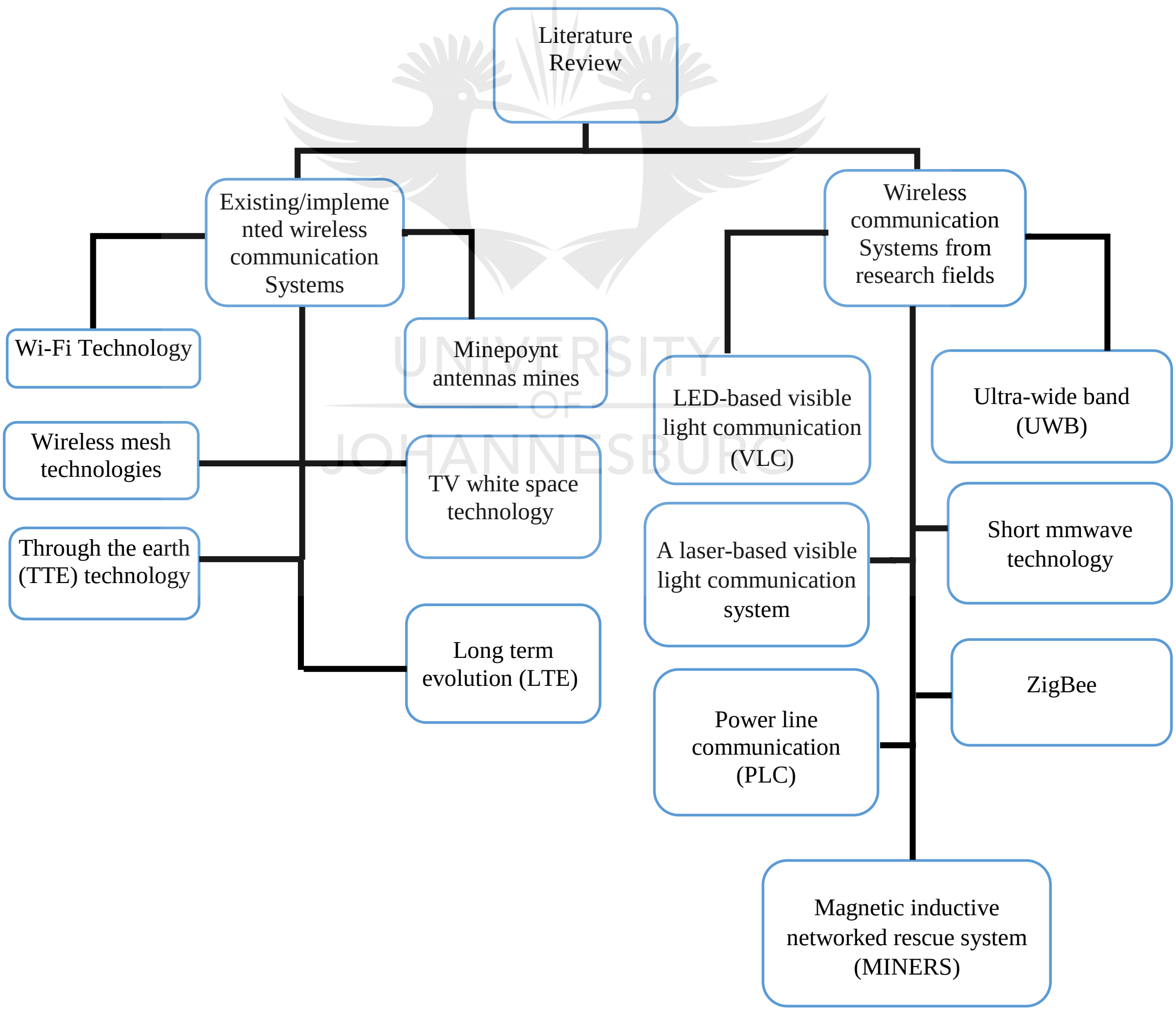

Figure 2: Wireless communication systems

2.2 Existing wireless communication systems

In this section, a discussion on existing wireless communication systems that have the potential of providing communication in underground mines is presented and discussed in brief detail.

2.2.1 Wi-Fi technology

Wi-Fi stands for *wireless fidelity*. This is a radio communication technology that employs the use of frequency to transmit data wirelessly through the air. How this works is that wireless transceivers transmit signals to wireless devices on the network in a range of roughly 100m. The coverage range around the transceiver is known as the hot spot and any computer in this zone can have access to the internet at varying speeds depending on the Wi-Fi standard (802.11a, b, g, n or ac). One of the main advantages of Wi-Fi technology is that it is dynamic since it is wireless. This advantage allows Wi-Fi technology to be easily scalable. One of the major drawbacks associated with this technology is that Wi-Fi mainly operates at 2.4 GHz, and so interference from other devices and networks is a major problem. In addition, security is also an important concern with Wi-Fi technology [10] [11]. Wi-Fi is a good technology for the mining industry [11]. Some of the mines, including Gold 1 mine in South Africa, have Wi-Fi technology providing communication in these harsh mine environments.

2.2.2 Wireless mesh technologies for underground mines

A study on wireless mesh networks has been conducted extensively in [12] [13] [14] [15]. Wireless mesh networks comprise of a collection of wireless access points (WAPs) which have inbuilt routing capabilities and can utilize immediate neighbouring WAPs to transfer information in a peer-to-peer fashion to the broadband network [16]. The mesh capability of each mesh node allows the nodes to be able to transmit and receive information at the same time [17]. Auto-discovery techniques incorporated in WAPs enable them to identify neighbouring WAPs and possible routing paths autonomously without the assistance of technicians or management systems. These features which are incorporated in the WAP, including adaptive routing algorithms, resulting in “self-healing” network that can recover from the loss of a wireless access point by autonomously connecting to other WAPs using alternative routes to transmit data [18]. For this reason, wireless systems are robust and reliable [18].

Radio transceivers with mesh capabilities can be used to set a mesh network in the stope of an underground mine to provide communication. The challenge with mesh technology is that it is difficult to determine the best way to interconnect the WAP nodes to achieve longer coverage distances and data speeds. Despite these challenges, wireless mesh networks provide broadband capabilities for data, voice, and video communication [19]. In addition, underground wireless mesh networks support machine-to-machine (M2M) data communication, which allows for monitoring how machines are performing their jobs and for tracking equipment in the mines. Wireless mesh networks will be investigated in more detail in Chapter 3; however, it is interesting to observe latest industry developments of wireless mesh transceivers that enable the deployment of wireless mesh networks.

In September 2016, MST (mine site technologies) announced the release of a lightweight, portable, self-contained wireless repeater node for underground communication [20] as shown in Figure 3. The WRN is MST's industry-leading mobile self-meshing network extender/access point. The device is designed for extending an existing Wi-Fi network and is capable of Voice over Internet Protocol (VoIP), tracking and data transport. The WRN has been devised for short and medium-term deployment in the dynamic areas of the mine where communication is urgently needed. These areas include hazardous and development sections, such as the stope of an underground mine. The WRN is battery operated and can last about 120 hours [20]. The repeater provides full access to Wi-Fi connectivity in a mesh topology without the use of data or power cables. In addition, the WRN is portable and has multiple hanging and mounting options and transmission power of 16dBm which is below the standard power limitation requirement. By strategically placing the WRN nodes in the mine tunnel, a mesh communication network can be established. However, the transmission power of the WRNs is small compared to other wireless mesh units. This affects the transmission range which can be achieved on the nodes. Longer transmission range can be achieved with a higher transmission power and high-gain antennas. In addition, the units are very expensive compared to other mesh units in the market.

Figure 3: Wireless Repeater Node [21]

2.2.3 Through the earth (TTE) wireless communication technology

Underground mines are hazardous environments to work in. Accidents such as fire, gas poisoning, rock bursts, etc. result in miners being trapped without means to communicate with the surface mine operators. When communication infrastructure is severely damaged during a mine accident, TTE technology offers a promising solution for communicating and tracking trapped mineworkers by establishing communication through rock [22]. In principle, TTE transceivers generate a low-frequency electromagnetic signal which is propagated through several meters of rock underground to mine workers or to another TTE transceiver located underground [23]. Voice and text can be transmitted using ultra-low frequencies in the order of 2 to 10 kHz [24]. The deployment of TTE technology results in improved safety of mineworkers in underground mines.

Some major limitations that would hamper the deployment of this system are that TTE communication is one way and there is no portable TTE transceiver that miners can use to transmit voice and text back to the mine surface operators. In addition, TTE transceivers require over 1 kW of power to generate and transmit TTE signals, which considering the power limitations in the mines, the deployment of this system would present some challenges. Despite these major drawbacks, MST has designed and implemented a TTE personal emergency device (PED) system in the Australian mines which have been deployed for over 25 years [25]. It is the only approved TTE transceiver system in the world.

The PED system has a transmission range of nearly 1000m through rock and is used on normal operations to communicate important instructions to mineworkers located anywhere in the mine. Other companies have designed and tested various TTE transceiver prototypes and the achieved results are documented in Table 1. Table 1 also presents the approach taken by each company in designing the TTE transceiver, the operating frequency and the maximum achieved distance for voice and text communication using TTE technology. These results show that TTE technology is feasible for underground mines.

Table 1: Summary of field test results for TTE Prototype tests conducted in various mines [24]

Company Name	Approach Taken	Operating Frequency (Hz)	Maximum Vertical Depth (m)	Maximum Distance (m)
Alertek LLC Company	Analogue large loop magnetic field	3150	177 (voice)	305 (voice)
MS2 Company	Digital large field magnetic field	330 or 3200	305 (voice) 594 (text)	640 (voice)
Stolar Inc.	Small loop Magnetic field	2000 or 4000	244 (text)	335 (text)
Ultra-Electronics	Digital Large group magnetic field	4820	183 (voice and text)	183 (voice and text)
E-Spectrum technologies	Compact Electric field	10 or 22	177 (text)	640 (voice) 1494 (text)

2.2.4 Long term evolution (LTE) wireless communication technology for underground mines

LTE is one of the communication technologies that can improve data, text, voice and video communication in underground mines. The deployment of LTE technology promises a further hike in the efficiency and productivity of mines through automation of autonomous machinery based on M2M applications, IoT and other smart mining-related tasks.

A press release by Ericson [26] on March 27, 2018 details Ericson and Ambra Solutions delivering an LTE network in one of the deepest Canadian mines, the Agnico Eagle mining site, LaRonde in Abitibi, Quebec. The project is intended to deploy an LTE network (data and voice) three kilometres underground using Ericson equipment. The chief executive officer of Ambra Solutions, Eric L'Heureux, reckons that LTE is the most cost-effective and reliable technology to provide real-time coverage to several kilometres of underground tunnels. He mentions that a single LTE radio can cover about 6km of the tunnel, whereas 60 Wi-Fi access points would be required to cover the same distance [26].

Reporting on LTE, Lux Maharaj, Director – Africa Sales, Parallel Wireless, acknowledges that the ultra-high-speed connectivity and low latency enable LTE to provide communication to the most distant corners of the mine [27]. Tracking and localization of people and vehicles can be achieved with an accuracy of 1 cm, and also, LTE is the best available technology for automation and digitization of the mining activities because of its long coverage distance and high network throughput [27]. However, the implementation of LTE has proven very challenging. LTE works in licensed spectrums and the challenge has come from obtaining the spectrum to run an LTE network. Another serious challenge of running LTE network in the mining environment is the requirement of many mining applications to communicate over the Layer 2 connection, while LTE is a Layer 3 technology. Developments of platforms that can support LTE network in underground mines is underway

Kashif Ali, the communication engineer for Facebook Company [28], announced the release of a newly designed and tested wireless access platform aimed at improving communication in remote areas of the world where there is no communication infrastructure. The platform supports a range of wireless networks; 2G, LTE, and Wi-Fi. In addition, the access platform is designed to be lightweight and portable with ease of mounting on virtually any support structure. The platform can provide wireless cellular connectivity to various population densities, even communities that are as small as 100 people. Today, one of the emerging solutions to provide safety, efficiency, and productivity of underground mines is based on cellular LTE technology. In Canada, Ambra solutions and Ecotel are providing the industrial market with private LTE networks [29]. The use of LTE networks for open pit and underground mines presents a new range of possibilities for enabling Smart Mining related tasks in a very cost-effective way. Therefore, the wireless access platform can be used to establish an LTE network for the mines or extend the existing Wi-Fi network in dynamic areas of the mine.

2.2.5 Minepoynt antennas for wireless communication in underground mines

The circular polarised helical antennas called MinePoynt antennas (Figure 4) have been designed and engineered over the past 10 years in South Africa to provide wireless communications specifically for underground mines and tunnels. Numerous tests of MinePoynt antennas in South African and Australian mines reveal transmission ranges of over 1000m. MinePoynt antennas provide the best Wi-Fi propagation in varying tunnel topologies and support VoIP using a Wi-Fi enhanced handheld phone. The antennas are small in size, portable and can easily be mounted on the tunnel roofs or walls to extend networks such as Wi-Fi, LTE, IoT (LoRa/Sigfox) coverage for staff communication and telemetry application for real-time data reporting and control of the various machines [30].

Figure 4: Mine Poynting Antennas [30]

2.2.6 TV white space technology

TV white space technology refers to the use of unutilised channels which are located in the ultra-high frequency (UHF) spectrum which is made available for radio communication application at a given time and geographical location by making use of cognitive radio technology [31]. As depicted by the "on" gaps in Figure 5, TV white spaces can be understood as an interleaved spectrum that is left unused by broadcasting which can be used to provide internet broadband connection. White space communication network systems are thus categorized into two types of networks base station terminal type and mesh type [32]. In base station type, wireless communication occurs between TV White Space enabled devices and the base station, which means that other devices cannot access the wireless network services. The mesh type allows only base stations to connect to each other to create a large infrastructure.

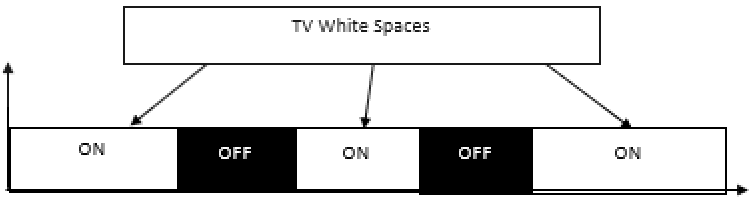

Figure 5: Basic concept of TV White Spaces

Other interesting wireless technologies being explored in TVWS are the internet of things (IoT) applications in low power machine-to-machine (M2M) communication devices and smart metering applications. TV white space technology has been implemented and tested in several countries, such as the United Kingdom, India, the United States of America, Singapore and South Africa, with the aim of providing connectivity in rural areas where there is no internet connectivity infrastructure.

Field test results of TVWS reveal that TV white space technology has a transmission range of several kilometres with data rates as high as 10 Mbps [33], [34]. Further, TVWS technology has better in-building penetrating abilities and is non-line of sight [35]. TVWS technology in underground mines has not yet been implemented, however, because of its high data rates and better in-building penetrating abilities, its deployment in the mining industry would be advantageous. The challenge with this technology is it requires devices to be frequency agile, of which most equipment in the mines are designed to operate on a single frequency. The integration of this technology in underground mines would require frequency agile TV White Space radios.

2.3 Wireless communication systems from research fields

In this section, wireless communication systems that are still in the development phase and have the potential to enhance communication in the mining industry will be presented and discussed. Each system will be compared against the set requirements to determine if any of these systems would present the best solution to the problem. The application of the systems in the mining industry will also be highlighted. We begin this section by looking at visible light communication and its application in the mines.

2.3.1 LED-based visible light communication (VLC)

A VLC system is a type of communication technology that transmits data and/or information using visible light from an optical source, such as an LED. The basic architecture requires an LED optical transmitter and an optical receiver, such as a photodiode, to establish a wireless optical communication link. By modulating the intensity of an optical source at a very high rate, data is transmitted from one point to another.

The application of VLC technology in the mining industry is primarily focused on positioning systems, also referred to as localization [36]. To perform localization, two significant techniques are used, range-based and range-free techniques [37]. The range-based technique works on the assumption that the device whose position is to be determined, is fitted with extra hardware capable of determining the range information [38]. The range-free technique depends on connectivity information to perform localization. The position of an underground miner, mine vehicle or machinery can be determined by using range-based or range-free localization techniques provided that the VLC wireless optical network has some special nodes with prior knowledge of their location and that VLC network topology supports mobility of nodes whose position is to be determined [38].

The advantages of a VLC system are that it is cheaper to install using existing lighting infrastructure and can provide illumination and communication simultaneously. The major challenges of this technology include interference from other light sources and shadowing [39]. In addition, transmission data rates and the number of devices that can connect to the VLC transceiver depend entirely on the chosen VLC network topology; a directed line of sight, a non-directed line of sight, diffuse or tracked.

2.3.2 A laser-based visible light communication system

LEDs have traditionally been used as optical transmitters in VLC systems, however, the demand for higher data rates, at least in the gigabit range, has shifted focus into laser diodes as a potential source in the application of VLC systems. This is so because laser diodes have very high modulation bandwidth, are more efficient and have a better beam convergence [40]. The basic architecture of data transmission for LED and laser-based VLC remains the same with the differences in the type of optical source being utilized for the VLC system. The difference between LED and laser-based VLC systems is manifested in the added advantages of using laser diodes over the alternative, which are discussed below.

The advantages of LD-VLC over LED-VLC system [40] are:

- It has higher modulation speeds compared to LED-VLC systems.
- Converts electrical energy to optical energy more efficiently than LED-VLCs.
- It can achieve higher data rates than LED-VLC systems [41].
- Can provide special type of illumination for machine vision.

The application of LD-VLC in the mining industry rests on positioning systems, point-to-point data communication, and backhaul applications. The challenge with the LD-VLC system for the mining industry application would be the safety concern of using lasers. Furthermore, the transmission range is very limited to just a few meters depending on the system configuration [42]. In addition, to transmit and provide illumination using the LD-VLC system, a colour combination of red, blue and green is required, however, the mixing of colours using laser diodes offers some tremendous complexities, making LD-VLC difficult to implement.

2.3.3 Power line communication (PLC) for the mining industry

PLC is a newly emerging communication technology that has the potential of providing broadband connection via the electrical supply network. PLC technology has the capacity of extending existing local area networks or providing internet connection through electrical plugs because of its ability to transmit data via the electrical supply network. More research is being conducted to characterise the performance of PLC systems in different environments, including the mining sector. In principle, a high-frequency PLC signal is superimposed (at low energy levels) over a 50 Hz electrical transmission signal [43]. The transmitted PLC signal can be received and decoded remotely using any PLC receiver located anywhere on the same electrical network.

The basic architecture of a PLC system consists of a PLC transmitter which transmits a PLC signal over a transmission channel and a PLC receiver located anywhere on the same channel which receives and decodes the transmitted signal. Using a PLC system in underground mines would be cost-effective in that the PLC system can use existing electrical infrastructure to establish a communication network.

Research conducted by NIOSH [44] on PLC systems in underground coal mines reveals some major challenges. These challenges include limited bandwidth, power systems noise interference and safety concerns of using high voltage transmission power lines. The work in

[45] revealed some of the effects of coupling circuits on impulsive noise in power line communication.

2.3.4 Ultra-wide-band (UWB) communication technology

UWB is a developing wireless communication technology that is receiving significant attention from both academia and industry as a viable wireless communication system for underground mines and/or tunnel communication. UWB is defined by FCC as any wireless communication system that occupies a fractional bandwidth $\frac{B}{F_c} \geq 20\%$ with B referring to the transmission bandwidth and F_c being the centre frequency/band [46]. UWB operates in the unlicensed spectrum of 3.1 to 10.1GHz [47], as such, UWB has a greater channel capacity and is thus capable of delivering high-speed data transmission based on a very short radio transmission range of about 15 to 25m line of sight [46].

The advantages of UWB include:

- Higher data rates [48] [49].
- Low equipment cost for establishing wireless communication links [50].
- Low interception probabilities due to low energy spectral density associated with the UWB wireless system.
- Provides accurate ranging and high-speed communication simultaneously.

The major challenge associated with UWB is that it is very limited in transmission range.

2.3.5 Short mmwave technology

The demand for high data rate communication systems for businesses and industries is driving much research in the field of communication. Businesses and industries which would like to make use of high data rate applications, such as video surveillance of underground mines, cannot fully realise this on the current communication systems operating in the narrowband. Communication systems with data rates in the order of several gigabits/s would be ideal for such applications, however, current communication systems cannot provide such data speeds. This is where short mmwave technology comes in as a promising candidate for a higher data rate wireless communication system for underground mines.

Short mmwave technology is a wireless communication system that operates in the unlicensed spectrum of frequencies that are greater than 10 GHz. As a result, the wavelength of the waves in this unlicensed spectrum is extremely short and as such, short mmwave can only be used for short-range communication applications.

Advantages of short mmwave technology [51] are:

- Higher data rates in the order of several Gb/s can be achieved,
- Has very low interference with other networks because of oxygen resonance in frequencies of magnitude $\pm$ 60 GHz,
- Short mmwave can use miniature antennas of just a few cm^3.

Disadvantages of short mmwave technology:

- The system suffers from large propagation losses compared to 2.4 GHz and UWB systems due to short wavelengths,
- The propagation waves cannot penetrate obstructions such as rock, buildings or any other opaque objects, as such, it is reported that human interference (shadowing) can cause attenuations of greater than 20 dB on indoor wireless mmwave 60 GHz device-to-device links.

Despite these limitations, short mmwave technology can be utilised for high data rate transmission backhaul applications in the underground mines.

2.3.6 ZigBee based mine safety monitoring communication system

ZigBee is a short-range wireless communication technology that is safe and reliable for data transmission [52]. In underground mines, ZigBee technology can be used to monitor mine parameters, such as gas concentrations, temperatures and humidity levels [53]. If gas concentration levels exceed safety levels, an alerting signal is sent to the mine surface operators so that proper action can be carried out. In this way, the safety of underground mine workers is improved.

The basic architecture of ZigBee technology has a hardware circuitry that is attached to the body of a mine worker. The modules can be configured to operate in a mesh topology for data transmission. In addition, the ZigBee modules are very cost-effective, operate on very low power, with data transmission ranges in the order of 30 to 100m and data rates of 250 kbps [54]. The system operates in the frequency band of 2.4 GHz, GSM. ZigBee technology has the potential to serve as a telemetry application wireless communication system for monitoring underground mine parameters. The challenge with ZigBee technology is that it has a limited data rate.

2.3.7 Magnetic inductive networked rescue system (MINERS)

MINERS [55] is a wireless system that is based on low-frequency magnetic fields for communication. MINERS is designed to monitor mine parameters (gas concentrations, temperature, humidity, etc.) of normal operations and to establish through the earth (TTE) communication between trapped mine workers and the surface mine operators in the event of a mine accident. It is a hybrid system that operates on ZigBee technology and magnetic field generation for TTE communication. Figure 6 illustrates the block diagram of a magnetic transceiver node. The DSP is the heart of the system and essentially functions as a software-defined radio (SDR) which allows for evaluating various modulation techniques over the magnetic channel. The analog-to-digital converter (ADC) and digital-to-analog converter (DAC) enable the DSP to modulate and receive data from the magnetic channel. The magnetic field is generated and detected by the triaxial antenna and the ZigBee (802.15.4) transceiver is fitted to allow for short-range, high-data-rate communication. Field test results of MINERS reveal a maximum achievable TTE transmission range of 35m at a carrier frequency of 2 kHz and a bit rate of 32 bps.

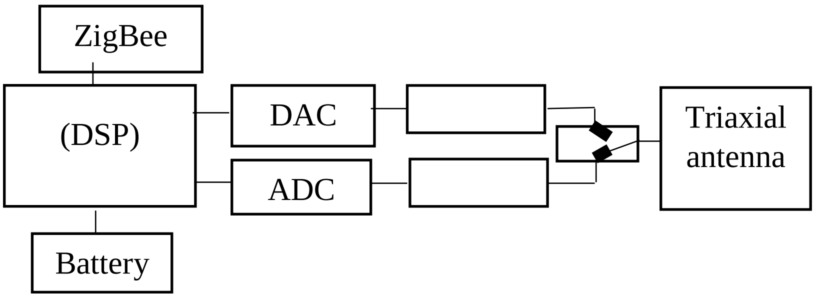

Figure 6: Block diagram of MINERS magnetic transceiver node [55]

2.4 Conclusion

Various communication technologies have been presented and discussed. To choose one system for implementation is not an easy choice because the advantages and disadvantages are different from system to system. Based on the cost implications of the system and the availability of system components in the market, as well as the application of the technology in the mines, mesh technology will be implemented for performance analysis in the mining industry. The next chapter focuses on the detailed literature study of wireless mesh technology.

CHAPTER THREE

3. LITERATURE STUDY OF WIRELESS MESH SYSTEMS

3.1 Introduction

In the previous chapter, an overview of various wireless communication systems was presented and discussed. Each wireless communication system was evaluated against the set system requirements. After much consideration, the wireless mesh technology was chosen as a communication system to provide communication in underground mines. In this chapter, an in-depth study of mesh technology and a careful analysis of this system is presented. Some of the keynotes discussed in this chapter include mesh system description, the basic architecture of wireless mesh networks, mesh system applications, mesh transceivers, and routing protocols.

3.2 Wireless mesh system description

A wireless mesh network (WMN) is a type of communication network that is composed of radio communication devices which are capable of transporting data from one of the interfaces to another [56]. This type of network is also referred to in [57] as an ad hoc network. To begin to understand what wireless mesh networks are all about, we need to appreciate the type of network topology that is represented by a wireless mesh network.

Figure 7 illustrates a four-node mesh network and the associated interconnections. The wireless connections that connect each node to the other are referred to as links. The one important thing to realise is that as the number of nodes in the network increases, the number of links also multiplies. Consider, for instance, one link is required to connect two nodes, 3 links for three nodes, 6 links for 4 nodes, 10 links for 5 nodes.

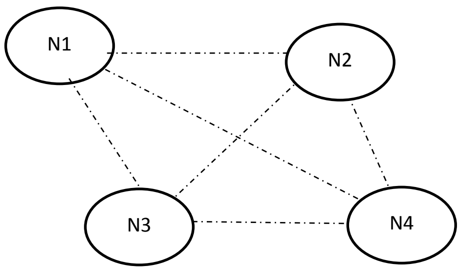

Figure 7: Four-node mesh network

This shows that the classical understanding of each node being able to connect to every other node in a mesh network becomes impractical and even impossible as the number of nodes increases. The number of links that need to be configured also increases significantly. This means that more processing power is required by each node to compute each link, which may cause the node to saturate. Therefore, there is a limit to the number of nodes that can be connected in a mesh network. To overcome this limit, partial mesh networking is one of the best solutions. With partial networking, only a certain number of nodes are connected to certain nodes, instead of having each node interconnected to every other node. This introduces as to network structures.

There are two types of network structures: peer-to-peer and infrastructure. In a peer-to-peer structure, each node can communicate with any other node that is in range. In an infrastructure network, all communication or data traffic flows through one centralised node called an access point (AP). An access point is thus a two-port bridge with one port connected to the wired network and the other port representing a radio frequency (RF) transmitter/receiver. In an infrastructure set up, if two nodes want to communicate with each other, the message must first be sent to the access point, which then relays or forwards the message to the other node.

Figures.8 and 9 illustrate the two types of network structures. As can be seen from Figure 9, the network structure is not that reliable because if the access point fails, all communication between N1 and N2 is lost completely. However, for a peer-to-peer network structure, the failure of one node does not affect all other nodes; the network is able to survive in harsh conditions. A mesh network can thus be understood as a sequence of peer-to-peer transmissions where each node functions both as a router and repeater. This leads us to understand the basic architecture of mesh systems.

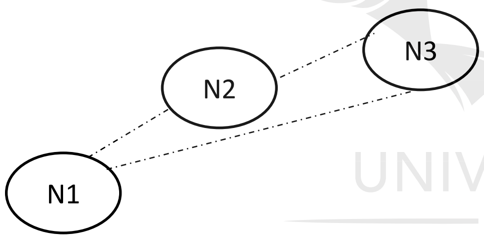

Figure 9: Peer-to-peer mesh network

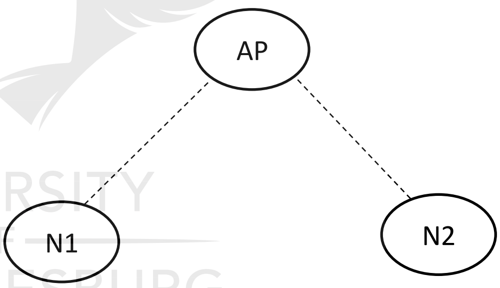

Figure 8: Infrastructure mesh network

3.3 Basic architecture of wireless mesh networks

The basic architecture of a wireless mesh network (Figure 10) consists of a mesh gate (MG), mesh routers (MR), client sensors (S) and the main wired internet network. The MG connects the wireless mesh network to the wired network of the mine. The MG functions as a bridge that relays data packets from all sensor clients and mesh routers to the existing network of the mine. Mesh routers are ordinary mesh nodes/transceivers that are configured to function as routers and repeaters to relay data packets from the sensor clients to the mesh gate.

The sensor clients are devices that measure physical mine parameters such as temperature, gas concentration, etc. and transmit this data to the routers which function as base stations that relay information to the mine surface operators. In principle, mesh nodes have two major functions to fulfil; the first is to provide services to clients that want access to services that are available on the wired network, e.g. voice communication. The second is to provide a return path for information from the clients to the wired network and vice versa. The provision of the return path is called backhaul. Because of this, wireless mesh networks are called ad hoc networks.

3.4 Ad hoc wireless mesh networks

Figure 10 depicts the basic architecture of a wireless ad hoc mesh network. In simple terms, a series of nodes communicating as peers in point-to-point or multipoint topologies constitute an ad hoc mesh network.

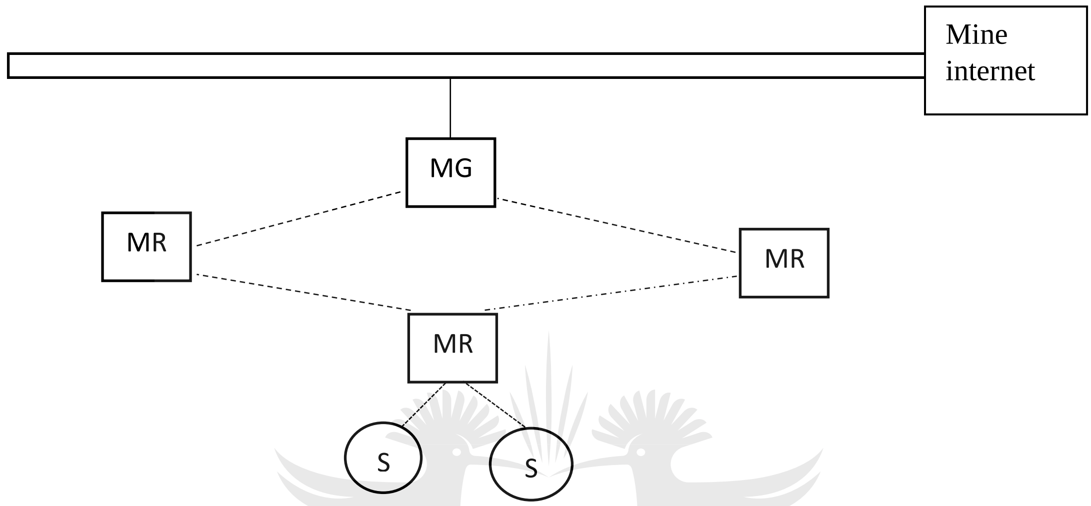

Figure 10: Basic architecture of underground wireless mesh network

In a typical WMN, nodes (routers) communicate with other nodes on the same channel in order to relay data packets to the intended destination. This makes mesh technology very attractive in the sense that the network becomes easily scalable and self-forming and self-configurable. However, radio nodes communicating on the same channel are subject to contending for the available bandwidth on the channel [57], which is a problem. In certain cases, nodes can even prevent each other from utilizing the channel, thus degrading the noise floor, which may result in a reduced data rate, range or both.

Another concern with ad hoc WMN is the reduced bandwidth associated with adding more nodes to the network. Research work in [57] shows that radio nodes do not receive and transmit at the same time. In fact, when a node receives a data packet, it stores the packets, computes the route to the next node/hop and then forwards the data packet. During this forwarding process, the node loses some of its bandwidth as it attempts to transmit data packets up and down the network.

The loss of bandwidth associated with the number of hops (nodes) that are relaying data packets can be seen in the relationship,

$$\boldsymbol{C} = \boldsymbol{B} \times \frac{\mathbf{1}}{\mathbf{2}^{\boldsymbol{n}}} \tag{3.1}$$

where *C* is the channel throughput, *B* is the radio bandwidth and *n* is the number of nodes [57].

What this relationship means is that to transmit data packets from a single node (single hop) will result in the loss of half the available radio bandwidth, and after 3 hops (nodes) the user will be left with one-eighth of the available bandwidth, which results in reduced throughput and affects the performance of the mesh network as a whole. This is where multi-radio multi-channel comes in as a solution.

The multi-radio multi-channel approach is proposed as a solution to the loss of bandwidth associated with wireless mesh networks [57]. This results in increased capacity in three radio architecture node networks through simultaneous transmission on multiple orthogonal frequency channels. The use of multiple radios tuned to different channels enables nodes to communicate with each other simultaneously without interference with nodes in the interference range of each other. Figure 11 illustrates a three-radio architecture node in the wireless mesh backhaul network for the longwall coal mine [57].

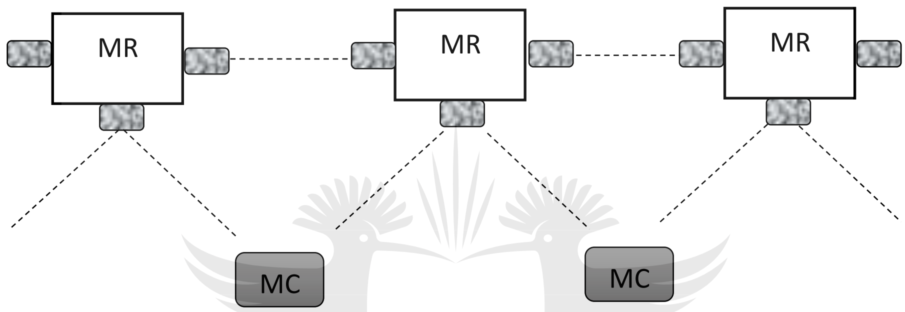

Figure 11: Three radio architecture node

Two radios with the 802.11a (5.8 GHz) and the 802.11g (2.45 GHz) standards are used to provide uplink and downlink backhaul application and the other radio is used to provide services to the mesh clients (MC). Therefore, each node in the interference range can avoid interference with other nodes by communicating over different channels. With this proposed architecture, the network capacity is dependent on channel assignment, i.e. when the number of nodes is smaller than orthogonal channels. Also, the capacity is dependent on orthogonal channels supported by a radio node and the number of radios per node. To further understand and appreciate wireless mesh networks, we need to understand the flow of data in the network. In the next few sections, we take a look at how data flows in WMN in terms of network addressing, bridging and routing protocols.

3.5 Network addressing

In [56], a discussion is presented on three basic types of network addressing which are technically known as unicast, multicast and broadcasting. Network addressing has everything to do with how data flows in a given mesh network. This is important because understanding how network addressing impacts the flow of data will influence the design of a mesh network topology.

3.5.1 Unicast network addressing

In this type of network addressing, a single data packet that is being transmitted has one specific destination address. This principle is derived from one of the earliest types of network architectures that involved the connection of a front-end processor to control units, with each control unit interfaced to a group of terminals [56]. In this networking structure, each control unit represented a node and the connection between the front-end processor and the node represented a link. Data flowing from the front-end processor to a specific terminal connected to the control unit needed a specific terminal address to reach its destination. That address which represented a specific terminal became known as a unicast address.

3.5.2 Broadcasting

If the same message needs to be delivered to all the nodes in a network, then broadcasting is used. In broadcasting, a common data packet is sent from a control unit to all the nodes in a network, in which case, only the destination address changes for each node.

3.5.3 Multicasting

Clients subscribe to receive certain packets/frames that are associated with a specific multicast addressing. To further illustrate this point, consider ten clients on a mesh network and only five clients need to view video surveillance of the underground mining process. One way can be that each client can receive a unicast transmission of the video. However, more network resources such as bandwidth and router processing power will be needed to send each client a copy of the video. To save up on these resources, the five clients can subscribe to multicast addressing in which case only a single copy of video frames can be sent and received by all the clients with a multicast associated address. This alleviates pressure on the mesh network.

3.6 Routing protocols

3.6.1 General concepts of routing protocols

The main function of routing protocols is to find and perform path selection to transport data packets between the source node and the destination node [58]. This has to be done in the most efficient and reliable way with very minimal overhead. That being said, let us consider some of the routing protocols and their applications in wireless mesh networks.

On a general scale, there are two main types of routing protocols for multi-hop ad hoc wireless mesh networks: topology-based and position-based routing protocols [59]. Routing protocols that are based on the topology of the network select paths based on topological information. On the other hand, position-based routing protocols select paths depending on geographical information with geometrical algorithms [58].

As depicted in Figure 12, topology-based protocols are further categorised into reactive, proactive and hybrid routing protocols. Reactive routing protocols which are also referred to as ‘on-demand’ protocols, compute and maintain a route only when it is needed. The main advantage with this approach is that computing a path only when it is needed reduces the control overhead but introduces latency for the first packet to be transmitted due to the time needed for the on-demand route set up. Ad hoc on-demand distance vector (AODV) and Dynamic Source Routing (DSR) are examples of reactive topology-based protocols.

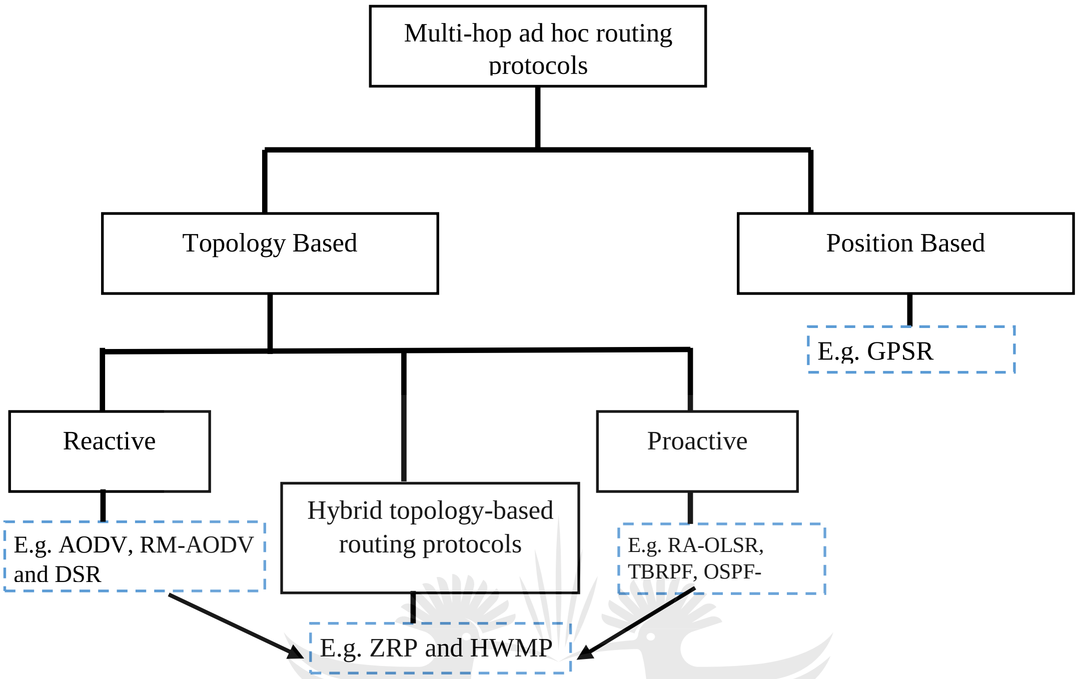

Figure 12: Classification of routing protocols [58]

Proactive routing protocols maintain information about routes to all the nodes in the networks such that every node always knows the path to every other node always. The added advantage with this approach is that there is no latency, however, to permanently maintain unused routes increases the control overhead. Examples of proactive protocols include Destination Sequenced Distance Vector (DSDV) and Optimized Link State Routing (OLSR).

Hybrid topology-based routing protocols try to combine the advantages of reactive and proactive protocols to compute the most efficient path for data transport. In this approach, a proactively based protocol is used for near nodes or paths which are often used, whereas reactive based protocols are used for more distant nodes or less used paths. What is important to note is that, in principle, wireless mesh networks can utilize any of the above protocols to transport data from source to destination. However, not every protocol will work well and as such, a suitable protocol to be used must be chosen based on the application and performance requirements of the mesh network.

3.6.2 Major requirements on routing in WMN

For the wireless mesh network to perform very well, certain major routing requirements must be met in the choice of an optimal routing protocol. These requirements include:

- *Fault Tolerance*: In the event of a node or link failure, the network must survive and continue to function. This means that routing protocols must be able to support route reselection subject to link failure.

- *Load Balancing*: Routing protocols must be able to choose the most efficient path for data transport.
- *Reduction of routing overhead*: Routing protocols must be efficient/optimal enough to conserve bandwidth for the success of the wireless mesh network by reducing routing overhead, especially the one caused by rebroadcasts.
- *Scalability*: Wireless mesh networks are scalable and can handle hundreds or thousands of nodes. Given this number of nodes in WMN, the scalability support in the routing protocols is very important.
- *Quality of Service support*: Routing protocols must support the quality of service. This means that routing protocols must be able to avoid interflow and intra-flow interferences caused by two different links in a range of each other sharing the same channel so that data is relayed easily.

3.6.3 Types of routing protocols

This section will give a brief description of selected routing protocols for wireless multi-hop networks to illustrate the general concept of routing protocols. A comprehensive study of all routing protocols will not be provided since this is not the main focus of this study. Interested readers can refer to literature. The four routing protocols that will be discussed include Ad Hoc on Demand Distance Vector (AODV), Dynamic Source Routing Protocol (DSR), Optimized Link State Routing (OLSR) and Destination Sequenced Distance Vector (DSDV).

3.6.3.1 Ad Hoc on Demand Distance Vector (AODV) routing protocol

Ad hoc on-demand distance vector routing protocol is one of the most commonly used routing protocols in wireless mesh networks. Under this routing algorithm, routes are set on-demand basis and by using a simple request-reply mechanism, routes are discovered [60], [61].

AODV uses periodic "HELLO" messages to track the state of the link between two nodes. This is achieved as follows; let us say that the source node (S) wants to transmit data packets to the destination node (D), but does not have a route set up to D in its route table, then S will have to conduct a route discovery process to set up a route from S to D.

A route request (RREQ) containing the hop count, an RREQ identifier, the destination address, and destination sequence number, and the originator address and originator sequence number, is broadcasted by S up and down the network [58]. Upon receipt of an RREQ, if the node is the requested destination D, a route reply (RREP) message is generated and sent back along the created reverse path to the source node S. Once the source node receives the RREP packet from the destination node D, buffered data can now be sent to the destination node D on the newly discovered path.

3.6.3.2 Dynamic Source Routing (DSR) Protocol

DSR, similarly to AODV, is a reactive routing protocol that is based on RREQ/RREP data packets and computes routes only if one is needed [62], [60], [58]. In general, route request packets are broadcasted up and down the network, however, instead of setting a reverse-path in the routing tables of each node, the RREQ data message collects the addresses of the traversed nodes on its way to the destination. RREQ sends the path to the source where all the addresses are stored in a route cache. When the source is ready to send data packets, the path which is a list of addresses from the source to the destination node, is included in the header of each data packet such that each node forwards a received packet to the next node in the network based on the list of addresses in the header (source routing). If a route fails, DSR uses route error (RERR) for the notification of route breaks [63].

3.6.3.3 Optimized Link State Routing (OLSR).

Optimized Link State Routing (OLSR) is a topology based proactive routing protocol that uses the shortest-path algorithm to compute routes to transport data from source to destination [58], [59], [60]. The optimization is based on specific neighbourhood detection and multipoint relays.

3.6.3.4 Destination Sequenced Distance Vector (DSDV)

Destination Sequenced Distance Vector (DSDV) makes use of routing tables which are stored at each node to transmit data packets. Each routing table at the nodes/stations lists all the available destinations and the number of hops to each available destination. In other words, each node maintains its own routing table with information about network topology and the cost of the links between the nodes [59]. Data packets can be forwarded from the source node to the destination node since each node has a routing table with available destination addresses. This routing protocol presents the ability for determining the shortest route to the destination node.

3.6.3.5 Better Approach to Mobile Ad hoc networks (B.A.T.M.A.N)

BATMAN is an example of a proactive routing protocol; however, it does not have knowledge about all the nodes in a network. It determines the next best route for data transmission by broadcasting originator messages (OGM). Transmitted OGM messages are sent to all the neighbouring nodes, in this way it broadcasts its existence to its first hop nodes in a network. The nodes in turn transmit the OGM message from the source node to other nodes in a network based on condition that the links are best links. Links with poor signal strength are dropped. The transmitted OGM has fields that has the source address, TTL and sequence number which is constantly updated in the routing table [64]. If multiple OGMs are received by the destination node, the node will consider the OGM with the minimum delay, all other OGMs will be dropped. The chosen OGM will indicate the shortest path.

3.6.4 Performance analysis of routing protocols in wireless mesh networks

A study conducted in [59] on routing protocol performance in wireless mesh networks showed that OLSR and AODV protocols were considered efficient routing algorithms. The simulation results for throughput as a function of nodes for AODV and OLSR revealed that the two protocols outperformed the DSDV and DSR routing protocols. The study also showed that the packet delivery ratio is better achieved with AODV and OLSR routing protocols. Other studies have shown that BATMAN is the best routing protocol when it comes to building high speed networks. Therefore, it all comes down to preference. BATMAN would be best suited for high speed networks, whereas AODV and OLSR would be best for networks with greater bandwidths. In the next section, we look at system components that make up a mesh network.

3.7 Components of WMNs

Now that we understand what WMNs are, their basic architecture and how data flows in a given WMN, it is also vital to discuss the components that constitute WMNs. In this section, we examine several components that make a wireless mesh network operable. A list of potential components will be presented and discussed. The main components that will be discussed include antennas and mesh routers.

3.7.1 Antennas

Antennas are important components of WMNs. An antenna can be considered to represent a conversion device that changes electrical energy into a magnetic force also referred to as RF energy and RF energy back into electrical energy. Antennas are used to pick up a signal. The gain of an antenna is measured in dBi and it indicates the ability of an antenna to pick up a radio signal. A higher gain is preferable to a lower value because, with a higher gain, the antenna's sensitivity and ability to pick up a signal are increased.

There are two main categories of antennas: omnidirectional and unidirectional. Omnidirectional antennas radiate in all directions and unidirectional antennas radiate only in one direction. An antenna increases its gain when it concentrates its RF energy in one direction. Omnidirectional antennas increase their gain by concentrating emitted energy out of the antenna horizontally. Because WMNs require a near LOS path due to their low power and high frequency, some mesh routers/access points include dual antennas. Such antennas are called diversity antennas and the software selects the antennas receiving the better signal as a means to reduce signal reflections [56].

When the distance between mesh nodes increases, one can either use signal amplifiers or repeaters or one can make use of directional antennas to extend coverage. There exists however a relationship between power injected into an antenna and the antenna gain and this relationship assists in the choice of a suitable antenna. Table 2 presents this relationship at the 2.4 GHz band.

Table 2: Legal relationship among power injected into an antenna, Antenna Gain, and EIRP in the 2.4 GHz band [56]

Power at the antenna (dBm/Watts)	Antenna Gain (dBi)	EIRP (dBm)
30 (1W)	6	36
27 (500mW)	9	36
24 (250mW)	12	36
21 (125mW)	15	36
18 (62.5mW)	18	36
15 (31.25mW)	21	36
12 (15.125mW)	24	36

Consider a transmitter with a transmitter power of 27 dBm. This means that you can only use an antenna with an antenna gain of 9 dBi and less. Anything over 9 dBi will result in higher effective isotropic radiated power (EIRP) over 36 dBm which is not allowed. The principle here is that one needs to consider the power injected into the antenna and the associated antenna gain to choose the most suitable antenna to be used.

3.7.2 Mesh Routers

Mesh routers are one of the main components used in a WMN. Mesh routers relay data from one point to another wirelessly. Mesh routers can be connected in a mesh network to provide a robust intelligent communication system that is self-healing. There are various Wi-Fi routers available on the market which can be used to set up a wireless mesh network. This section looks at various possible transceivers that will be deployed in this project. Each transceiver will be discussed in terms of its power transmission levels, maximum data rate, and cost.

3.7.2.1 The EnGenius ECB1200

This Wi-Fi transceiver (Figure 13) is a dual band 802.11ac wireless access point and client bridge that can be deployed in various indoor environments such as corporate offices, hotels, schools and universities. The EnGenius ECB1200 operates on both 2.4GHz and 5GHz frequency with a transmission power of 26dBm yielding a total of 1200Mbps of data speed. The access point is fitted with four detachable 5dBi Omni-Directional antennas; two on 2.4GHz and two on 5GHz. The idea of detachable antennas will make it easier to test the performance of the transceiver with other third-party antennas.

Figure 13: EnGenius 1200Mbps high Power indoor desk/wall AP [65]

3.7.2.2 The TP-Link WR941HP Wi-Fi router

This high-power router (Figure 14) offers three modes of operation: router, access point and range extender. The three 9dBi high-gain detachable antennas provide superior range of up to 900m². Rated at 30dBm of transmission power, the TP-Link WR941HP provides speeds of up to 450Mbps, ideal for video streaming and VoIP application. Supported standards include IEEE 802.11b/g/n at an operational frequency of 2.4GHz.

Figure 14: TP-Link WR941HP 450Mbps High Power Wi-Fi Router [66]

3.7.2.3 Tenda AC1200 Smart Gigabit Wi-Fi Router

The Tenda AC1200 router in Figure 15 operates on both 2.4GHz and 5GHz frequencies with data speeds reaching up to 1167Mbps. The supported operation modes include a wireless router, universal repeater, WISP and AP Mode. Fitted with MU-MIMO technology, beamforming technology, built-in high-powered amplifiers and four 5dBi external antennas, AC10U has a long operating range to achieve greater network coverage.

Figure 15: Tenda AC1200 Smart Gigabit Wi-Fi Router [67]

3.7.2.4 Tenda 600Mbps WiFi Router

The Tenda F9 Wi-Fi router in Figure 17 repeater offers data speeds of up to 600Mbps at an operating frequency of 2.4GHz. Fitted with four 6dBi non-detachable external antennas, the F9 can provide longer range at the following transmission powers and standards: 802.11b-1M: 21.5 dBm ± 1.5 dBm 802.11g-54M: 17.5 dBm ± 1.5 dBm 802.11n-MCS7: 17 dBm ± 1.5

dBm 802.11n-VHT: 15 dBm ± 1.5 dBm The supported operation modes include router, WISP, universal repeater, and AP.

Figure 16: Tenda F9 600Mbps Wi-Fi Router and Repeater

3.7.2.5 Open mesh access points

Open Mesh (OM) access points (Figure 17, 18) provide wireless Wi-Fi network coverage wherever an internet connection is needed. Each router can function as an access point (AP), mesh gateway and repeater all in one compact and reliable unit. OM access point has indoor and outdoor enclosures for professional installation and CloudTrax software, a cloud-based network controller to manage the network. The OM access point operates on 2.4GHz only with 23dBm of transmission power and data speeds reaching up to 150Mbps. The OM AP is a plug and play access point with zero configuration features.

Figure 17: Indoor Wall Plug Enclosure [74]

Figure 18: OPEN-MESH AP – 150Mbps [74]

3.7.2.6 Nova

The Nova mesh Wi-Fi system (Figure 19) is a set of three units that provides up to 557m² of network coverage area while a single unit covers up to 8m². The Nova mesh system is powered with mesh technology and Smart Auto-path Selection technology to ensure a robust and reliable wireless network. Nova units are plug and play devices, straight out of the box, Nova units arrive paired to each other with zero configuration. Nova Wi-Fi systems operate on both 2.4GHz and 5GHz frequencies providing high data rates; 5GHz: up to 867Mbps and 2.4GHz: up to 300Mbps. Nova units are fitted with two 3dBi built-in antennas that allow for beamforming for enhanced signal strength and reliability.

Figure 19: Nova MW6 Whole Home Wi-Fi Mesh System

3.8 Advantages and disadvantages of WMNs

To further appreciate WMNs, let us consider some of the associated advantages and disadvantages of using wireless mesh networks.

Advantages

- Reliability: The failure of one link or node does not affect the entire communication but will result in data packets being transmitted using alternative routes.
- Self-configuration: Nodes in a mesh network learn about other networks and routes so there is no need to configure each node.
- Scalability: If the coverage area increases, it is easy to extend the network by simply adding more nodes to the system since one does not need physical access to the system.
- Economics: WMNs are less expensive to set up and operate than conventional networks.

Disadvantages

- Security: Because mesh nodes transmit data wirelessly, it is possible for intruders to have access to information being transmitted, if not properly secured.
- Overhead: The efficiency of routing algorithms, level of traffic in the network, etc. can affect the performance of the node to perform other tasks.

Having considered the components that make up a mesh network and the associated advantages and disadvantages of wireless networks, it is vital to understand how RF signals from access points travel in a given channel.

3.9 Channel characterization

In this section, we examine how radio waves propagate in an underground environment. This understanding will aid in the design of a robust wireless mesh network. The frequencies under consideration are 2.4 GHz and 5.8 GHz.

3.9.1 Radio-wave propagation for WMNs at 2.4 GHz and 5.8 GHz

Before designing WMNs, it is important to understand the performance of the channel in terms of the propagation of the radio wave into an underground mine environment, i.e. its associated characteristics at a given bandwidth. The mine environment is chosen because the WMNs are intended to operate in these environments where radio waves suffer heavily from attenuations due to reflections, diffractions, and scattering. The chosen frequencies are targeted because they are commonly used in wireless communication applications in underground mines. A considerable study conducted in [68] of the performance of channels at 2.4 GHz and 5.8 GHz in terms of path loss, outage probability, delay spread, and the coherence bandwidth. These parameters are discussed in this section.

3.9.2 Path loss

Path loss refers to the attenuation of the signal's transmitted power as it propagates from the transmitting antenna to the receiving antenna. The path loss parameter is important in the evaluation of the link budget of a telecommunication system and in estimating radio coverage. As depicted in Figure 20, path loss increases with an increase in distance between the transmitter and receiver. When the distance between transmitter and receiver increases from 1m to 23m, the path loss increases almost linearly, typifying a direct proportionality relationship. At 23m, path loss for 2.4 GHz sits at 75 dB and 87 dB for 5.8 GHz bandwidth. A 2.4 GHz channel has better path loss characteristics in comparison to 5.8 GHz and 60 GHz channels. Studies conducted in [69] and [70] show similar path loss results of the channel at 2.4 GHz.

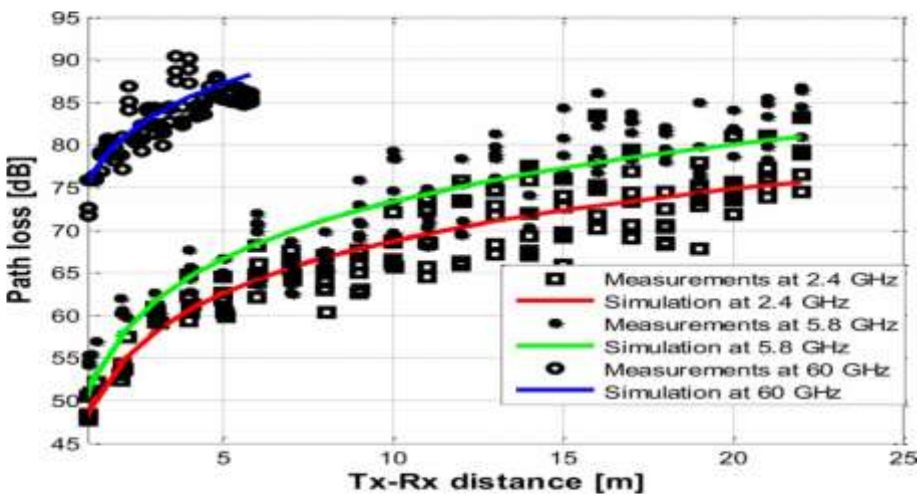

Figure 20: Path loss versus distance in meters at 2.4 GHz, 5.8 GHz and 60 GHz [68]

3.9.3 Outage probability

The probability that the received power of a signal at a given distance falls below minimum threshold power is called outage probability. Studies conducted in [68], [69] and [70] for a probability outage of 1%, which is commonly used in wireless communications, show the results in Figure 21. From Figure 21, at frequencies of interest, the outage probability increases with an increase in distance between transmitter and receiver. The 2.4 GHz channel performs better in comparison to 5.8 GHz and 60 GHz frequencies in terms of outage probabilities.

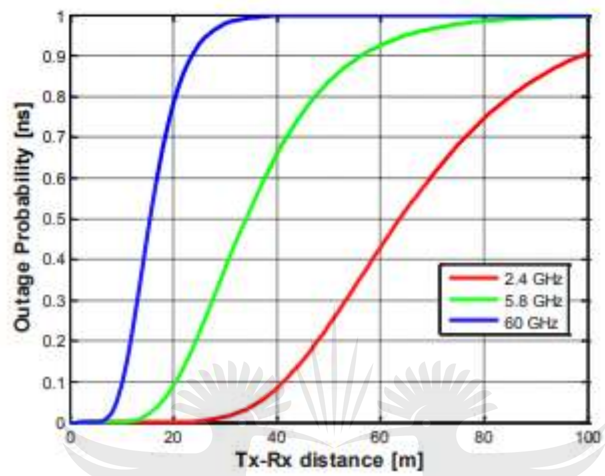

Figure 21: Outage probability at 2.4 GHz, 5.8 GHz and 60 GHz [68]

3.9.4 Delay spread

Multipath and delay spread are very closely related. When a transmitter transmits symbols, due to multipath, the symbols are received multiple times at the receiver. This creates an echo and the duration of this echo orchestrates what is known as delay spread. Delay spread characterizes the time dispersion of the propagation channel [68]. In Figure 22, the RMS delay spread is depicted as a function of the distance at all three frequencies from the experiments conducted in [68]. At 2.4 GHz, 5.8 GHz and 60 GHz, the RMS delay spread falls between 1.29 ns to 12.36 ns, 1.04 ns to 15.74 ns, and from 1.94 ns to 3.87 ns, respectively. The delay spread for 60 GHz has a lower range because the signal is stronger at 60 GHz.

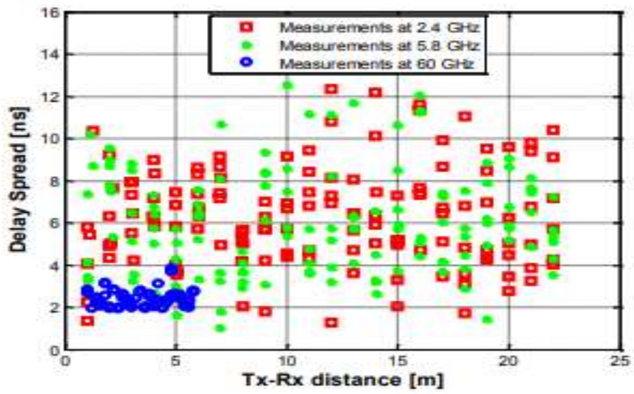

Figure 22: RMS delay spread at 2.4 GHz, 5.8 GHz, and 60 GHz [68]

3.9.5 Link fading margin

A link margin can be thought of like an allowance that is designed to provide sufficient received power to overcome channel fading in order to maintain quality of service (QoS) in terms of packet delivery ratio. The fading margin parameter assists network designers to design a mesh network system that is robust such that any changes in modulation techniques, antenna polarization or channel losses will be catered for using the set link margin. Link fading distribution (fading models) differ between environments, indoor, underground tunnels, and underground mine environments. However, in principle, the worst-case fading model is that which yields a high value fading margin.

3.10 Conclusion

In this chapter, we have considered some of the components that make up a mesh system as well as the advantages and disadvantages associated with mesh systems. We also considered the channel characterization of RF signals at 2.4 GHz and 5.8 GHz. The following chapter aims at discussing the design of a proof of concept mesh network.

CHAPTER FOUR

4. RESEARCH METHODOLOGY

4.1 Introduction

This chapter discusses the type of research methodology used to investigate the performance of wireless mesh networks for data, voice and video transmission in underground mines. The approach taken, success criteria and experimental setup designed to test the performance of wireless mesh networks are described.

The research presented attempts to quantify the performance of wireless mesh networks in transmitting data, voice and video in underground mines. To achieve this, standard network parameters are measured and analysed to see if the wireless communication system will be able to transmit data, voice and video in underground mines.

The network performance metrics studied in order to quantify the performance of wireless mesh networks include:

- Average network throughput.
- Average network latency.
- Signal-to-noise ratio.
- Coverage range using high-gain antennas.

The standard performance of wireless networks can be quantified by measuring network parameters and studying the influence of internode spacing on the network, as well as the increasing wireless mesh access points on the network. This is achieved by analysing the average network throughput, latency, SNR, and coverage distance for data, voice and video communication on the network. A high network throughput and packet delivery ratio, very low network latency and SNR and long coverage distance are network parameters that are used to determine the performance of the network. The following section discusses the experimental setup for investigating the performance of wireless mesh networks.

4.2 Experimental setup

This research makes use of practical experimental setup to analyse the performance of wireless mesh networks in underground mines. To achieve this, a testbed of 7 wireless mesh network is developed and experiments are conducted in an actual mine to evaluate the performance of the wireless network. This approach is favoured simply because simulation models fail to accurately model the physical environment in which wireless network are deployed. As such, developing a prototype system of a wireless mesh network is chosen so that experimental data collected from practical experiments represent the performance of the system in a real mining environment.

4.2.1 System model and test environments

The main components include a router, wireless mesh access points and two laptops to serve as client and server. A wireless mesh network test bed of seven radio node is developed and tested in an underground platinum mine. Prior to these tests university passageways are used for several indoor tests. Also, a mock mine of 2.4m wide, 3m high, and 120m long was used to further validate the performance of the system and to prepare for tests in a real mine. Six hour-long indoor tests are repeated eight times, two times for mock mine tests and one time for real mine tests. Each parameter is measured three times and the results are averaged, recorded and statistically analysed.

4.2.2 Measurement tools and software applications

The AirCheck G2 wireless spectrum analyser is used in measuring Wi-Fi signal strength, the signal-to-noise ratio of the channel, and other important network parameters. The AirCheck G2 wireless tester is a useful tool for engineers performing network analysis because it is highly portable, easy to use, and yields very accurate results. Also, iPerf, a bandwidth measuring tool, is used to measure network speed and latency to verify the results from the AirCheck G2. CloudTrax, a cloud-based network controller application, is used to provide configuration of the wireless network, management, and monitoring of the network.

4.2.3 Experimental design and measurement process

Standard network performance tests are conducted on the wireless network to characterise the performance of WMNs. The first part of the experiments investigates latency and throughput as a function of increasing mesh nodes on a wireless mesh network. The second part of the experiments investigates the effect of internode spacing on network latency, throughput, signal-to-noise ratio (SNR), and received signal strength (RSS). The third part of the experiment aimed to investigate the feasibility of enhancing the coverage distance of a wireless mesh network by using a 15 dBi high-gain antenna.

4.2.3.1 ***Throughput and latency as a function of increasing mesh nodes***

In this experiment, access points are mounted on tripods interspaced at 20m apart along the mine tunnel in a point-to-point topology. The first OM2P series is powered on and network metrics are taken 10m away from the access point using an AirCheck G2 Wi-Fi tester and iPerf tool. The second access point is powered on and network metrics are taken using the AirCheck G2. This is repeated up to the seventh wireless access point. The internode spacing is kept constant at 20m at all times.

4.2.3.2 Influence of internode spacing on network throughput, latency, SNR and RSS

In this experiment, seven access points were used to study the influence of distance on network latency and throughput. This was achieved by interspacing 7 nodes at 20m and increasing internode spacing in steps of 10m and observing the trend in the measured network metrics. Network metrics were measured 10m from the seventh mesh node across the network using the AirCheck G2 and iPerf tool.

4.2.3.3 Enhancing network coverage distance by using high-gain antennas

For this experiment, a wireless mesh node 1 is fitted with a 15 dBi high-gain antenna. The second mesh node is placed at the point where the received signal strength from node 1 is reading -67 dBm indicating the furthest coverage distance with good signal strength. The distance between node 1 and node 2 is then measured in meters. Network parameters are then measured at node 2. The rest of the access points are wirelessly connected to node 2. Considering that the transmission range of access points reduces from $\pm$100m in outdoor environments to $\pm$50m in indoor environments due to high attenuation levels, internode spacing of 50m is chosen for this set of experiments to observe if 100m coverage distance can be achieved by each access point as per system requirements and specifications. The obtained results are recorded to observe the trend in the performance of the network.

4.3 Experimental data collection and analysis technique

A significant amount of experiments on wireless mesh networks has been conducted and statistical data has already been published in many scholarly articles. However, in this research, primary empirical experimental data is collected from experimental tests to analyse the performance of wireless mesh networks. This approach is chosen because the test environments and the system tools used in this experiment are different from those that have already been used in other research experiments.

By using the tools and experimental processes mentioned above, data is collected, recorded and analyzed by varying the topology of the network. Internode spacing and increasing the number of wireless access points are used as independent variables to study the influence of factors on the performance of the network.

Office tool (Excel) is used to record and statistically analyse the data. Statistical data analysis is employed to determine the performance of the network and to study the relationship between increasing internode spacing as well as the influence that increasing access points has on the overall performance of the network. Furthermore, results from indoor, mock mine and the actual mine tests are compared to validate the performance of the network and to ensure that the obtained results are reliable.

4.4 Conclusion

In conclusion, the quantitative research methodology will be used to answer the objectives of this research. By developing and testing a prototype system, obtained results can be compared with other results from literature review to validate the results. The next chapter focuses on the design and construction of a proof of concept wireless mesh network.

CHAPTER FIVE

5 WIRELESS MESH SYSTEM DESIGN

5.1 Introduction

A poorly designed network can have serious cost and safety implications. This chapter presents design considerations that must be considered by network engineers when designing a wireless communication system. This chapter begins by discussing link budget analysis, Fresnel zone clearance and network topology designs that must be considered by network engineers. This chapter ends with a discussion on experimental designs that will be conducted to analyse the performance of the wireless mesh network.

5.2 Link budget analysis for radio systems

Link budget analysis is a calculation of the amount of power that is received by a receiver that is some distance apart from a transmitter. It considers the losses that a signal will experience throughout the network. As shown in Figure 23, some of the losses include cable losses and path loss. These losses attenuate the signal making it difficult to establish a communication link. Link budget analysis is thus a helpful tool that assists network engineers to design wireless networks that are both functional and reliable by considering all the losses in the network. In this way, the coverage distance of the wireless network and its throughput, as well as other network performance parameters, can be determined. This section will focus on the calculations that are considered when performing link-budget-analysis. The scope of this work will only be limited to line-of-sight radio systems.

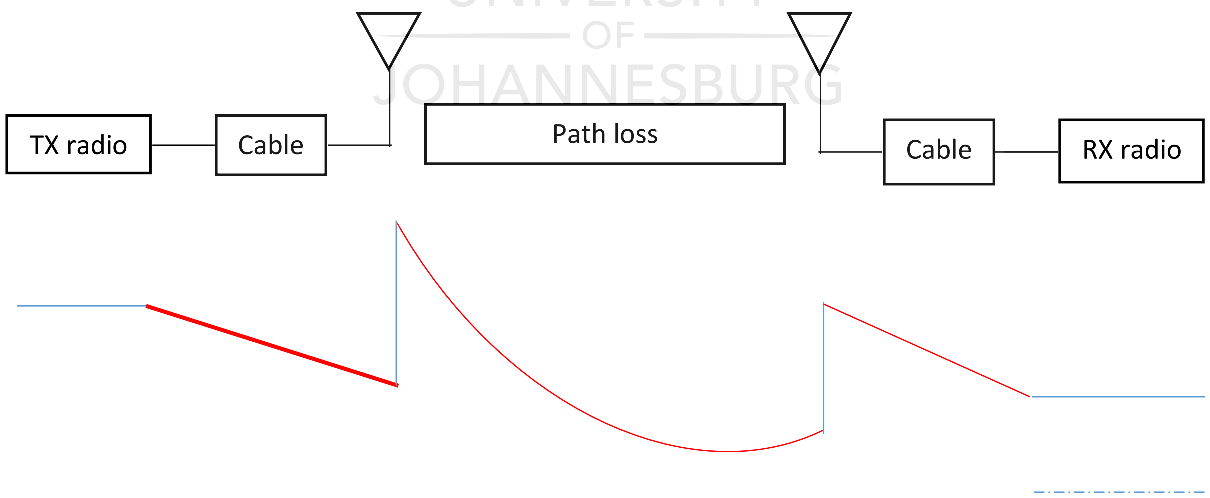

Figure 23: Losses in a wireless link

The link budget equation for a line of sight radio system is given in (4.1) and expressed in more detail in (4.2).

$$\text{Received Power (dBm)} = \text{Transmitted Power (dBm)} + \text{Gains (dB)} - \text{Losses (dB)} \quad (4.1)$$

$$P_{RX} = P_{TX} + G_{TX} + G_{RX} - L_{TX} - L_{FS} - L_m - L_{RX} \quad (4.2)$$

where:

P_{RX} = Power of the receiver in dBm,

P_{TX} = Power of the transmitter in dBm,

G_{TX} = Antenna gain of the transmitter in dBi,

G_{RX} = Antenna gain of the receiver in dBi,

L_{TX} = transmitters losses from cables and connectors in dB,

L_{FS} = free space losses or path loss in dB,

L_m = miscellaneous losses from fading margin or body losses in dB, and

L_{RX} = receiver losses from cables and connectors in dB.

For this mesh radio system, the following parameters will be considered as follows:

- Miscellaneous losses (*LM*) from fading margin or body losses will be set to zero for this approximation.
- Since radios with the same parameters will be used in this project for transmitting and receiving signals, it follows that the transmitter and receiver gains will be the same and that the losses experienced at the transmitter and receiver will be the same.

Therefore, for this approximation,

- $G_{TX} = G_{RX}$
- $L_{TX} = L_{RX} = L_{Total}$

Equation (4.2) can now be expressed in terms of free space loss as follows:

$$L_{FS} = P_{TX} - P_{RX} - 2\,L_{Total} + 2G_{TX} \quad (4.3)$$

$$L_{FS}\,(dB) = 10\,log_{10}\left(\frac{4\pi Df}{c}\right)^2 \quad (4.4)$$

$$\lambda = c/f \quad (4.5)$$

$$L_{FS}\,(dB) = 20\,log_{10}\left(\frac{4\pi D}{\lambda}\right) \quad (4.6)$$

where *D* is the distance between radio nodes, λ *is* the signal wavelength and L_{FS} is the power loss in dBm.

Equation (4.3) can now be written as:

$$10\ log_{10}\left(\frac{4\pi Df}{c}\right)^2 = P_{TX} - P_{RX} - 2\ L_{Total} + 2G_{TX} \qquad (4.7)$$

Solving for D:

$$D = \lambda \frac{10^{\frac{P_{TX} - P_{RX} - 2\ L_{Total} + 2G_{TX}}{20}}}{4\pi} \qquad (4.8)$$

According to (4.8), *D* is the largest distance that can separate the transmitter and receiver and still establish communication between the radio nodes. The radio nodes for this project have about 45m indoor coverage range and 150m outdoor coverage range. When this mesh system is deployed in underground mine tunnels, the coverage range might reduce due to high signal propagation losses in the mine tunnels.

5.3 Fresnel zone clearance

Physical obstructions between transmitting radio nodes contribute to propagation losses on a wireless communication link. Figure 24 illustrates a radio frequency line of sight that is characterised by Fresnel zones, elliptic radiation patterns between radio nodes. In order to achieve a reliable communication link, physical obstructions must be removed to maintain a clear line of sight between radio nodes, because objects that lie in the Fresnel zones cause signal attenuation. This can be achieved by placing the radio antennas several meters above the ground.

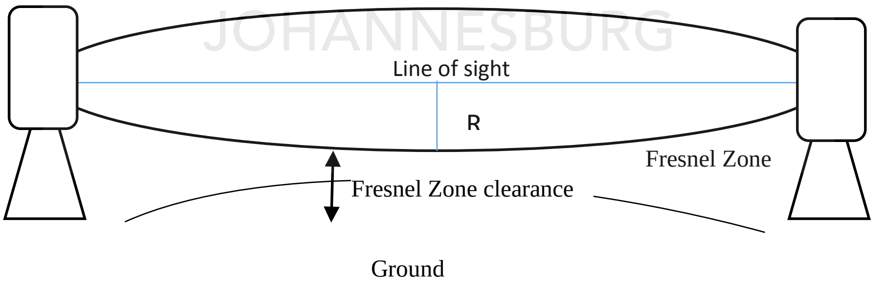

Figure 24: Fresnel Zones

The equation for determining the *nth* Fresnel zone can be expressed as [71]:

$$F_n = \left(\sqrt{n}\right) F_1 \qquad (4.9)$$

$$F_1 = \sqrt{\frac{\lambda\ (d_1 d_2)}{d}} \qquad (4.10)$$

Where:

d_1 = distance to the near end of the path

d_2= distance to the far end of the path

d=total path length

Taking d in km and f in GHz we get:

$$F_1 = 17.32\sqrt{\frac{(d_1 d_2)}{f \times d}} \tag{4.11}$$

Assuming that $d_1 = d_2 =$ d and using the 45m indoor range of the OM2P, the first Fresnel zone can be calculated as follows:

$$F_1 = 17.32\sqrt{\frac{d}{f}} \tag{4.12}$$

$$F_1 = 17.32\sqrt{\frac{0.045}{2.45 \times 10^9 GHz}} \tag{4.13}$$

Resulting in a Fresnel diameter of 2.44m and a Fresnel radius of 1.22m.

This means that at least a 0.5m clearance distance off the ground is needed to avoid the ground from interfering with the Fresnel zone. Therefore, the use of 1.8m tripods will be suitable to take care of the Fresnel zone clearance as shown in Figure 25.

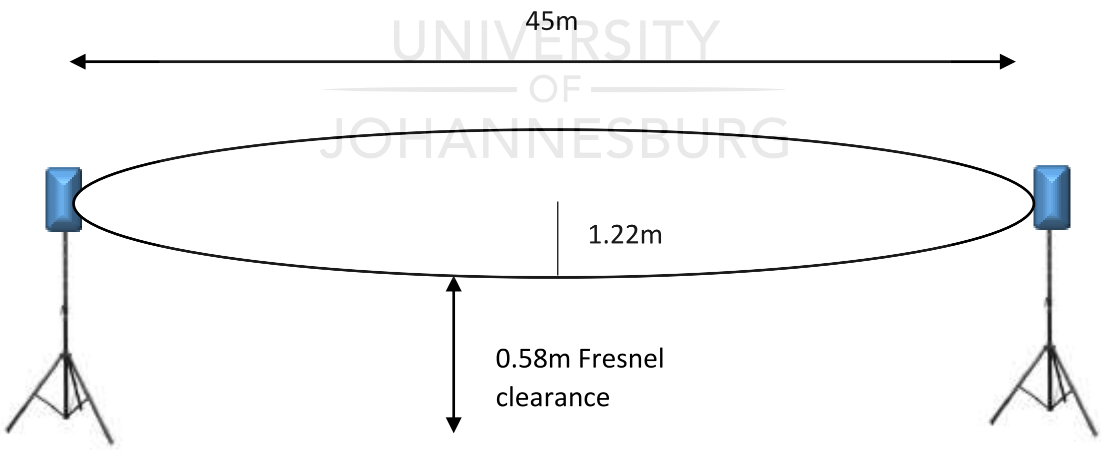

Figure 25: Fresnel zone for OM2P 45m apart

5.4 Mesh network topologies

In this section, an overview of topology design options for wireless mesh networks is presented and the options are compared against each other of which, one option is chosen for implementation.

5.4.1 Point-to-point WMN

The wireless point-to-point mesh network topology design is illustrated in Figure 27. The network consists of a personal computer (PC1), mesh gate router (MGR), mesh routers (MR1-MR3) and mesh clients (MC1–MC7). On the surface, the PC1 computer is connected to the MGR using a network cable. Mesh routers (MR1-MR3) are wirelessly connected to each other and with the mesh gate router (MGR) at a separation distance of at least 100m apart. End devices (MC1-MC7) are wirelessly connected to mesh routers at the same separation distance. In this way, data from end devices such as wireless sensors, VoIP phones, etc. can be communicated wirelessly to the surface control operators.

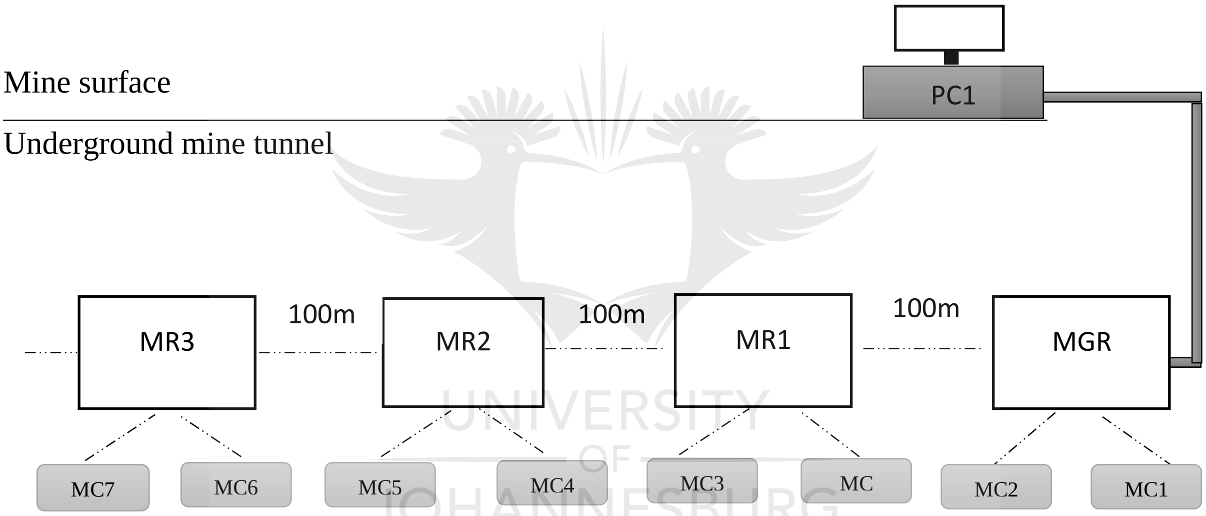

Figure 26: Block system design of point-to-point network topology

5.4.2 Long-range mesh network with high-gain antennas

A long-range mesh network can be achieved by using mesh routers and high-gain antennas as depicted in Figure 27. The network topology consists of a multi-point full mesh network where every mesh router (MR2-MR4) is linked to every other router in the stope of an underground mine. Data collected from mesh clients (MC1-MC3) in the stope is then transmitted to the MGR via high-gain antennas that have a transmission range of over 1km. The wireless network can be monitored and managed by PC1 on the surface of the mine.

The advantage of this network topology is that with the help of high-gain antennas, the most distant dynamic areas of the mine can be monitored. The deployment of this network topology would be cost-effective because the number of mesh routers required for long-distance coverage is few due to the use of high-gain antennas. However, high-gain Poynting antennas are bidirectional and not omnidirectional, as such, signals from other angles cannot be picked up by the antenna.

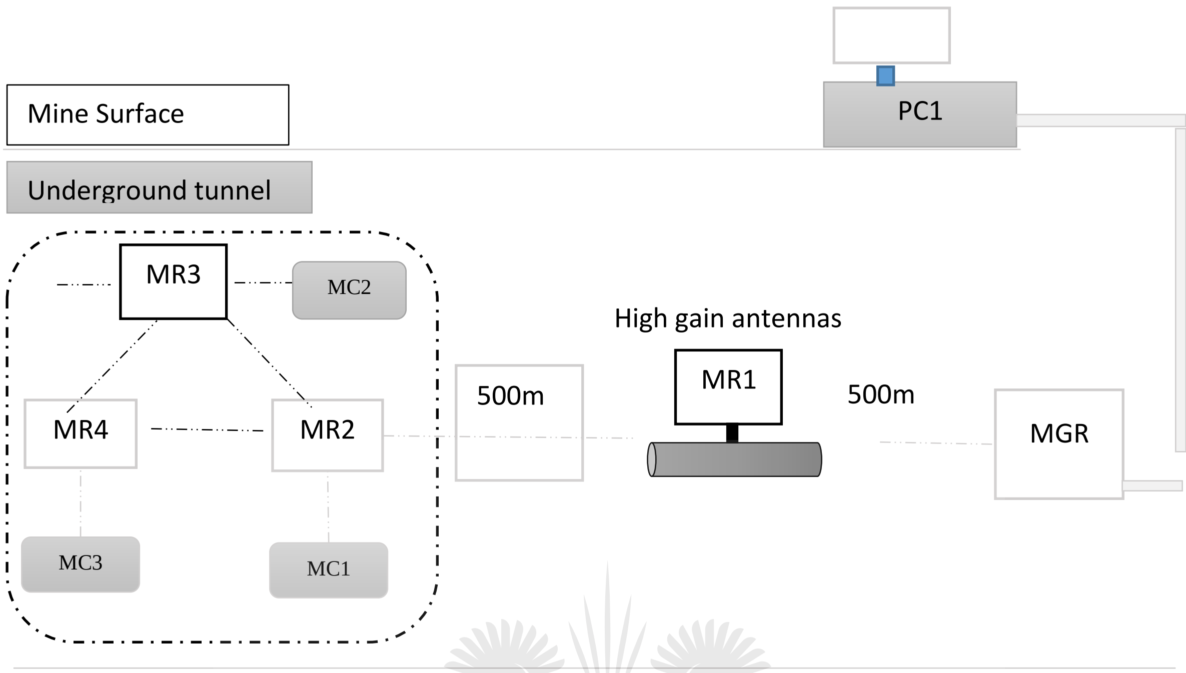

Figure 27: Wireless mesh network design using high gain antennas

5.4.3 Clustered mesh network topology

A clustered mesh network topology is one in which the network is dynamically grouped into sub-groups called clusters. Each cluster is composed of a cluster head, cluster members and gateway nodes that connect to clusters. Figure 28 illustrates this network topology. Routers 4 and 5 are connected to the rest of the network via router 7. Data from mesh clients (Laptop 1 and VoIP phones) can be transmitted to the surface mine operators. This type of network topology can be useful when establishing communication between devices that are around the corners of an underground mine. Instead of having a full mesh network around a corner, a clustered mesh network would prove cost-effective with ease of deployment.

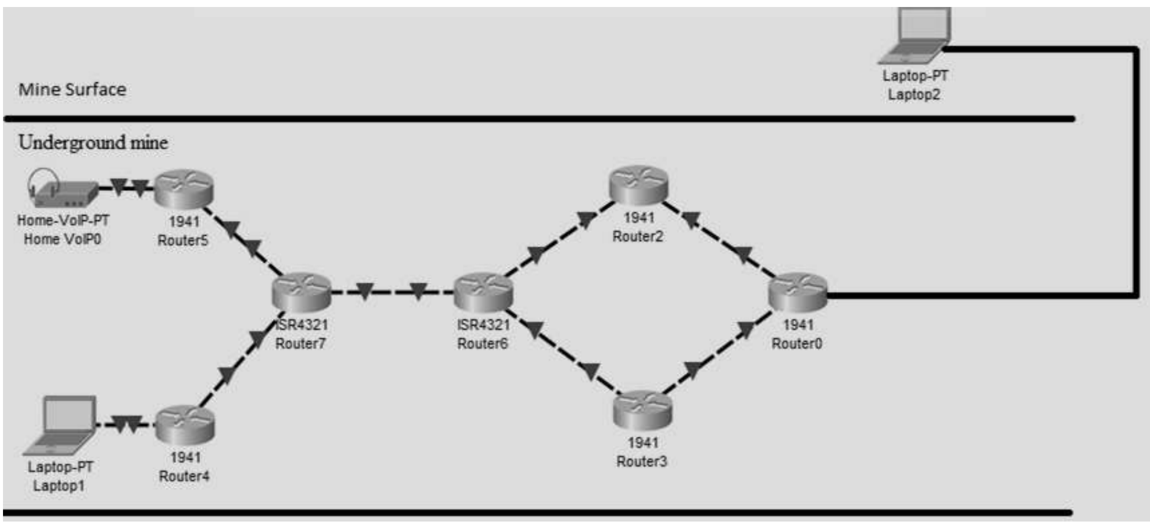

Figure 28: Cluster mesh network topology

However, the failure of a cluster-head wireless access point would result in communication failure from that point forward. Considering the different mesh topology designs and their related advantages and disadvantages, a point-to-point and long-range mesh topology with high-gain antennas would be suitable for implementation because of the limited number of radios which will be used in laying out a mesh network. Clustered wireless mesh networks will require more radio nodes to achieve the same coverage distance of the point-to-point mesh network. In addition, the mine tunnels are not wide enough to cater for the clustered network topology. The next section discusses the measurement methodology for the experiments that will be conducted on the network.

5.5 Experimental design and measurement process

In this section, we will be discussing some experiments that will be conducted on a mesh network and the methodology that will be used to collect the results on the performance of the mesh network. Experiments that will be conducted include; signal strength as a function of the distance between radio nodes, throughput as a function of the number of radio nodes on the network, throughput, latency, signal to noise ratio of the network and coverage distance of the network.

5.5.1 Signal strength measurement

Signal strength measurement will be conducted as a function of the distance between radio nodes. The objective of this experiment is to define the relationship between the radiated RF power and the increase of distance between radio nodes. Understanding this relationship is vital for network engineers to strategically place the radio nodes in the right locations that will facilitate a workable mesh network. The inverse square law for the intensity of radiated electromagnetic waves states that the intensity is inversely proportional to the square of the distance from the source as shown [72]:

$$I \propto \frac{1}{r^2} \tag{4.10}$$

This law will be verified in this experiment. To achieve this, radio nodes will be connected in a point-to-point topology at a separation distance of 5m apart. Using the Wi-Fi tool, the signal strength will be measured 5m away from the furthest radio node. The distance between radio nodes will be increased by 5m and the measurement process will be repeated until the separation distance between the radio nodes is 25m. The results will be collected and recorded for analysis.

5.5.2 Throughput as a function of radio nodes

Network throughput refers to the amount of data units that a system can process. It is a measure of the amount of data measured in bits per second that can be transmitted on a given network. Throughput affects the performance and application of a network the, the amount of throughput can be used to determine whether a given network is capable of transmitting data, voice and/or video. In this experiment, the overall data speed of the wireless mesh network will be determined as a function of radio nodes. To achieve this, radio nodes will be connected in a point-to-point (PTP) topology with a 20m separation distance. iPerf, a bandwidth measuring tool will then be used to measure the maximum achievable bandwidth on the networks. In theory, the gateway access point should have higher throughput than all mesh nodes in a PTP topology. The experiment will be repeated four times with a 10m increase in the separation distance between the radio nodes for every iteration. The results collected from this experiment will indicate an influence of distance on radio throughput.

5.5.3 Latency

Standard 32-byte ping packets will be sent for 10 seconds. The ping reports will indicate the round-trip time of the packets; this is the latency of the network. To some degree, latency should be directly proportional to the number of hops in a specific route when sending data, however, other factors such as interference, number of users on the network, or poor quality links contribute significantly to the quality of network latency. Network latency is very important when it comes to sending real-time data on the network.

5.5.4 Packet delivery ratio

The ping tool also reports the amount of packet loss that occurred over the duration of the ping test. As such, radio nodes will be set up in a PTP topology at a separation distance of 5m. Two computers will be connected to the network, one at 5m from the mesh gateway and the other will be 5m from the furthest node. A ping tool will be used to send ping packets between the two PCs. By looking at a ping report, the number of packets delivered, and the number of packets lost will indicate the packet delivery ratio of the network. This experiment will be repeated with varying distances between the radio nodes.

5.5.5 Signal to noise ratio (SNR)

The ratio of the transmitted signals to the noise signals in the channel is called the signal-to-noise ratio. This ratio is very important as it indicates the feasibility of transmitting data on a given network. By using the Wi-Fi tool, SNR will be measured 5m from the furthest node on a PTP mesh topology. This experiment will be repeated five times with varying distances between the nodes.

5.5.6 Mesh capability of mesh nodes

In this set of experiments, the aim is to confirm that the mesh nodes are actually meshing together to transmit data packets across the network. To investigate the mesh capabilities of the mesh units, the units will be connected in a point-to-point topology at 20m of internode spacing. When all the mesh units are connected to the network, a server machine will be connected to the first mesh node and a client machine will be wirelessly connected to the last node. Ping packets will be transmitted from the client to the server across the network and vice versa. Trace Route command line will then be used to trace the path taken by ping packets. Traceroute will count the number of hops traversed by the ping packets and also show the IP addresses of the mesh access points. Nodes will be added/removed from the network by turning them on/off. Ping packets will then be transmitted across the network and traceroute will be used to trace the path taken. By evaluating the route changes in the path taken by ping packets, and observing the increase or reduction in network speed when nodes are added or removed from the network, one can verify the self-forming and self-healing properties of wireless mesh networks.

5.5.7 Communication around corners of the mine

One of the main challenges associated with communication in underground mines is communication with devices that is around a corner or is hidden by big machinery. This is a big challenge more especially for the line of sight communication in undergrounds mine tunnels. Long mine tunnels behave as waveguides and underground mine tunnel corners tend to leak signals. As a result, there is poor communication around a corner due to path loss, signal reflections, scattering, etc. which results in reduced received signal strength. For wireless mesh networks, this challenge can be solved by simply altering the topology of the network and the number of radio nodes to facilitate communication with devices around a corner. Depending on the type of a corner that is encountered, L-shaped or T-junction corners, the topology of the network can be easily altered, respectively.

In this experiment, the radio nodes will be connected in a U topology as shown in Figure 29. Ping packets will be sent from node 1 to node 6 to ensure that communication with devices on either side of the corner is feasible.

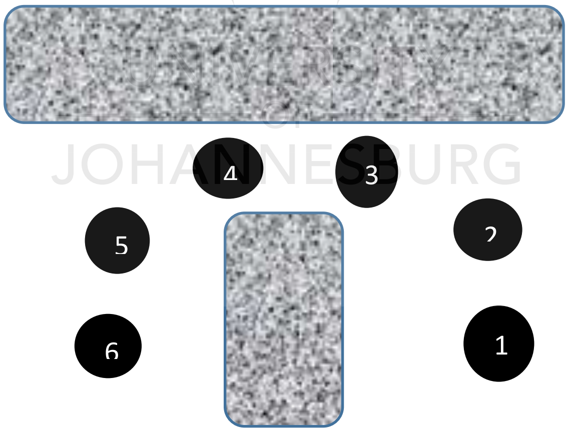

Figure 29: Network layout around the corner of a mine

5.5.8 Enhancing mesh network coverage range

One of the main disadvantages of high-frequency underground wireless mesh networks is that they are limited in coverage range. There are various methods that are employed in extending the coverage range of underground wireless networks. Some of these methods include the use of range extenders, such as battery-operated wireless repeaters, using transceivers with high transmission power and the use of longer network cables. In this experiment, a unidirectional

15 dBi high-gain Poynting antenna will be used to extend the network coverage distance. The mesh network will be laid out as depicted in Figure 30 (A-D). By using a high-gain Poynting antenna, the coverage range of the wireless mesh network will be extended. The objective of this experiment is to determine how effective the use of high-gain antennas in extending coverage distance is.

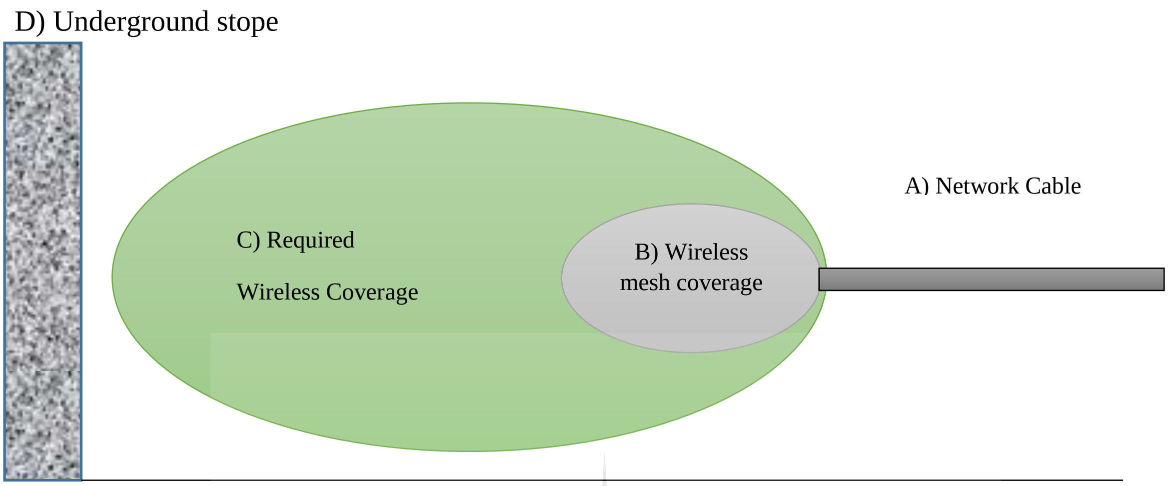

Figure 30: Mesh network layout in an underground mine tunnel

The idea is that an access point will be connected to a network cable at point A. The access point will serve as a gateway to the existing network. When configured, a 15 dBi high-gain antenna will be attached to the gateway access point. Six wireless repeater nodes will then be configured and connected in a point-to-point topology to the gateway access point. With nearly maximum separation distance between the radio nodes, the coverage distance will be measured from the gateway router to the furthest radio node on the network.

5.5.9 Conclusion

In this chapter, we have considered design parameters for wireless mesh networks and including the link budget analysis methodology as well as the measurement process for conducting experimental tests. The next chapter presents an implementation overview of the mesh system.

CHAPTER SIX

6 CONSTRUCTION AND IMPLEMENTATION OF A PROOF OF CONCEPT MESH NETWORK

6.1 Introduction

This chapter describes the construction of the mesh network that will be deployed to characterise the performance of wireless mesh networks in underground mining environments. This chapter begins by discussing the different components of the mesh network and highlights the cost implications associated with the construction of the wireless mesh prototype system. The implementation overview is then presented at the end of the chapter.

6.2 Description of mesh network components

This section aims at giving a brief description of system components for the proof of concept mesh network.

6.2.1 Stream PC

Two laptops will be required for this project. One laptop will be used to manage the network and the other will be used to function as a client on the network. The following are the specifications:

STREAM PC: N3060, 1.6 GHz., 4 GB, 32 GB Emmc

6.2.2 TP-Link WR941HP Wi-Fi router

Figure 31 shows a Wi-Fi router that will be used to give IP addresses to clients on the network. This high-power router offers three modes of operation: router, access point, and range extender. The three 9 dBi high-gain detachable antennas provide a superior range of up to 900 m^2. Rated at 30 dBm transmission power, the TP-Link WR941HP provides speeds of up to 450 Mbps, ideal for video streaming and VoIP application. Supported standards include IEEE 802.11b/g/n at an operational frequency of 2.4 GHz.

Figure 31: TP-Link WR941HP 450Mbps High Power Wi-Fi Router [66]

6.2.3 Open mesh access points

Figure 32 shows an open mesh (OM) access point for extending a wireless network wherever an internet connection is needed. The OM2P series uses BATMAN advanced (BATMAN Adv.) routing protocol. In general, BATMAN comes in two types: BATMAN, a user space daemon (BATMANd) routing on layer 3 and BATMAN adv. a layer 2 routing protocol. BATMAN Adv. protocol offers better performance compared to BATMANd. Some of the special features in BATMAN Adv. include OGM aggregation which reduces the overhead introduced by sending many small frames, as well as optimizations to harness the availability of multiple interfaces among other special features [73].

Figure 32: Open-Mesh AP – 150mbps [74]

6.2.4 OM2P Enclosure

The access points will be tested in underground mines which are full of dust and water, it is important to protect the access points by placing them in protective enclosures. As such, Figure 33 shows the outdoor OM2P enclosures which will be used to protect access points from dust and water.

Figure 33: Outdoor OM2P Enclosure

6.2.5 12V Lead-acid batteries

The 12V lead batteries shown in Figure 34 will be needed to provide power to Open Mesh access points. The batteries are rated as follows:

- Voltage: 12V
- Nominal capacity: 7.2 A.H.
- Weight: 2.15kg

Figure 34: RT1272 Lead Acid battery

5.2.5.1 Battery run-time

To calculate the battery run-time when subjected to an access point, we consider the following:

- Duration runtime= Battery capacity (A.H.) / load current (A).
- The load current for the access points at 12V DC is 1A.

Therefore, the battery run time of the acid batteries will be 7.2A.H/1A=7.2 hours.

This result shows that the battery capacity is sufficient enough to power access points for approximately 7 hours during experimental tests. However, this time duration is an estimate of the battery run-time, the battery may run for about 5-6 hours in real life, which is enough to run experiments on the wireless mesh network.

6.2.6 Lead-acid battery charger

The acid battery charger, Figure 35, will be used to recharge the batteries when the energy in them is depleted.

Figure 35: Charger for sealed lead acid battery

6.2.7 *Wireless network tester*

The wireless spectrum analyser in Figure 36 will be a useful tool in measuring Wi-Fi signal strength, signal to noise ratio of the channel and other important network parameters. The AirCheck G2 wireless tester is a useful tool for engineers performing network analysis. In addition, the device is highly portable and easy to use.

Figure 36: AirCheck G2 Wireless tester

6.2.8 *HELLI-4 Poynting antenna*

The Poynting antenna shown in Figure 37 will be used to extend the coverage range of the mesh network. The antenna is a unidirectional antenna that has a gain of about 15 dBi, operates in the 2 400 – 2 500 MHz range and weighs about 1.25 kg. The antenna is hard wearing and thus best suited for the mining environment.

Figure 37: HELLI-4 Poynting antenna

6.2.9 *Power over Ethernet (PoE) switch*

The PoE switch in Figure 38 will be used to power Wi-Fi devices such as access points and to transmit data at the same time.

Figure 38: TP-Link 5 Port Gigabit Desktop PoE Switch.

6.2.10 Tripod stands

Figure 39 shows tripod stands which will be used to suspend access points 1.8m from the ground during experimental tests in underground mines.

Figure 39: 1.8m Tripod Stands

6.2.11 Equipment protective case

The 1610 Pelican case in Figure 40 will be useful in carrying equipment several meters underground. The case is dustproof and watertight. This case will ensure that the equipment is transported and kept in a safe way.

Figure 40: 1610 Pelican Protector Case

6.3 Total cost of equipment

The cost of each equipment is shown in Table 3. Purchasing mesh equipment is fairly cheap, what made this system expensive is the Wi-Fi measuring devices (AirCheckG2) and Acer Laptops which takes over 50% of the budget.

Table 3: Cost of Equipment

Equipment	Quantity	Prices
OM2P Series	7	R10 289,93
OM2P Series Enclosures	7	R2 768,50
Acer Laptops	2	R8 661,00
12V RITAR Sealed Lead Acid Battery	7	R1 680,00
13,8V 1A2 Charger for 12V Batteries	1	R909,00
AirCheck G2	1	R35 410,00
1,8m Tripod stands	8	R3 560,00
GIGASET VoIP Phones * Items purchased for another study using the same network setup.	2	R2 901,80
HELI 4 15dBi POYNTING Antenna	1	R4 195,33
PELICAN equipment case	1	R6 050,00
TP-LINK 5 port switch with 4-Port PoE	1	R1 640,00
Total without VAT		**R78 065,56**
VAT		**R11 709,84**
Total with VAT		**R89 775,40**
Allotted Budget		**R90 000.00**

6.4 Implementation overview of mesh systems

This section aims at discussing the process taken to implement a wireless mesh network. A step-by-step measurement process for collecting experimental results and the associated challenges with implementing this system have also been presented and discussed in this section.

6.4.1 Mesh system specification

Having purchased the required equipment, a wireless mesh network testbed of seven radio nodes was set up with the following system specifications:

- Access points: 7 Open Mesh access points.
- Radio: 802.11 b/g/n
- Frequency: 2.4GHz.
- Rated speed: 150Mbps.
- Transmitter power: 26dBm
- Processor: 400 MHz QCA9331, MIPS 24K.
- Range: 22m-45m indoor per access point and 100m-150m outdoor.

6.4.2 Implementation overview

A wireless mesh network was set up at the University of Johannesburg (UJ) in an attempt to study the performance of wireless mesh networks. The first set of experiments was conducted at UJ Auckland Park Kingsway (APK) campus along the passage/ways, these tests are referred to as indoor tests. The second set of experiments was conducted in a mock mine at the Doorfontein campus at UJ. The last set of experimental tests were conducted in an underground tunnel of Bathopele Platinum Mine. The experimental results from the three environments were then compared against each other to observe the performance of the wireless mesh network.

Figure 41 illustrates UJ passage/ways that were used to set up and test the indoor network. Figures. 42 and 43 illustrate the setup of the wireless mesh network in a mock mine tunnel at UJ and the mesh system set up in Bathopele Platinum Mine. In all the experimental tests, a computer was connected to the router and DHCP configurations were set on the router. A cloud-based network management software called CloudTrax was then used to manage the mesh network. Network settings such as network SSIDs, transmitter power, bandwidth, etc. were configured on CloudTrax. OM2P access points were then connected to the internet through the router to download their settings from CloudTrax. The first access point connected to the router acts as a gateway node and it also gives out IP addresses to other OM2P access points. The remaining six OM2P series had to be mounted on the tripods and a 12V DC battery pack was used to provide power for the mesh units.

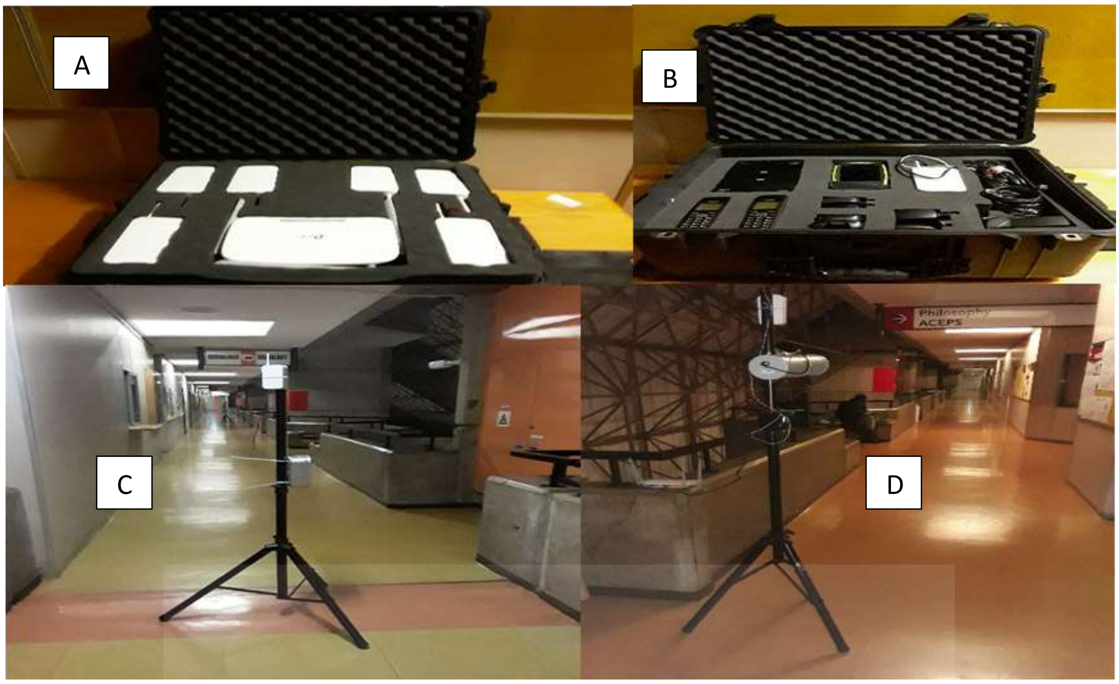

Figure 41: Experimental set up along the UJ passageway. A-B shows equipment which was used, C-D illustrate the passageways that were used for testing the system.

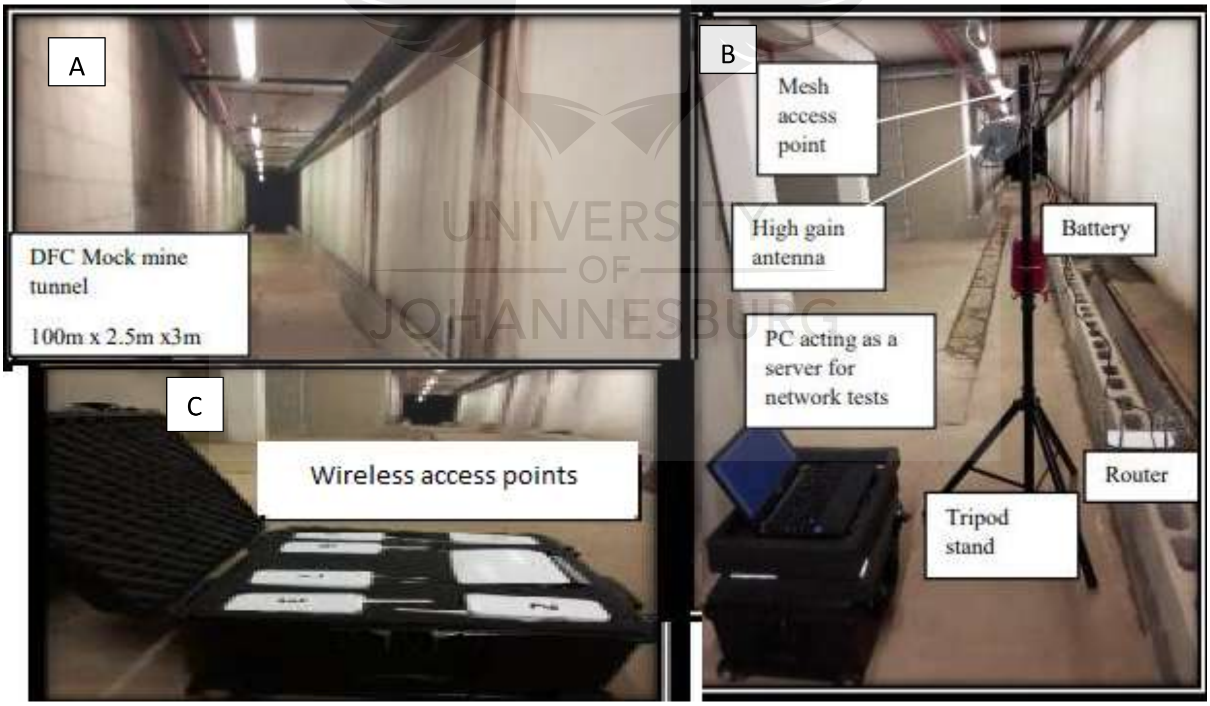

Figure 42: Experimental set up in a mock mine tunnel. Figure A illustrates the mock mine at UJ. B shows the system setup and C shows the OM2P accesspoints which were used in this experiment.

The underground mine tunnel in Bathopele Mine was 6m wide, 2.1m high and over 500m long. The tunnel also had stagnant water, very rough uneven tunnel walls and tunnel junctions leading to other tunnels. The mine tunnel was used to set up the wireless mesh network and conduct experimental tests. Figures. 43 and 44 show how the network was set up for experimental tests.

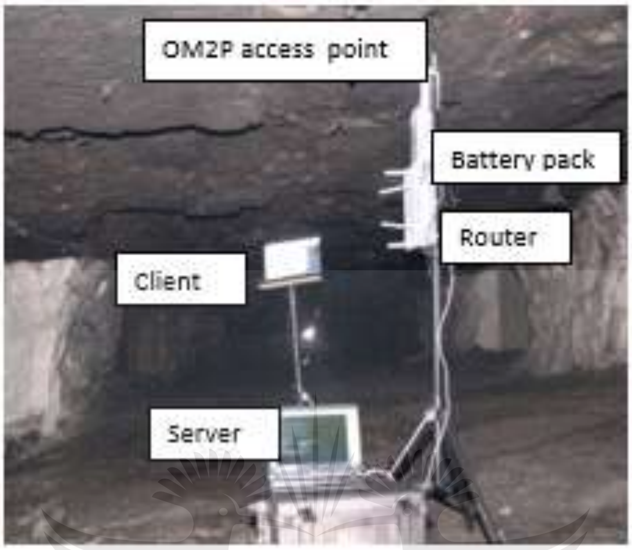

Figure 43: Experimental set up in Bathopele Platinum Mine tunnel

6.5 Experimental tests and measurement process

6.5.1 Throughput and latency as a function of increasing mesh nodes

For this experiment, access points were mounted on tripods interspaced at 20m apart along the mine tunnel in a point-to-point topology as shown in Figure 45. The first OM2P series was connected to the router and then powered. The one Acer laptop was connected to the network at the router to act as a server. The second Acer laptop was used as a client on the network. When the first access point was powered on, network metrics were measured 10m away from the access point. The second access point was powered on and network throughput and latency were measured using the AirCheck G2 Wi-Fi tester and iPerf tools across the network between the client and server laptops. This was repeated up to the seventh OM2P access point. The internode spacing was kept constant at 20m at all times.

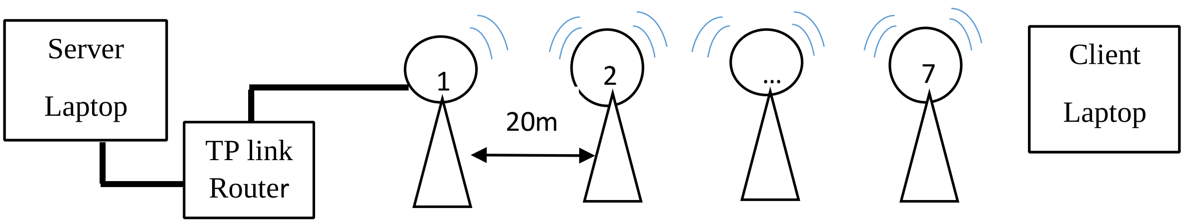

Figure 44: Point to point mesh network set up

6.5.2 *Influence of internode spacing on network throughput, latency, SNR and RSS*

In this experiment, due to the short tunnel length of 500m, three access points were used to study the influence of distance on network latency and throughput. This was achieved by interspacing 7 nodes at 20m and increasing internode spacing in steps of 10m and observing the trend in the measured network metrics. Network metrics were measured 10m from the furthest mesh node 7 across the network by using the AirCheck G2 and iPerf tool.

6.5.3 *Enhancing network coverage distance by using high-gain antennas*

For this experiment as shown in Figure 45, mesh node 1 was fitted with a 15dBi high-gain antenna. The second mesh node was placed at the point where the RSS from node 1 was reading -67dBm. The distance between node 1 and node 2 was then measured in meters. Network parameters were then measured at node 2. The obtained results were recorded to observe the trend in the performance of the network.

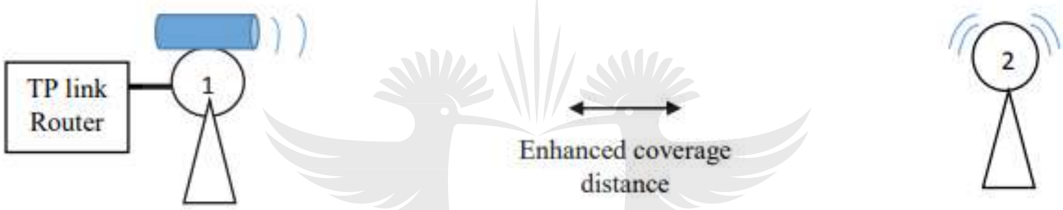

Figure 45: Enhancing network coverage range

6.6 Challenges experienced on setting up a mesh network

6.6.1 *Choosing the right networking equipment*

There is a wide variety of networking equipment in the market and so choosing equipment that is mesh enabled and that best meets the project requirements and system specifications can be a huge challenge. Attention was directed to studying several different kinds of mesh networking equipment to ensure that the equipment to be purchased was the right equipment. Some of the major important factors in choosing the right equipment included the cost of the equipment, local suppliers of the equipment and specific functionalities of the networking equipment.

6.6.2 *Long procurement period*

Procuring equipment took about three months in all because of other equipment that needed to be shipped from the United States of America. This delay affected progress in conducting experimental tests.

6.6.3 A limited supply of specific networking equipment

The other challenge experienced while procuring equipment is a limited supply of equipment. The Open Mesh Company that we initially ordered mesh equipment was bought by another company called Datto which had an exclusive supply of mesh routers to the USA only. This change meant that we had to consider alternative options. Fortunately, EasyMesh Company supplied their last stock of OM2P series which was then used to set up a mesh network.

6.6.4 Safety of equipment

A secure lab space to study and store equipment was difficult to maintain since there are no telecommunications lab facilities at school just yet. This challenge meant that experimental tests had to be conducted along UJ's passage walkways or exam halls that had better space to set up and test the network.

6.6.5 Long experimental tests

The tests took long hours, over 4 hours, in most instances per experiment and working alone on this project was a bit difficult in the sense that carrying the equipment to the test location required at least two people. In addition, some tests required one to be 400m away from the equipment and leaving the equipment unattended was a significant risk. To counter this, help was sought from friends, however, their availability during the recess period was a bit of a challenge and that resulted in the delay of some of the experiments.

6.7 Conclusion

The setting up of a wireless mesh network was successful despite the challenges that were experienced on the project. The alternative course of action to counteract major drawbacks proved successful. The experiments in the Bathopele Platinum Mine were also successfully conducted without technical difficulties whatsoever. Every component in the system was fully compatible and functional. The next chapter discusses the experimental results.

CHAPTER SEVEN

7 ANALYSIS AND PRESENTATION OF RESULTS

7.1 Experimental results

In this section, preliminary experimental results are presented and analysed. Results obtained from Bathopele Platinum Mine, the mock mine tunnel and indoor tests are compared against each other to observe any environmental influence on the performance of the wireless mesh network.

7.1.1 Throughput as a function of mesh nodes

Experimental test results from the Bathopele Platinum Mine tunnel, mock mine tunnel, and indoor environment show that the average network throughput decreases with the increasing number of mesh nodes on the wireless network. The results in Figure 46 show that nearly half of the network throughput is lost on the second mesh node and adding more mesh nodes to

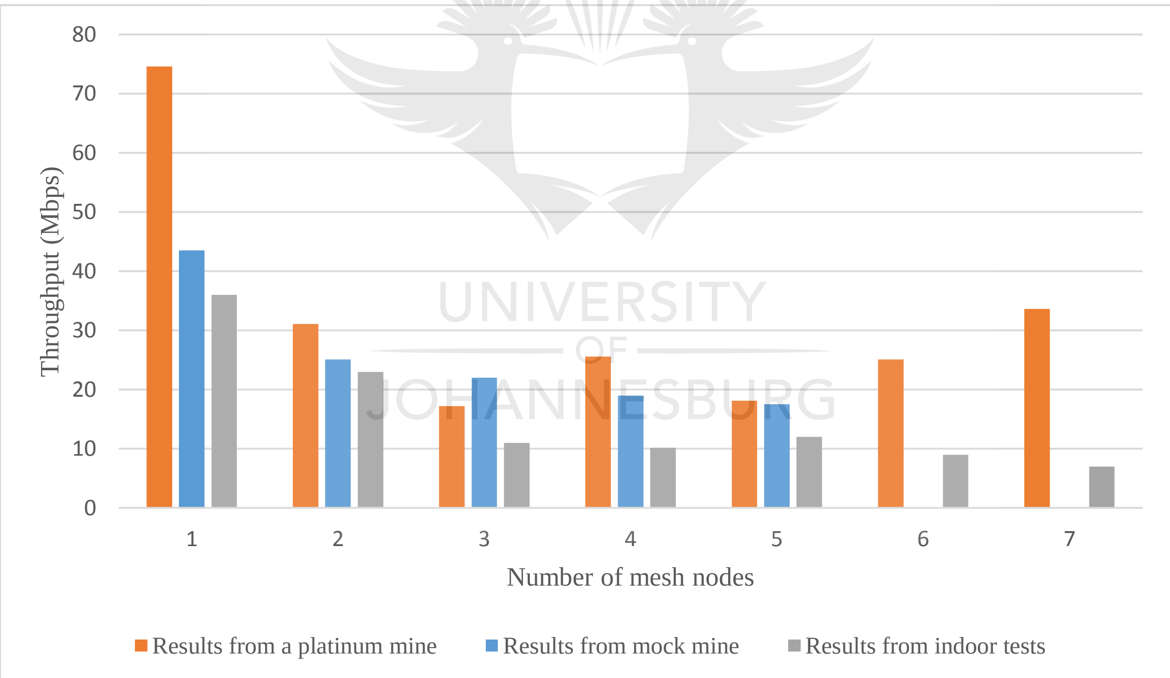

Figure 46: Throughput as a function of increasing mesh nodes

the wireless network results in a gradual decrease in the average network throughput. The reason for this observation is that when an access point receives data packets, it stores this data and determines a route to send the data packets to their intended destination. During this time, an access point will lose some of its bandwidth, hence the drop in network throughput. It is interesting to observe that throughput results from the Bathopele Platinum Mine tunnel are much higher compared to the indoor and mock mine throughput test results. This can be attributed to the behaviour of mine tunnels as waveguides for RF signal propagation. There are slight deviations to be considered. At nodes 3 and 5 there is a rapid decrease in the network speed. The reason for this observation is that the nodes were placed at positions in the mine tunnel with a larger cross-sectional area due to tunnel junctions at these points. Tunnel junctions allow for signals to escape the tunnel which is acting as a waveguide. This results in reduced signal strength, which inevitably reduces the network speed at these points.

Tunnel junctions act as openings that allow RF signals to escape the waveguide. The junctions contribute to the signal loss at these points; therefore, lower network speeds can be expected due to high signal attenuation at these junctions. Another interesting observation is the sudden increase in the network speed at node 7. This can be attributed to the inconsistency of the iPerf measuring tool in measuring network speeds on the network. Despite these abnormalities, adding more nodes on a wireless network constitutes a reduction in the overall network speed as is evidenced by the additional mock mine and indoor tests. As for network speeds in a mock mine being higher than indoor network tests, a mock mine tunnel with smooth walls without obstacles have path loss very close to zero [75]. Signal attenuation is much less compared to outdoor or indoor environments; thus, we should expect higher throughput and longer signal coverage in tunnels compared to indoor environments.

7.1.2 Latency as a function of increasing number of mesh nodes

The results in Figure 47 shows a relationship between network latency and increasing mesh nodes on the wireless mesh network. The results show that network latency for indoor tests is much higher compared to network latencies from a mock mine and platinum mine tunnels. This is because of high signal attenuation due to path loss in indoor environments. The observed network latencies from the platinum mining tunnel are very low indicating a high-speed wireless network. The average network fluctuates which shows an element of inconsistency in network latencies over a growing wireless mesh network. What can be deduced from these results is that running VoIP applications on a WMN with inconsistent network delays would prove difficult due to delays that would vary outside the tolerance of VoIP, on the contrary, telemetry applications would be suitable for wireless mesh networks. In general, the observed network delays are impressive for data transmission on the network.

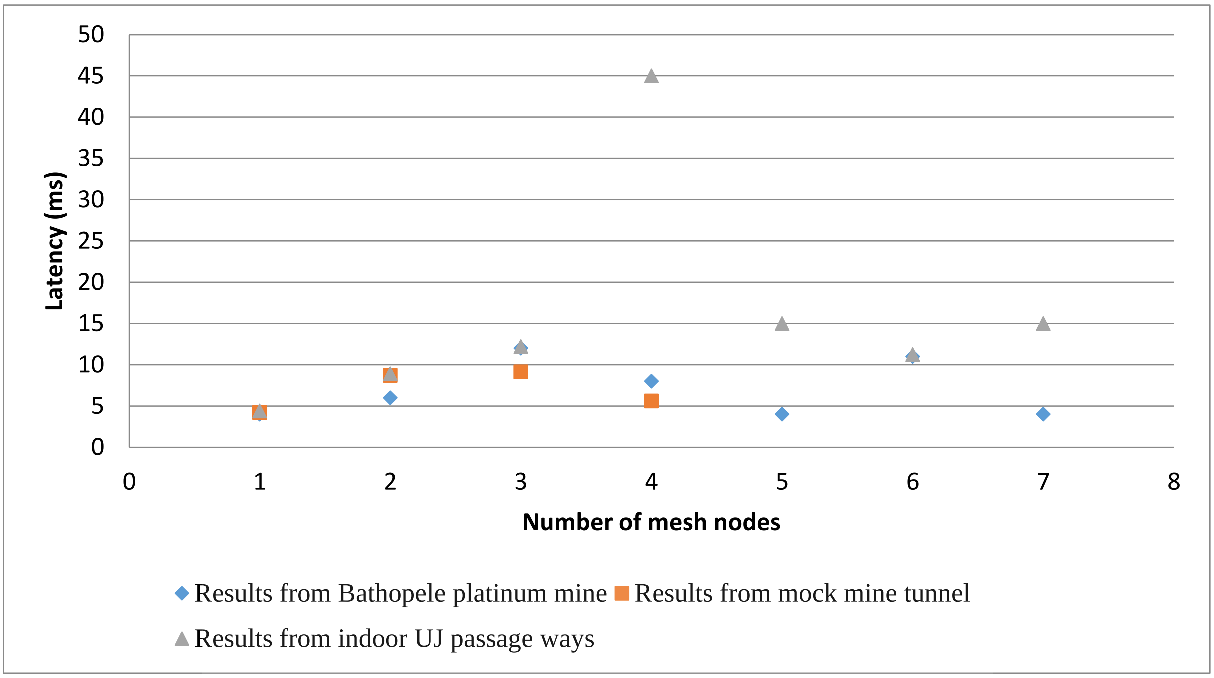

Figure 47: Latency as a function of increasing mesh nodes

7.1.3 Influence of internode spacing on network parameters

Experimental results that are shown in Figs. 48, 49, 50 and 51 illustrate the influence of internode spacing on network latency, throughput, RSS and SNR. The results in Figure 48 show a direct relationship between internode spacing and network latency for all environments under consideration. The reason for this observation is that increasing distance between mesh nodes means that the data packets will take longer to traverse the network. Therefore, increasing internode spacing will result in increased network latencies. However, the results also results show that the increase in distance does not yield very high network latencies, in fact, a 50m internode spacing of 7 mesh nodes in a platinum mine environment yields an average network latency of less than 10ms which is very good for data, voice and video transmission. Internode distance does not have a strong negative influence on network latency.

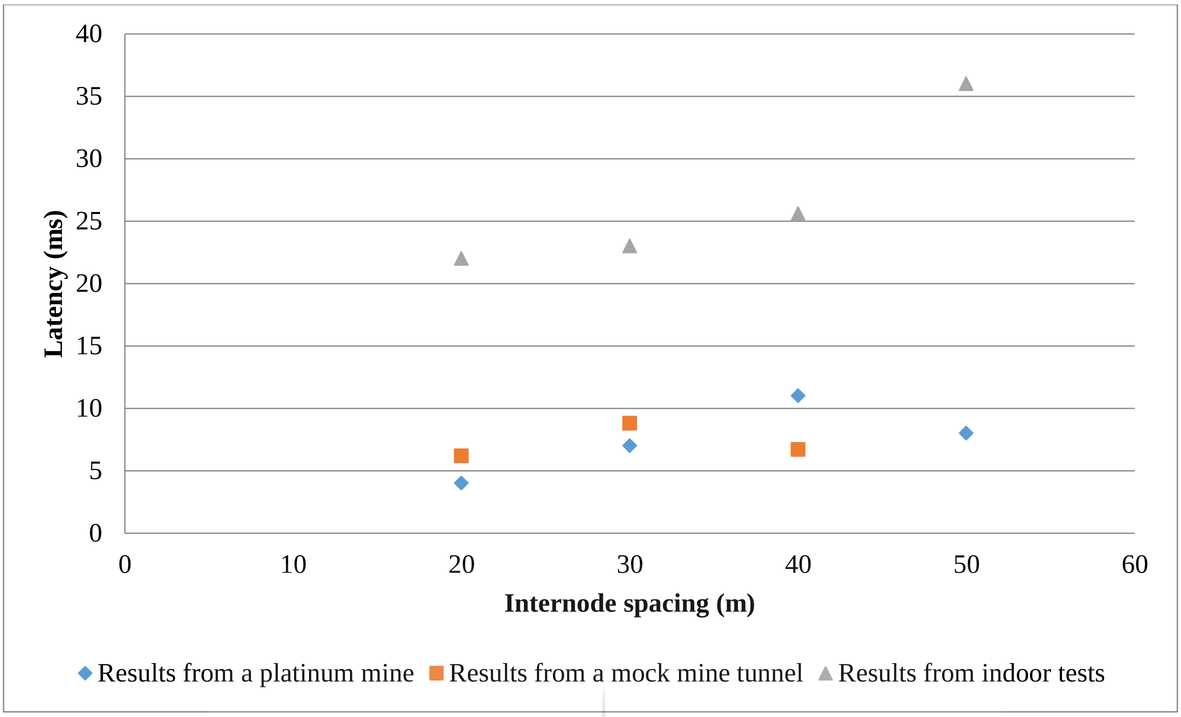

Figure 48: Latency as a function of internode spacing

The results in Figure 49 depict an inverse relationship between network throughput and internode spacing. It can be observed that increasing internode spacing reduces the average network throughput. Results from the platinum mine tunnel show that interspacing seven mesh nodes at 50m yields an average network throughput of 5.87 Mbps and a coverage distance of approximately 400m. Similarly, interspacing 3 mesh nodes at 20, 30, and 40m in a mock mine tunnel reduces the average network throughput on the network. However, the average reduction of throughput is less rapid in comparison to the indoor mesh network. These results indicate the influence of the geometry of an environment in which a wireless network is deployed on the performance of a communication system. These results also show that a 50m internode spacing is suitable to yield at least 1 Mbps of network speed.

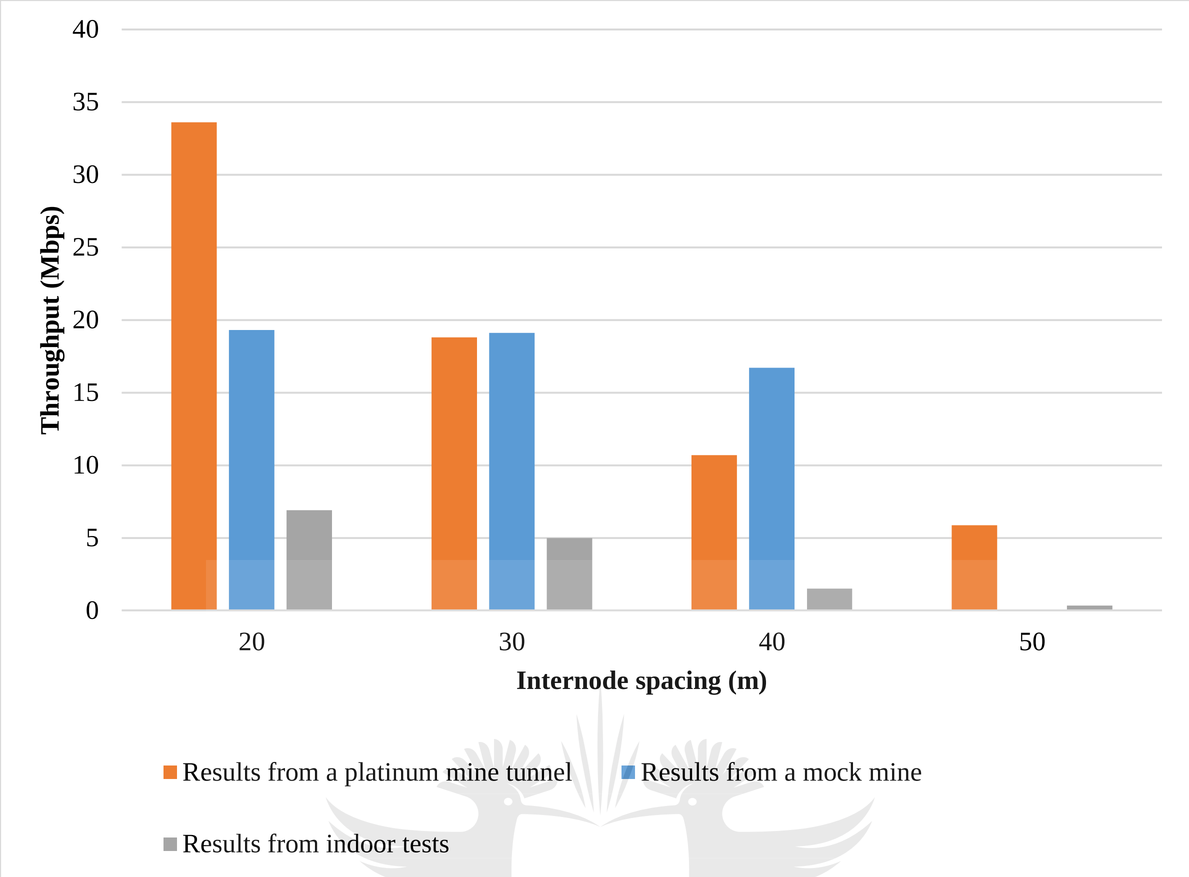

Figure 49: Throughput vs. internode spacing

The results in Figures 50 and 51 further illustrate the negative influence of internode spacing on RSS and SNR. RSS and SNR were measured using the AirCheck G2 network troubleshooting device. The transmitter was fitted with a 15dBi circular polarized unidirectional antenna. Measurements were taken 10m from the transmitter in increment steps of 10m. It can be seen that increasing the distance between the transmitter and receiver reduces the received signal strength and signal to noise ratio on the network. This can be attributed to the refraction of the transmitted signal into the surrounding environment as well as other signal attenuating factors such as signal reflections and path loss. However, it is interesting to observe that the power loss in the transmitted signal is less rapid because at 210m, the power of the transmitted signal is still good, -68dBm. Furthermore, from 10-210m, a gradual reduction in SNR is observed in Figure 51. Therefore, it can be concluded that there is an inverse relationship between RSS and distance, as well as SNR and distance. As such, care must be taken in choosing an internode spacing that will yield the required quality of service on the network.

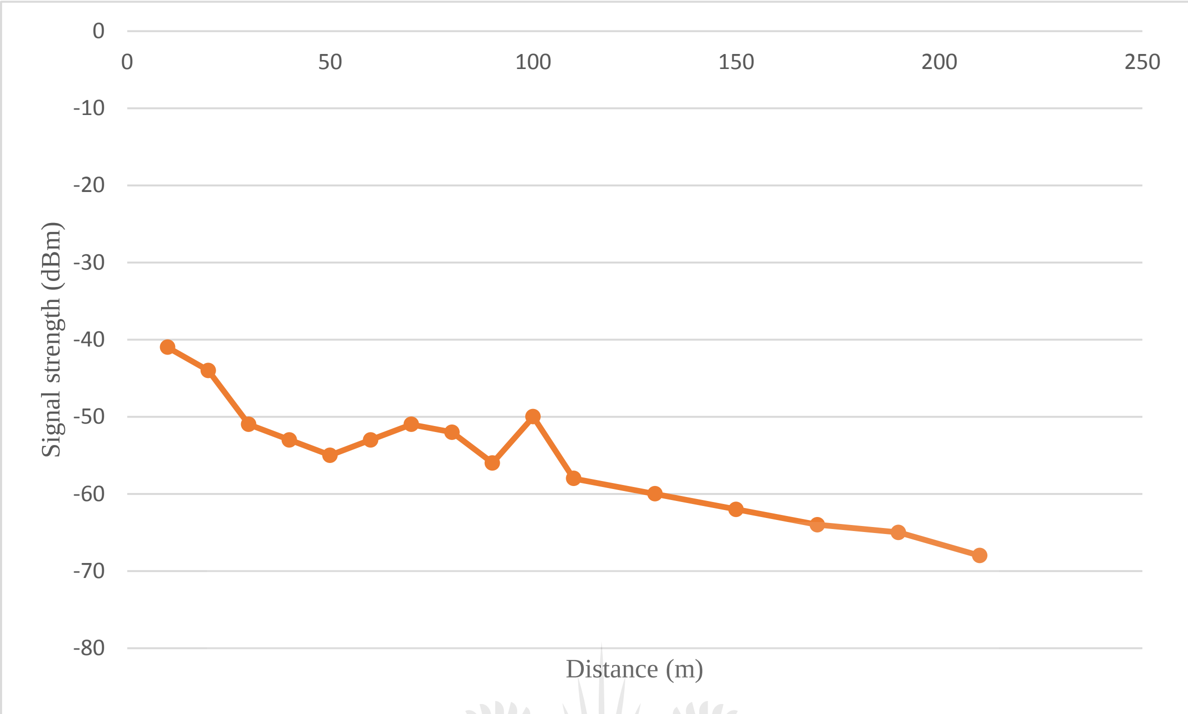

Figure 50: RSS vs. internode spacing, results from Bathopele Platinum Mine

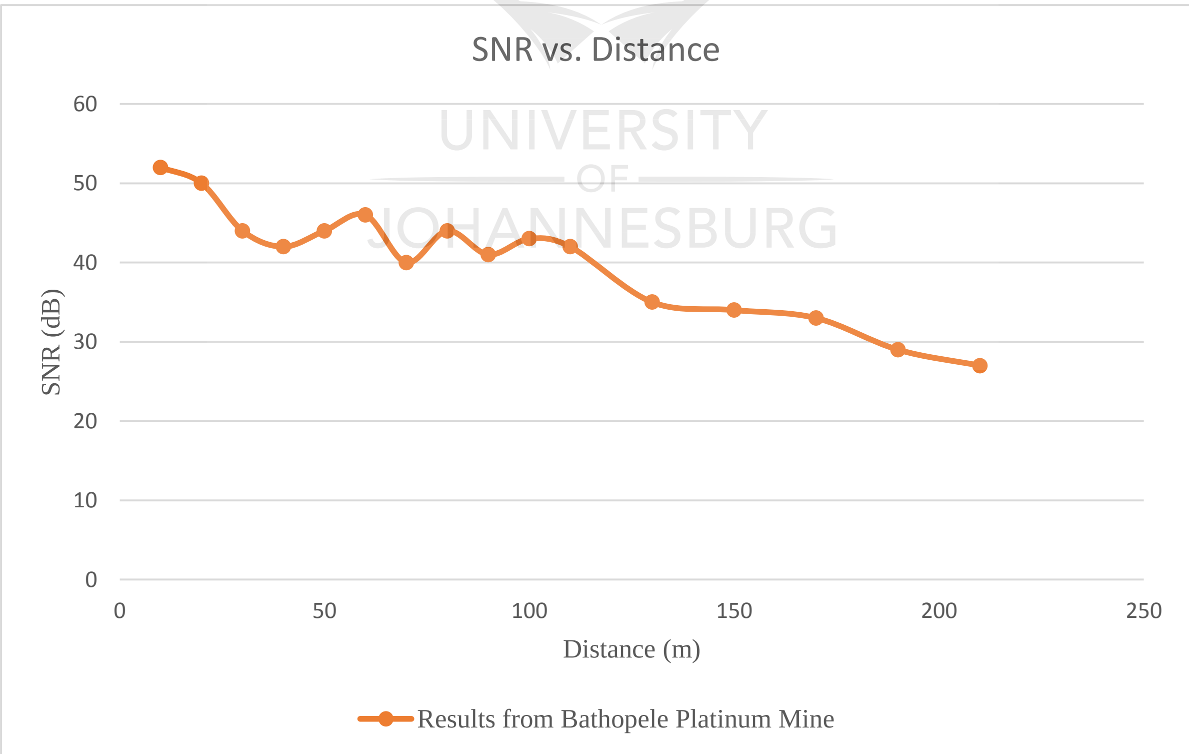

Figure 51: SNR vs. internode spacing

The results in Table 4 illustrate the feasibility of extending coverage range by making use of a high-gain antenna on one of the mesh access points in a platinum mine tunnel. Generally, each OM2P access point has an indoor coverage range of 45-50m, however, in this experiment; 210m of coverage range was achieved on a single access point with a 15dBi circular polarized antenna attached to it. At 210m from node 1, the received signal strength from node 1 was found to be -68dBm, which still indicates strong signal strength for data transmission. This, however, is not the maximum range that can be achieved. There is an antenna polarization mismatch that is to be considered.

The OM2P access point communicates using a 2dBi vertically polarized omnidirectional antenna and so when a circular polarized unidirectional antenna is attached to one of the units, the polarization loss factor is 2, which means that half of the power is lost during transmission. The network parameters that were observed at 210m distance from the first node show a network speed of 58.4 Mbps and a 6ms delay. The second node was wirelessly connected to node 1 and placed at the 210m distance from node 1. The results at node 2 indicate a reduction in network latency from 6ms to 4ms and a reduction in network speed from 58.4 Mbps to 33.6 Mbps.

This observation further confirms that adding more wireless access points to a wireless mesh network results in the reduction of network speed. Adding two more nodes reduces the network speed to 19.5 Mbps. It can be seen that adding 3 more nodes would yield a coverage range of 560m which is 160m longer than 400m of coverage range achieved with 7 mesh nodes without a high-gain antenna. The extended range was not according to expectations. We expected extended coverage range to be over 500m as a result of using the high-gain antenna. A polarization mismatch is a major limitation.

7.2 Conclusion

Experimental results presented in this report indicate that:

- An inverse relationship exists between network throughput and the increasing number of hops/mesh nodes.
- Increasing mesh nodes increases the average network latency.
- Internode spacing negatively affects the network parameters of a wireless mesh network, and that careful planning should be considered when deploying a WMN.
- 50m meters of internode spacing is maximum internode spacing to yield at least 1Mbps of network speed.
- Voice and video communication can be transmitted on the network because the latencies on the network are less than 150ms and network speeds of about 5Mbps can be realized on the network, which makes VoIP and video transmission on the network to be possible.
- High-gain antennas can be used to extend network coverage and still maintain a good performance of WMNs.

These results show that a wireless mesh network can provide communication in the mines. Considering the project requirements set by Schauenburg Systems, the results indicate that a data rate of at least 1Mbps can be achieved on the wireless mesh network for telemetry applications. CloudTrax network management software can be used to manage the network from anywhere in the world and has proven user-friendly. The transmission power of the transceivers can be set to anything less than 500mW. The transceivers on this mesh system are portable and easy to configure. The mesh system has been tested and was found to have met all the set requirements. Transceivers with MIMO technology are recommended for better performance.

Table 4: Enhancing network coverage distance using a high-gain antenna

Node	Distance (m)	SST (dBm)	SNR (dB)	Latency (ms)	Throughput (Mbps)
Node 1	10	-41	52	-	-
Node 1	20	-44	50	-	-
Node 1	30	-51	44	-	-
Node 1	40	-53	42	-	-
Node 1	50	-55	44	-	-
Node 1	60	-53	46	-	-
Node 1	70	-51	40	-	-
Node 1	80	-52	44	-	-
Node 1	90	-56	41	-	-
Node 1	100	-50	43	-	-
Node 1	110	-58	42	-	-
Node 1	130	-60	35	-	-
Node 1	150	-62	34	-	-
Node 1	170	-64	33	-	-
Node 1	190	-65	29	-	-
Node 1	210	-68	27	6	58,4
Node 2	210	-	-	5	33,6
Node 3	260	-	-	4	19,8
Node 4	310	-	-	4	19,5

CHAPTER EIGHT

8 CONCLUSION AND FUTURE WORK

This dissertation has demonstrated that wireless mesh networks are capable of providing communication in underground mines. The performance characteristics of a WMN demonstrated that a seven-node mesh system, interspaced at 50m can provide a network speed of over 5Mbps at network latencies of <150ms and a coverage range of over 400m in an underground mining environment. The experimental test results showed that data, voice and video communication can be achieved on the mesh network for communication in the mining environment. Considering the fact that the development of the prototype mesh system was achieved in view of the company's set requirements and system specifications, it can be concluded that the research project was successfully completed.

8.1 Summary of contribution

The specific contributions made during the course of this research project include a summarized literature study of current communication technologies that are applicable to the mining environment. A scholarly article on the performance of wireless mesh networks in underground mines has been prepared for publishing which will assist other researchers in understanding the challenges associated with building and deployment of wireless mesh networks in harsh mining environments. This research will help mining companies to understand how to deploy wireless mesh networks for their communication needs and in this way improve the efficiency of mine operations through better management of resources. By providing wireless mesh networks in dynamic areas of underground mines, the safety of mine workers will also improve. In summary, the results of this work will improve the mining industry through better communication systems.

8.2 Future work

The work presented in this dissertation was mainly focused on standard performance analysis of wireless mesh networks. The study on data, voice and video communication on the wireless mesh network is left for future studies. As part of future work on wireless mesh networks, it would be interesting to observe the performance of these networks in three different mining environments, because arrangements to conduct tests in underground gold, lime and chrome mines were not made on time, as such, experimental tests could not be conducted in these environments and it would be good to observe the performance of mesh systems in such environments as well. The last aspect of future work on this project includes a comparative analysis of the performance of various routing protocols in data transmission on the wireless mesh network.

8.3 Conclusion

Wireless mesh networking has enormous potential to redefine connectivity paradigms in the most dynamic areas of underground mines. Wireless testbeds such as the ones developed in this dissertation will undoubtedly play a significant role in accelerating the research, development, and uptake of these technologies in underground mines in South Africa and across the African continent.

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