

Design of a digital mobile radio network for a rail-bound mission-critical wireless network

Nkosinathi Nhlanhla Nyawose

Dissertation submitted in fulfilment of the requirements for the degree

Master of Engineering in Electrical Engineering

in the

Department of Electrical, Electronic and Computer Engineering
Faculty of Engineering, Built Environment and Information Technology

at the

Central University of Technology, Free State

Supervisor: Prof AJ Swart

Co-supervisor: Prof PE Hertzog

Bloemfontein

2025

DECLARATION

I, Nkosinathi Nhlanhla Nyawose (Student number: _____) hereby declare that this research project, which has been submitted to the Central University of Technology, Free State, for the degree of Master of Engineering in Electrical Engineering, is my own independent work; complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State and has not been submitted before by any person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

Student Signature:_____.

Date: 03/10/2025

ACKNOWLEDGEMENTS

First and foremost, I would like to thank God for granting me the strength, wisdom and perseverance to complete this journey. I also extend my appreciation to myself—for the unwavering commitment, long hours and personal sacrifices. Through resilience, discipline and faith, I remained focused and determined to see this research through and I am proud of the dedication and strength I have shown.

I am deeply grateful to my friends, family and colleagues for believing in me. Your constant encouragement, motivation and support sustained me through the most challenging times.

I wish to express my sincere appreciation to Professor James Swart and Professor Pierre Hertzog for their expert guidance, supervision and insightful feedback throughout this research. I am also thankful to the Central University of Technology (CUT) for providing the academic environment and institutional support necessary for the completion of this research.

Lastly, I would like to express my heartfelt gratitude to my manager, Mrs Portia Pungula, for her unwavering support and leadership and to Transnet for enabling me to undertake and complete this research while serving within the organisation.

ABSTRACT

The migration from analogue to digital communication systems has become a strategic imperative for industries that depend on mission-critical communication (MCC), such as the railway sector. This study investigates the feasibility and implementation of a Digital Mobile Radio (DMR) network as a replacement for the legacy Private Mobile Radio (PMR) analogue infrastructure used in railway MCC. The research evaluates various digital technologies—Terrestrial Trunked Radio (TETRA), Long Term Evolution (LTE) and Digital Mobile Radio (DMR)—through comparative analysis, technical specifications and practical deployment considerations. DMR is identified as the most suitable technology due to its spectrum efficiency, superior voice quality, low power consumption and cost-effectiveness.

A pilot DMR site was designed and configured using Wireless Radio Planning (WRAP) simulation software, incorporating link budget calculations, antenna configurations and terrain-based propagation modelling. The pilot site was implemented to validate the simulation outcomes, using a Tait TB9300 repeater, Webb CR400 antenna and Hytera PD785 handheld radio. Measurements focused on key performance indicators, including Received Signal Strength Indicator (RSSI) values ranging from -72 dBm to -119 dBm; harmonic distortion, with second and third harmonic suppression of 56.87 dB and 59.30 dB respectively; and system power efficiency, achieving a 57% reduction in current consumption compared to analogue mode. The results demonstrated close correlation between predicted and actual performance, with a mean absolute percentage error (MAPE) of 2.53%. The DMR system met regulatory requirements, including harmonic suppression thresholds set by the Independent Communications Authority of South Africa (ICASA) and the International Telecommunication Union Radiocommunication Sector (ITU-R), thereby affirming its technical compliance and operational robustness. This research presents a validated implementation model for adopting DMR in railway communication systems, supporting reliable, scalable and secure voice communication infrastructure for Transnet and other mission-critical applications.

LIST OF FIGURES

Figure 1-1- DMR network design block diagram.....	4
Figure 2-1- Basic PMR radio communication [18]	9
Figure 2-2- Basic architecture of an LTE network [27].....	12
Figure 2-3- Basic architecture of TETRA network [40].....	13
Figure 2-4- TDMA operation in 12.5 kHz physical channel [51]	16
Figure 2-5- Audio quality: Digital vs. analogue [55].....	17
Figure 2-6- DMR network overview [51].....	18
Figure 3-1- Muiskraalkop high site Google map	27
Figure 3-2- DMR design block diagram	28
Figure 3-3- Antenna gain configuration.....	38
Figure 3-4- Antenna horizontal pattern.....	39
Figure 3-5- Antenna vertical radiation pattern.....	39
Figure 3-6- DMR repeater transmitter configuration.....	40
Figure 3-7- DMR repeater modulation configuration.....	41
Figure 3-8- WRAP system configuration	41
Figure 3-9- Repeater software setup.....	43
Figure 3-10- Repeater workshop setup.....	44
Figure 3-11- Communication service monitor readings	44
Figure 3-12- Duplexer configuration.....	46
Figure 3-13- Insertion loss measurement results for the duplexer.....	46
Figure 3-14- Antenna VSWR measurement.....	47
Figure 3-15- Bird analyser VSWR measurement	48
Figure 3-16- Complete DMR radio site.....	49
Figure 4-1- DMR WRAP coverage simulated results	52
Figure 4-2- DMR Google map coverage practical results	55
Figure 4-3- Comparison of simulated and practical RSSI results at test points	55
Figure 4-4- DMR harmonic spectrum analysis.....	58
Figure 4-5- DMR and analogue current measurement.....	60

LIST OF TABLES

Table 2-1- DMR, TETRA and LTE Comparison [3] [4] [29] [30] [31] [32]	19
Table 2-2- Analogue and DMR comparison [1] [2] [3]	20
Table 2-3- DMR Technical Specifications [4] [5] [6]	23
Table 3-1- Equipment Specifications.....	29
Table 3-2- Webb Industries Duplexer DU400/6 Specifications [7]	33
Table 3-3- The CR400 Corner Reflector Specification [8].....	34
Table 3-4- DMR network radio design dimensioning results.....	36
Table 4-1- RSSI level colour codes	52
Table 4-2- WRAP test points simulated RSSI level	53
Table 4-3- Practical test points RSSI level results.....	54
Table C-1- Consolidated comparison of analogue PMR, DMR, TETRA, LTE/MCX and FRMCS/5G-R	89

LIST OF ABBREVIATIONS

Abbreviation	Meaning
AMBE	Advanced Multi-Band Excitation
DMR	Digital Mobile Radio
ERP	Effective Radiated Power
ETSI	European Telecommunications Standards Institute
FSL	Free Space Loss
GSM-R	Global System for Mobile Communications – Railway
ICASA	Independent Communications Authority of South Africa
LTE	Long Term Evolution
MAPE	Mean Absolute Percentage Error
PMR	Professional Mobile Radio
RSSI	Received Signal Strength Indicator
SNR	Signal-to-Noise Ratio
TDMA	Time Division Multiple Access
TETRA	Terrestrial Trunked Radio
UHF	Ultra-High Frequency
VHF	Very High Frequency
VSWR	Voltage Standing Wave Ratio
WRAP	Wireless Radio Access Planner
FRMCS	Future Railway Mobile Communication System
RAN	Radio Access Network

TABLE OF CONTENTS

DECLARATION	I
ACKNOWLEDGEMENTS	II
ABSTRACT	III
LIST OF FIGURES	IV
LIST OF TABLES	V
LIST OF ABBREVIATIONS	VI
CHAPTER 1: INTRODUCTION	1
1.1 Background	1
1.2 Problem Statement	2
1.3 Research Aim and Objectives	2
1.4 Research Questions	3
1.5 Research Methodology	3
1.6 Study Significance	4
1.7 Delimitations	5
1.8 Chapter Organisation	6
1.9 Summary	7
CHAPTER 2: LITERATURE REVIEW	8
2.1 Introduction	8
2.2 Analogue Public Mobile Radio	8
2.3 Digital PMR	10
2.3.1 Long Term Evolution (LTE)	10
2.3.2 Terrestrial Trunked Radio (TETRA)	12
2.3.3 Digital Mobile Radio	14
2.3.3.1 Time-Division Multiple Access	15
2.3.3.2 Four-ary Frequency Shift Keying	16
2.3.3.3 AMBE 3600	17

2.3.3.4	DMR Basic Architecture.....	18
2.3.4	Comparison of Digital PMR Technologies.....	19
2.4	Comparison of Analogue and DMR	20
2.5	DMR Case Studies	21
2.6	DMR Technical Specifications	23
2.7	Future Railway Mobile Communication System (FRMCS).....	24
2.8	Summary	25
CHAPTER 3: RESEARCH DESIGN		26
3.1	Introduction.....	26
3.2	Defining Requirements	26
3.2.1	Geographic Location.....	27
3.2.2	Design Project.....	28
3.3	Radio Network Dimensioning	30
3.3.1	Link Budget	30
3.3.2	Effective Radiated Power (ERP).....	30
3.3.3	Free Space Loss (FSL).....	31
3.3.4	RSSI (Receive Signal Strength Indicator)	32
3.3.5	Duplexer.....	32
3.3.6	Antenna Specification.....	33
3.3.7	Voltage Standing Wave (VSWR)	34
3.3.8	Feeder Cable Loss.....	35
3.3.9	Radio Dimensioning Outputs.....	35
3.4	Radio Propagation Model Tuning.....	37
3.4.1	WRAP Software.....	37
3.4.2	Antenna Configuration.....	37
3.4.3	Antenna Radiation Pattern Configuration.....	38
3.4.4	Repeater Configuration.....	40

3.4.5	System Configuration	41
3.5	DMR Network Pilot.....	42
3.5.1	Workshop Testing.....	42
3.5.1.1	Repeater Practical Configuration.....	43
3.5.1.2	Duplexer Configuration	45
3.5.1.3	Antenna configuration.....	47
3.6	Radio Site Installation.....	48
3.7	Summary.....	50
CHAPTER 4: RESULTS AND DISCUSSION		51
4.1	Introduction.....	51
4.2	Simulated Results.....	51
4.3	Practical Results.....	54
4.4	Design Simulation and Practical Results Comparison.....	55
4.5	Analysis of Harmonic Distortion in the DMR System	58
4.6	Power Consumption.....	60
4.7	Summary.....	61
CHAPTER 5: DISCUSSIONS, IMPLICATIONS AND CONCLUSION		62
5.1	Introduction.....	62
5.2	Reflection on Previous Chapters.....	62
5.3	Research Questions	63
5.4	Research Objectives.....	65
5.5	Recommendations.....	66
REFERENCES		68
ANNEXURE A: PERMISSION TO CONDUCT RESEARCH		78
ANNEXURE B: PAPER PRESENTED RTCSE-2025 CONFERENCE		79
ANNEXURE C: CONSOLIDATED TECHNOLOGY COMPARISON		89

CHAPTER 1: INTRODUCTION

1.1 Background

Over the past four decades, the evolution of mobile communication has progressed significantly, from 1G to 5G networks [9]. This transition has necessitated a shift from analogue to digital communication technologies [10]. As a result, analogue-based Professional Mobile Radio (PMR) systems, which have served as the backbone for mission-critical communications for over 25 years, are facing obsolescence [11]. The radio communication used in the railway industry is regarded as a mission-critical communication system since it directly impacts public safety. Railway communication applications range from in-car to inter-compartment to train-to-rail [12]. Transnet employs two wireless PMR communication networks to facilitate voice-based communication between the driver and the Train Control Officers. The Radio Train Order (analogue conventional network) and Trunking (MPT 1327) are two analogue-based communication systems. The emergence of new technologies has highlighted the need for more efficient and effective communication systems to replace the ageing analogue infrastructure.

The increasing pressure to implement digital migration from analogue to digital stems primarily from spectrum limitations. Telecommunications authorities worldwide have set deadlines for discontinuing analogue systems, driven by the scarcity of available radio spectrum resources. This transition is particularly relevant for industries reliant on mission-critical radio communication, z the railway industry, emergency services and law enforcement agencies.

Digital migration has sparked research to identify the most suitable technologies to replace analogue radio networks in various mission-critical applications. Technologies such as Terrestrial Trunked Radio (TETRA), Long-Term Evolution (LTE) and Digital Mobile Radio (DMR) have emerged as promising alternatives. These digital communication systems offer improved spectral efficiency, enhanced voice quality and increased capacity for data transmission compared to their analogue counterparts.

The transition from analogue to digital communication systems in mission-critical industries is driven by the need for more reliable, secure and feature-rich communication capabilities. Researchers and industry professionals are exploring the best technological solutions to ensure

seamless digital migration, paving the way for enhanced communication performance and operational efficiency in mission-critical environments.

1.2 Problem Statement

The problem is that the currently used analogue radio technologies are outdated, unreliable and longer supported by original equipment manufacturers (OEMs). Analogue technology does not meet current and future business requirements such as good voice quality, high data rates, broad radio coverage, low interference and security for train communication. The current system has high maintenance costs and a high mean time to repair, since some parts are not always available. Analogue technology comes with several drawbacks, including reduced audio quality over short distances, spectrum overcrowding leading to interference issues and limited battery life [13]. As the frequency spectrum is a shared and limited resource, the issue of inefficient utilisation with analogue systems affects not only the organisation but the entire radio communication user community.

To address these challenges, the study aims to explore and compare various digital radio systems, such as TETRA, LTE and DMR, with a particular emphasis on the DMR solution. The investigation will focus on identifying the most suitable replacement for the current analogue infrastructure, considering factors like voice and data quality, radio coverage, interference mitigation, security features and cost-effectiveness. By transitioning to a modern and reliable digital communication system, Transnet seeks to enhance its train communication capabilities and optimise the utilisation of the radio frequency spectrum, ultimately improving the overall efficiency and effectiveness of its mission-critical operations.

1.3 Research Aim and Objectives

The research aims to investigate different digital technologies to replace Transnet's outdated mission-critical analogue communication system and to design a new digital radio network. This is due to the current analogue radio systems being outdated and obsolescent. The research will look at various digital technologies that could be utilised as alternatives for Transnet's present radio infrastructure. The study will also conduct a pilot study as a practical proof of concept to advise Transnet on the optimal way to replace its PMR analogue radio communication network. The following are the objectives of the research:

1. Evaluate multiple digital radio systems capable of replacing Transnet's analogue radio systems to determine the most suitable option.
2. Design and simulate the digital radio communication system to assess its performance improvements over the existing analogue radio system.
3. Test the Received Signal Strength Indicator (RSSI) and overall coverage performance by deploying a pilot digital radio high site.
4. Evaluate the radio spectral efficiency of the digital radio system through spectrum analysis.

1.4 Research Questions

The research aims to answer the following questions:

1. What are the multiple digital radio systems' key characteristics and capabilities that could potentially replace Transnet's PMR analogue radio communication network?
2. Among the evaluated options, which digital radio system demonstrates the most promising performance improvements compared to the existing analogue radio system?
3. How does the tested Received Signal Strength Indicator (RSSI) and the overall coverage performance of the pilot digital radio high site compare to the mission-critical communication requirements in Transnet's operations?
4. What is the radio spectral efficiency of the selected digital radio system and how does it compare to the analogue system, as determined through spectrum analysis?

1.5 Research Methodology

The research methodology involves analysing different digital radio technologies, such as TETRA, DMR and LTE, to determine the most suitable option for mission-critical communication. Based on previous studies, DMR is identified as the optimal solution due to its cost-effectiveness, quick deployment, user functionality and minimal training requirements. The research will also compare the three digital radio systems to determine the best fit for the railway industry's communication needs. The design and planning of the radio network will be performed using WRAP (Wireless Radio Access Planner) software, which is a propagation modelling tool. Figure 1-1 illustrates the research design that will be followed.

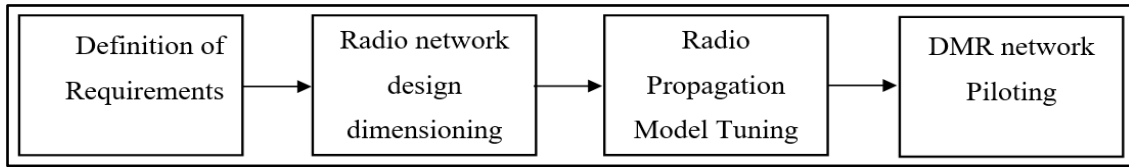


Figure 1-1- DMR network design block diagram

The research design process consists of several steps. The first step involves defining the requirements of the design by conducting extensive research on digital technologies and identifying the geographical area where the service will be offered. The technical specifications will be established based on recognised telecommunications regulatory agencies and standards. The second step is radio network design dimensioning, which includes link budget calculations to determine parameters such as antenna type, number of sites, transmit power and receive sensitivity. The power link budget will be determined using the free space loss model. The third step involves tuning the radio propagation model using WRAP software to simulate network propagation based on technical data and factors such as terrain and barriers. Key performance indicators like service footprint and availability will be considered during this stage. Finally, a digital radio network pilot will be conducted to compare the simulated results with the real outcomes and evaluate the performance of the proposed system. Tests will be performed on both the existing analogue system and the digital radio system to assess parameters like RF frequency error, transmit power, modulation, receiver sensitivity and spectrum analysis.

1.6 Study Significance

The research on DMR holds significant importance as it aims to enhance our understanding of the advantages and limitations of DMR technology as a wireless communication solution for mission-critical applications. A comprehensive examination of DMRs features, functionalities and performance will provide valuable insights into its suitability for various industries and use cases, particularly in the railway industry. Additionally, the research will compare DMR with other digital radio technologies, such as TETRA and LTE, to evaluate its effectiveness in meeting the specific communication needs of the railway sector.

The significance of this study further lies in its original contribution to the practical migration of rail-bound mission-critical voice communication from analogue PMR to DMR within the Transnet operating environment. While DMR is an established technology, this research

contributes by integrating technology selection, radio link-budget dimensioning, WRAP-based terrain propagation modelling, practical high-site implementation, field RSSI validation, spectral compliance testing and power-consumption comparison into one repeatable engineering design approach. The study therefore extends beyond general technology comparison by demonstrating how DMR can be practically designed, deployed and validated as a suitable replacement for ageing analogue PMR infrastructure in a railway mission-critical communication context.

Furthermore, this study may support the broader adoption of digital wireless technologies in mission-critical communication systems. By evaluating DMR as a practical alternative, the research provides technical evidence that can guide future railway communication migration decisions, improve operational reliability, support spectrum efficiency and enhance the resilience of communication services used in safety-critical railway operations.

1.7 Delimitations

The pilot project was conducted at a single site as a proof of concept due to the defined scope and resource limitations of the study. Although the pilot provided valuable technical validation, it did not fully represent the operational behaviour of a large multi-site radio network. Network characteristics such as coverage performance, traffic loading, call blocking, inter-site connectivity, redundancy and interference may vary when the DMR network is expanded across longer railway corridors and different terrain profiles. The single-site pilot should therefore be regarded as a validated engineering baseline for potential future network expansion rather than a complete network-wide deployment model. Further multi-site implementation and testing would be required to validate network scalability, roaming performance and resilience under wider operational conditions.

The literature review compared DMR, TETRA and LTE as potential digital radio technologies for replacing Transnet's analogue radio communication network. Following this comparative assessment, the study focused on DMR and implemented a single-site pilot to evaluate its technical suitability within the Transnet railway operational environment. The pilot scope enabled the practical assessment of DMR coverage, signal performance and operational functionality under actual site conditions. The single-site approach was appropriate because the study aimed to validate the technical feasibility of DMR as a proof of concept rather than assess the performance of a complete multi-site network.

1.8 Chapter Organisation

The following outlines the chapters for this research:

Chapter 1 provides the introduction and offers an overview of the research, including the background and problem statement. It outlines the research questions and objectives, emphasising the evaluation of digital radio systems, specifically DMR, as a replacement for analogue infrastructure. The chapter also discusses the significance of the study and highlights the limitations and delimitations. Additionally, the research methodology is presented, detailing the approach and methods used to conduct the study.

Chapter 2 provides a literature review of the research design, beginning with an overview of analogue radio communication systems and their limitations. The obsolescence and challenges associated with analogue PMR systems are discussed. The advantages and capabilities of digital radio communication systems, including TETRA, LTE and DMR, are explored. The literature review sets the foundation for evaluating and comparing these digital technologies as potential replacements for the existing analogue system.

Chapter 3 discusses the research design and methodology. The design and planning of the digital radio network will be conducted using WRAP software, a propagation modelling tool. The research design process, including the definition of requirements, radio network design dimensioning, tuning the radio propagation model and conducting a pilot study, is outlined.

Chapter 4 presents the data analysis, research findings and outcomes of the research. The key characteristics and capabilities of the evaluated digital radio systems are discussed, with a focus on their performance improvements compared to the existing analogue system. The chapter also compares the simulated and practical results to determine whether the proposed DMR design met the defined technical and operational requirements.

Chapter 5, which presents the discussion, conclusion and recommendations, interprets and analyses the research findings in relation to the research questions and objectives. The advantages and limitations of the DMR system as a wireless communication solution for mission-critical applications are explored. The effectiveness of DMR in meeting the communication needs of the railway industry is discussed. The significance of the research in promoting the adoption of DMR and wireless technologies in mission-critical communication

systems is highlighted. The chapter concludes with a summary of the research and suggestions for future work.

1.9 Summary

Chapter 1 serves as an introduction to the research, introducing the evaluation of digital radio systems as replacements for analogue infrastructure. It establishes the importance of upgrading the communication systems in mission-critical industries and highlights the specific challenges faced by Transnet in the railway sector. The research questions and objectives are outlined, providing a clear focus for the study. Additionally, the chapter provides an overview of the research methodology, indicating the approach taken to address the research question.

The next chapter will present a literature review on the research design, focusing on various digital radio communication technologies considered as replacements for analogue PMR systems. It will explore the technical aspects and characteristics of mission-critical communication technologies, providing a comparative analysis of their performance and suitability.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The literature review section aims to provide an in-depth analysis of the existing research on upgrading analogue radio communication systems to digital technologies, focusing on the suitability of Digital Mobile Radio (DMR) as a replacement for mission-critical applications in the railway industry. By reviewing relevant studies, scholarly articles and industry reports, this section seeks to establish a comprehensive understanding of the advantages, limitations and implementation considerations of digital radio systems compared to analogue counterparts.

This analysis will explore the existing analogue Private Mobile Radio (PMR) communication system used in mission-critical communications and investigate the benefits and functionalities of various digital radio communication systems, including TETRA, LTE and DMR. The literature review will encompass a thorough examination of the technical aspects, operational advantages and deployment considerations associated with each digital radio technology, offering valuable insights for decision-making and future deployments in mission-critical communication environments.

2.2 Analogue Public Mobile Radio

Analogue technology has been used for over a century. In the 1930s, one-way Amplitude Modulation (AM) radio broadcasts were commonly used to send emergency messages to law enforcement. During the same decade, two-way AM broadcasts for police use were introduced, followed by Frequency Modulation (FM) radio technologies in the 1940s. By the 1950s, hand-carried radios were introduced for use in public safety vehicles. In the 1960s, critical communication systems evolved from two-way radios, sharing radio frequency (RF) channels among many users to transmit information (mainly voice) and signalling in analogue format [14].

Analogue private mobile radio (PMR) systems, used in mission-critical communication (MCC), are conventional private radios enabling communication between a base station and multiple mobile radios [15]. Analogue PMR systems have demonstrated highly successful over the past 25 years for mission-critical communications and have garnered trust from numerous Protection and Disaster Relief (PPDR) services worldwide [16]. The PMR systems utilised for

MCC are standard private radios that facilitate communication between a base station and numerous mobile radios. These devices are mainly employed by public protection and disaster relief (PPDR) agencies, including firefighters, police, border security and ambulance services [15]. PMR networks are essential for public safety and security organisations, providing reliable and secure voice and data communications [17].

The basic PMR communication operates by allocating each user with a specific channel to use at a given time. Once the channel is free, it can be used by other users on the network. This process is typically coordinated by the trunking system, as illustrated in Figure 2-1 [18].

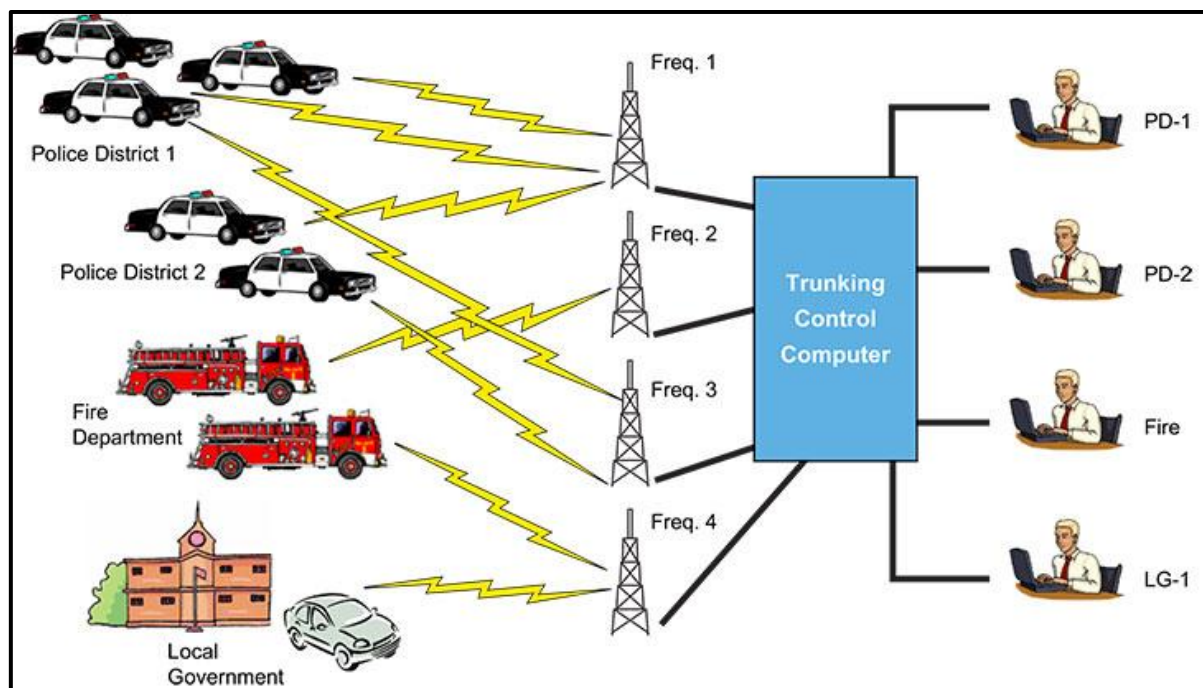


Figure 2-1- Basic PMR radio communication [18]

Despite the long-standing use of the analogue PMR network, these systems have notable disadvantages, including the following [19]:

- Low audio quality: Analogue PMR systems suffer from degraded audio quality over long distances [1].
- Analogue voice encryption: Most current Frequency Modulation (FM) or Phase Modulation (PM) systems can be easily tapped [20].
- Frequency band limitations: Operating in specific frequency bands (136-174 MHz for High VHF and 450-520 MHz for UHF), these systems can become crowded and inefficient.

- Lesser spectral efficiency: Analogue systems are less spectrally efficient than digital systems, which offer enhanced bandwidth and power efficiency [21].
- Power efficiency: Analogue radios generally have lower power efficiency compared to modern digital radios, which is crucial for portable devices used by emergency services [1].
- Backward compatibility issues: While some digital systems are backward compatible with analogue radios, integrating both in the same network can be complex and may not fully utilise the advantages of digital technology [19].

2.3 Digital PMR

There are numerous digital technologies capable of replacing the current analogue radio system. These digital PMR technologies include TETRA, Tetrapol, P25, DMR, dPMR and LTE [22]. This study will focus on LTE, TETRA and DMR as they are the primary technologies that can effectively replace the existing analogue radio network.

2.3.1 Long Term Evolution (LTE)

Long Term Evolution (LTE) is a standard for wireless broadband communication developed by the 3rd Generation Partnership Project (3GPP) [23] [24] [25] [26]. LTE represents a significant advancement over previous cellular network technologies such as 2G and 3G, offering higher data rates, lower latency and improved spectral efficiency [24]. LTE, a 4G technology, offers faster data transfer rates, reduced latency and enhanced spectral efficiency compared to older wireless technologies. It is extensively deployed in commercial networks and has the capacity to revolutionise public safety technology by delivering broadband connectivity and crucial support for both voice and data services in all situations [18] [27].

While LTE is still new to the PMR field, more research is being conducted to ensure that LTE meets all the PMR requirements for MCC applications. Since LTE was not initially designed for critical communications, the 3rd Generation Partnership Project (3GPP) has collaborated with various public safety communications officials and organisations to enhance LTE, to be fully compliant with MCC requirements [28]. LTE networking has the following advantages [29]:

- Fast wireless network communication rate and high throughput: LTE provides strong support for extensive services, ensuring robust performance for a variety of applications.
- Low latency: With minimal delay, LTE can meet most application scenarios with high real-time requirements, making it suitable for time-sensitive tasks.
- Convenient deployment of LTE Base Stations: LTE base stations can be easily deployed and used to supplement the existing wireless communication infrastructure, enhancing coverage and capacity efficiently.

While LTE offers many advantages for commercial applications, its use in MCC is still a new concept. The following are disadvantages of LTE for MCC:

- Coverage area: LTE networks in the 700MHz band require more sites spaced closer together to achieve comparable coverage to LMR, due to propagation characteristics [23].
- Cost Considerations: Installing more LTE sites to match PMR coverage in the 700MHz band is cost-prohibitive due to higher infrastructure costs [23]. This investment may be financially unviable for some public administration, indicating financial barriers to adopting LTE for MCC [27].

The LTE network comprises two main components: the Evolved UMTS Terrestrial Radio Access Network (E-UTRAN) and the Evolved Packet Core (EPC). The E-UTRAN, responsible for radio transmission functions, includes base stations known as evolved NodeBs (eNBs), which manage the entire radio protocol stack [23]. The EPC handles session and mobility functions [18]. The components of the LTE architecture are outlined below and illustrated in Figure 2-2 [23] [27] [30].

- E-UTRAN
 - Includes evolved NodeBs (eNBs) that manage the radio protocol stack.
- EPC
 - Mobility Management Entity (MME): Manages control functions like location management.
 - Serving Gateway (S-GW): Anchors user traffic from/to the E-UTRAN into the EPC.

- Packet Data Network Gateway (P-GW): Provides IP connectivity to external networks.
- Home Subscriber Server (HSS): Central database for user subscription information.

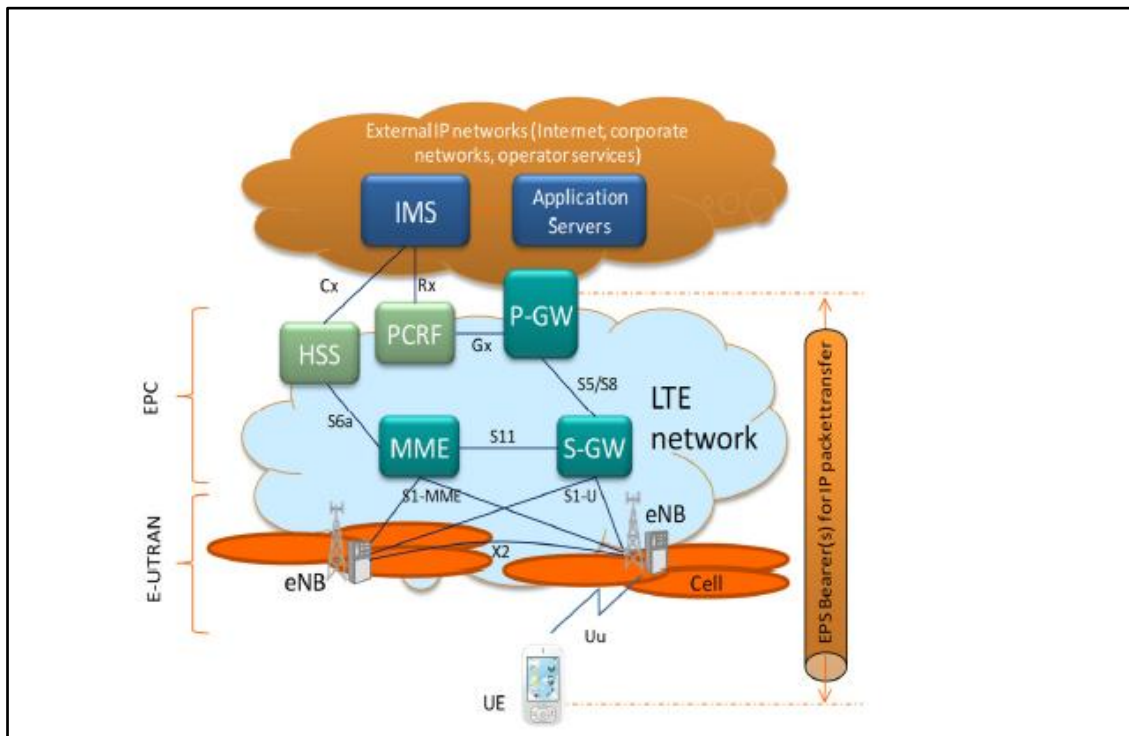


Figure 2-2- Basic architecture of an LTE network [27]

2.3.2 Terrestrial Trunked Radio (TETRA)

The European Telecommunications Standards Institute (ETSI) developed the Terrestrial Trunked Radio (TETRA), designed as a PMR, to enable cross-border networks across Europe [31] [32] [33]. TETRA supports standardisation of mission-critical voice services [34]. TETRA was designed for the military, emergency services (such as police, fire and ambulance), transport and public safety networks [35] [36] [33] [37]. It provides robust and secure voice and data communication capabilities with features such as group calls, emergency calls and encryption. The system offers several benefits, including its frequency domain design, which enables extensive geographical coverage with fewer receivers, thereby lowering operational costs significantly [38]. The following outlines the advantages of TETRA [20]:

- Digital speech transmission: TETRA provides clear and secure digital voice communication.

- Fast call setup: The technology enables rapid call setup, essential in emergency situations.
- Encryption support: TETRA supports multiple levels of encryption, enhancing communication security.
- High data transmission rates: Each channel in TETRA can support up to 7.2 kbps, with multi-slot operations reaching 28.8 kbps [31].
- Direct Mode Operation (DMO): TETRA allows devices to communicate directly with each other without the need for a network, useful in remote areas.
- Communication distance: TETRA operates in a low-frequency band and offers longer communication distances compared to the high-frequency technologies, such as LTE [34]

Disadvantages of TETRA include:

- High operational cost: The operational costs for maintaining centralised TETRA systems are expensive [20].
- High power consumption: These systems consume a significant amount of power [20].
- Channel bandwidth: TETRA requires a larger channel bandwidth when compared to counterparts such as DMR. [39].

The TETRA network architecture consists of several system entities and defined interfaces that ensure reliable operation. An overview of a typical TETRA network is presented in Figure 2-3.

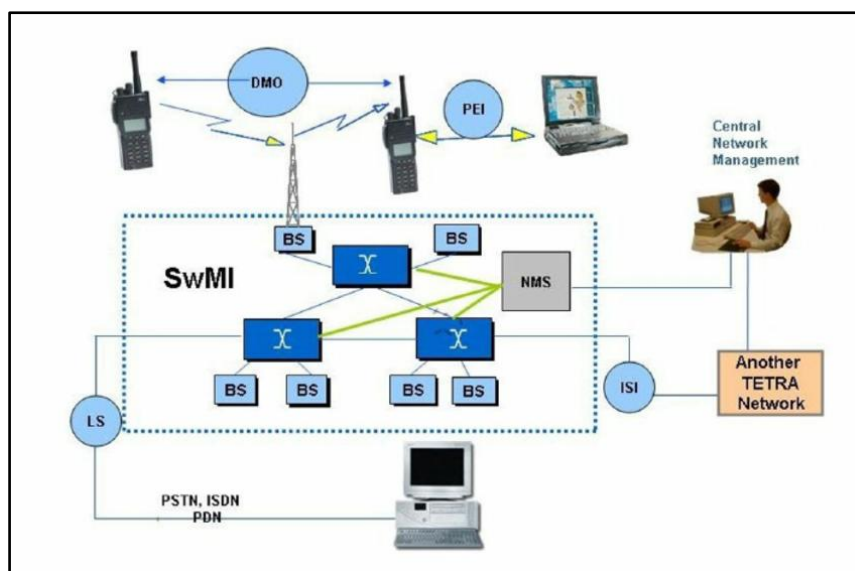


Figure 2-3- Basic architecture of TETRA network [40]

The central entity in the TETRA system is the Switching and Management Infrastructure (SwMI), which incorporates all equipment and subsystems of the network, including base stations. In addition, the Direct Mode Operation (DMO) air interface enables communication directly between mobile devices without reliance on a base station, ensuring connectivity in areas where coverage may be absent. This feature is particularly important in emergencies or remote locations. The SwMI also provides interfaces to external networks, facilitating seamless integration and interoperability across different communication systems [40].

The components of the TETRA system include [40]:

- Base Transceiver Station (BTS): A fixed radio station providing connections within a specific radio cell.
- Base Station Control Function (BCF): An element of the BTS responsible for switching communication channels and providing access to external networks.
- Base Station Controller (BSC): A device with greater switching and software capabilities than BCF, allowing data exchange between multiple BCFs.
- Dispatching Desk (DP): A terminal device for information exchange between the network dispatcher and users, often used for dispatching transmission and forming user groups.
- Mobile Radio Station (MS): Terminal radio stations used by mobile users, including handheld and transport stations.
- Stationary/Fixed Radio Station (FRS): Terminal radio stations used by participants in a stationary location.
- Terminal for Technical Maintenance and Operation (TO&M): A line terminal connected to BSC or BCF for monitoring the system, diagnosing faults and managing databases.

2.3.3 Digital Mobile Radio

DMR is a digital radio standard developed by the European Telecommunications Standards Institute (ETSI) for professional mobile radio (PMR) [41] [42] [43]. It is designed to provide reliable and efficient voice and data communications in private or public wireless networks. DMR can meet the needs of mission-critical communications at a reduced cost and is widely adopted by public safety organisations worldwide [11] [44] [4] [45] [45]. The DMR standard

is anticipated to become increasingly widespread, particularly on trunk, secondary and low-density railway lines [46] [47].

The DMR protocol includes three operating modes [52]:

- DMR Tier I is used for license-free devices with a maximum RF power of 0.5 W, suitable for small coverage areas and emergency applications.
- DMR Tier II was developed for licensed radio systems with advanced features, IP data services and uses TDMA with two slots in a 12.5 kHz channel.
- DMR Tier III is used for trunking radio operations in large areas, with support for voice, short messaging and packet services, including IPv4 and IPv6.

The advantages include [46]:

- Predictable doubling of capacity in existing 12.5 kHz licensed channels
- Backward spectrum compatibility with legacy analogue systems
- Efficient use of infrastructure equipment
- Longer battery life and greater power efficiency
- Ease of use and creation of data applications
- System flexibility through simultaneous voice and data calls
- Advanced control features
- Superior audio performance compared to analogue.

DMR, at the physical layer, employs 4-ary Frequency Shift Keying (4-FSK) Time Division Multiple Access (TDMA) technology with two slots in a 6.25 kHz frequency range, offering voice, data and a variety of additional functions and applications [48] [21] [49]. The following section will outline the distinct features that give DMR technology its advantages.

2.3.3.1 Time-Division Multiple Access

TDMA is a multiple access scheme where users share the entire channel bandwidth by taking turns to transmit in non-overlapping time slots, allowing for efficient use of the channel with reduced battery consumption and synchronisation requirements. In contrast, FDMA (Frequency Division Multiple Access) divides the available bandwidth into non-overlapping frequency bands, each assigned to a user for continuous, simultaneous transmission. While FDMA avoids interference with guard bands, it is less efficient in power consumption and bandwidth utilisation due to fixed allocations, even when channels are idle [50]. Figure 2-4

depicts the use of TDMA in a 12.5 kHz channel, where two conversations are sharing the same channel simultaneously [51].

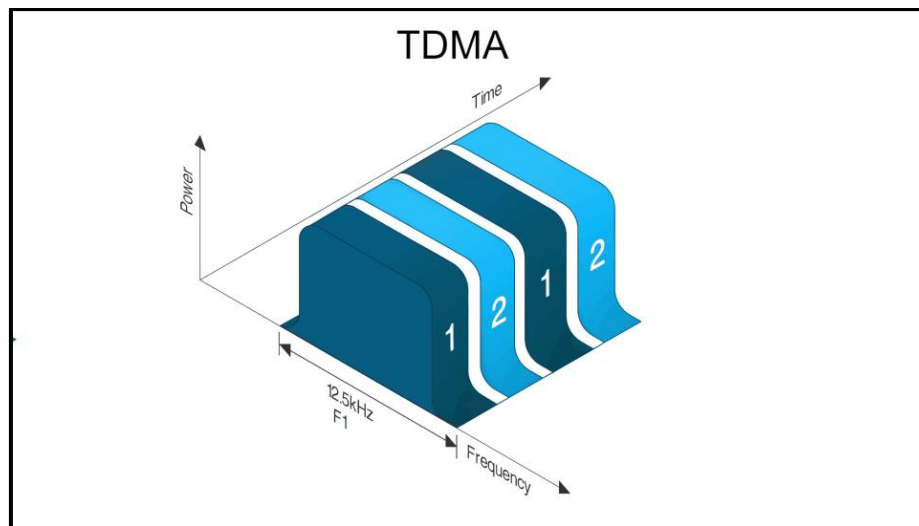


Figure 2-4- TDMA operation in 12.5 kHz physical channel [51]

The benefits of using TDMA over FDMA primarily lie in the spectrum savings, as TDMA uses two slots per one channel. This results in DMR radios consuming significantly less battery power due to more efficient power usage. According to [51], for a typical portable radio operating under the standard 5/5/90 duty cycle (5% Transmit, 5% Receive at full audio, 90% Standby), the transmitter is active only 2.5% of the time, as it transmits during half of the 5% transmission allowance. Since the highest battery drain occurs during transmission, the reduction in active transmission time to 2.5% significantly increases the battery's shift life by 40%, extending the time between charges. This is further supported by [52], which claims that DMR radios consume 40% less power compared to analogue radios.

In TDMA, each time slot is 30 milliseconds long. This alternating time slot structure allows one communication to use Time Slot 1 while another uses Time Slot 2. This setup ensures that the transmitter does not transmit continuously, unlike in analogue systems. Consequently, this periodic transmission pattern helps in saving battery life.

2.3.3.2 Four-ary Frequency Shift Keying

DMR's 4-FSK modulation involves frequency deviations that are precisely defined to ensure clear signal transmission and reception. This technique allows DMR to achieve robust performance even in challenging radio environments. 4-FSK is a modulation scheme that uses

four distinct frequencies to encode data. In DMR, this enhances transmission performance and efficiency by reducing the required speed for each sub-carrier. The frequencies used in 4-FSK modulation for DMR are [53] [54] [55] [56].

- Symbol 01 = 1.944 kHz
- Symbol 00 = 0.648 kHz
- Symbol 10 = -0.648 kHz
- Symbol 11 = -1.944 kHz

This means that each pair of bits (00, 01, 10, 11) is encoded into a specific frequency shift, enabling efficient and reliable digital communication.

2.3.3.3 AMBE 3600

DMR employs advanced Forward Error Correction techniques using the Advanced Multi-Band Excitation (AMBE) vocoder, specifically the AMBE 3600 version, designed to provide high-quality and intelligible voice communication [57] [58]. By using the AMBE 3600, the DMR network improves audio quality by focusing on voice or data while minimising background noise, employing automatic error correction to maintain clarity even in corrupted signals and leveraging advanced algorithms for clear voice transmission in extreme conditions, as seen in the comparison between DMR and analogue radio communication in Figure 2-5[55]. This advanced encoding approach enables DMR to support mission-critical applications.

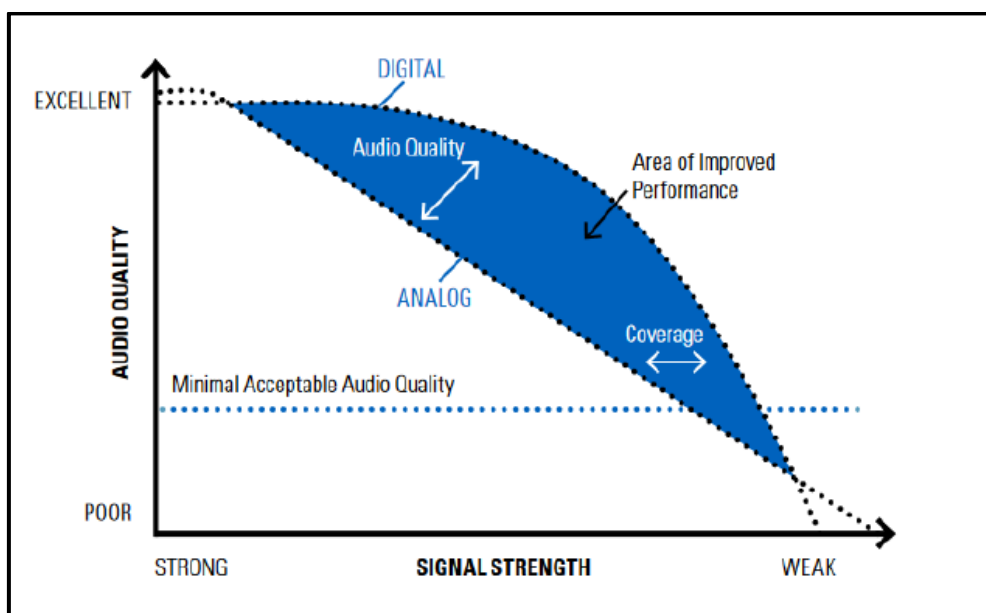


Figure 2-5- Audio quality: Digital vs. analogue [55]

2.3.3.4 DMR Basic Architecture

The basic DMR structure comprises essential components that make up the DMR network. Figure 2-6 illustrates different sites, each of which can have multiple repeaters interconnected by the network infrastructure. This structure is scalable, allowing for the addition of many other sites in various regions. Figure 2-6 provides an overview of the DMR network structure.

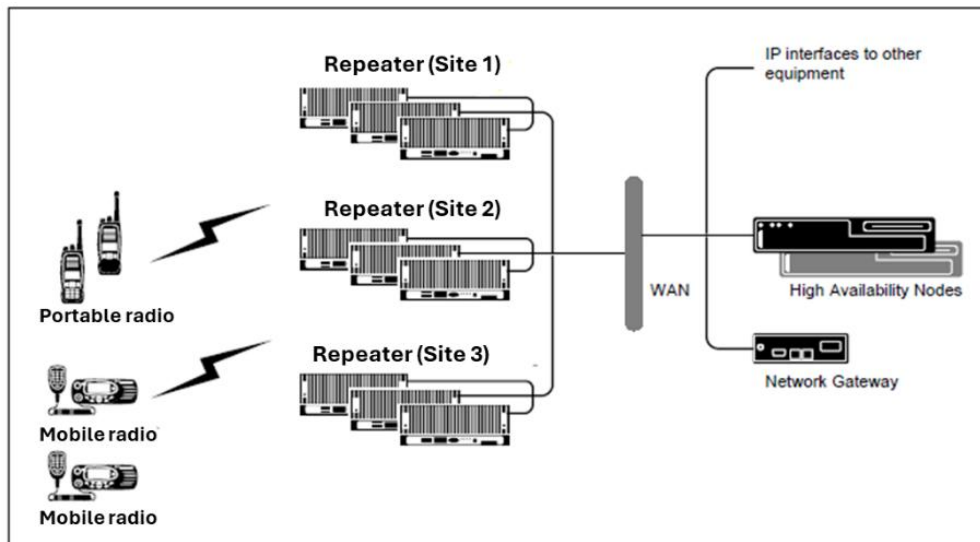


Figure 2-6- DMR network overview [51]

The following are some of the components that make up the DMR network [45] [51]:

- **Control stations:** Manage and monitor the network and communication traffic. Consists of centralised control units and network management systems.
- **Network infrastructure:** Facilitate communication between different components and extend the network's functionality. Consists of IP-based networking equipment, gateways and routers.
- **Base stations:** Connect mobile units to the communication network. Consists of radio frequency (RF) modules and control units.
- **Repeaters:** Extend the coverage area by retransmitting signals from mobile units. Consists of base station repeaters that receive and transmit signals.
- **Mobile units (radios):** Handheld or vehicle-mounted radios used by end-users for communication. Consists of handheld radios, mobile radios and dispatch consoles.
- **Dispatch consoles:** Enable dispatchers to communicate with mobile units and manage communication traffic. Consists of software applications and hardware interfaces.

- Data applications: Provide additional functionalities like GPS tracking, text messaging and telemetry. Consists of application servers and software modules.

2.3.4 Comparison of Digital PMR Technologies

Digital technologies were described in the previous section. This section aims to compare all the technologies to determine which is the best to replace the analogue radio communication system. Table 2-1 presents the technical comparison of digital PMR technologies.

Table 2-1- DMR, TETRA and LTE Comparison [3] [4] [29] [30] [31] [32]

Technologies	DMR	TETRA	LTE
Frequency bands (MHz)	VHF, UHF, 700,800	UHF	Various
Modulation	TDMA (2-slots)	TDMA (4-slots)	OFDMA
Channel spacing	12.5 kHz	25 kHz	Various (e.g., 1.4, 3, 5, 10, 15, 20 MHz)
Data Rates	9.6 Kb/s	28.8 Kb/s	Up to 100 Mb/s (downlink), 50 Mb/s (uplink)
Encryption	Yes	Yes	Yes
Compatible with analogue systems	Yes	No	No
Implementation (system scales)	Small to large	Large	Large
Supported by different manufacturers	Yes	Yes	Yes
System cost (per km ²)	€€	€€€	€€€€

DMR offers low data rates (9.6 Kb/s) compared to other digital technologies; however, it is suitable for medium-scale applications, which are the focus of this research design. It provides efficient TDMA (2-slot) modulation and compatibility with analogue systems. Its 12.5 kHz channel spacing minimises spectrum use, ensuring cost-effectiveness.

A more comprehensive technical, operational and relative lifecycle-cost comparison of the existing analogue PMR system and the principal digital migration alternatives considered in this study is provided in Annexure C, Table C-1. The comparison includes DMR, TETRA, LTE/MCX and FRMCS/5G-R, with the supporting references for each technology presented directly in the annexure table.

As shown in Annexure C, Table C-1, DMR provides the most appropriate balance of spectrum efficiency, mission-critical voice functionality, coverage capability, migration compatibility

and relative lifecycle cost for the defined pilot scope. Although TETRA, LTE/MCX and FRMCS/5G-R offer greater centralised network functionality, broadband data capacity and future integration capabilities, they require progressively higher investment in core-network infrastructure, transmission backhaul, system integration and operational support. DMR was therefore selected for detailed investigation and practical validation within the scope of

2.4 Comparison of Analogue and DMR

This section provides a detailed comparison between analogue and digital radio networks to highlight the advantages of adopting digital systems. The comparison covers various performance factors such as voice quality, throughput, spectrum efficiency, battery life, security, functions and features and cost. Table 2-2 presents a comparison of the DMR network with the analogue radio network.

Table 2-2- Analogue and DMR comparison [1] [2] [3]

Performance	Analogue Radio Network	DMR
Voice Quality	Degrade when signal strength is reduced	Better and consistent throughout the coverage area due to the use of FEC
Throughput	Lower throughput (2.4 kb/s), Voice only	Better throughput (9.6 kb/s)
Spectrum Efficiency	Uses 12,5kHz FDMA channel	50% Efficiency, uses 2-time slot TDMA of 12,5kHz signal
Battery Life	Shorter due to full power required for FDMA	Requires less power since it uses TDMA
Security	Less secure since analogue systems do not have a full encryption feature	More secure due to better encryption features in digital technology
Functions and Features	Application is based on only voice communication; no extra feature is supported	Support advanced features e.g., GPS location, text messaging, emergency calls, data capabilities, network monitoring.
Cost	Transmission in one radio channel	Lower licensing fees and maintenance costs

DMR offers significant advantages over analogue radio networks, particularly in voice quality, throughput and spectrum efficiency, as detailed in Table 2-2. It ensures consistent voice quality through Forward Error Correction (FEC), maintaining performance across the coverage area. With a throughput of 9.6 kb/s, DMR supports both voice and advanced data services such as

GPS, text messaging and emergency calls, far surpassing analogue's 2.4 kb/s voice-only capability.

By utilising 2-slot TDMA within a 12.5 kHz channel, DMR achieves 50% greater spectrum efficiency than analogue, which dedicates the entire channel to a single transmission through FDMA. This approach doubles communication capacity without additional spectrum requirements, making DMR a cost-effective and efficient choice in environments with constrained spectrum availability.

Additionally, DMR delivers superior security with encryption, unlike analogue systems that lack such features, ensuring communications remain protected. When combined with longer battery life, lower licensing fees and reduced maintenance costs, DMR provides a modern, scalable and secure solution for diverse communication needs.

2.5 DMR Case Studies

The researchers [59] utilised Digital Mobile Radio (DMR) to develop a sophisticated fire detection system that is both autonomous and reliable. Each DMR node in their system was equipped with a variety of sensors to monitor critical environmental parameters such as temperature, humidity, atmospheric pressure and gases like carbon monoxide. These nodes were designed to be energy-autonomous, powered by rechargeable batteries connected to solar panels. The DMR nodes primarily operated in deep sleep mode to conserve energy, waking up periodically to collect and transmit data. By implementing DMR technology, the researchers ensured robust and continuous communication, essential for early fire detection and prompt intervention in forested areas, thereby enhancing the overall effectiveness of fire prevention efforts.

[11] examined a DMR trunked radio system that can serve all mission-critical public safety services in the Corfu region. Using simulations of radio coverage, the study was able to obtain radio coverage of 98% on land and 99.8% on sea. Additionally, the study revealed that the DMR network may be adjusted to increase land coverage to 99% by including new base stations. The study serves as a good proof of concept for the feasibility and adaptability of DMR systems in mission-critical communication, demonstrating their capability to provide reliable coverage, scalability for network expansion and cost-effectiveness compared to alternative technologies.

[60] assessed which digital radio system is suggested to replace the present analogue system in the Russian railway system, considering the cost of migration. The research evaluated GSM-R, DMR and TETRA, which are popular alternatives for existing analogue railway systems. According to the study, there is a rising demand for DMR radio communications, which compare favourably to the GSM-R and TETRA standards since they enable a low-cost transition from analogue to digital communication systems. This makes DMR a practical and cost-effective solution for modernising railway communication infrastructure.

[1] demonstrated Digital Mobile Radio (DMR) technology for mission-critical applications and compared it to other professional mobile radio (PMR) standards, with a specific emphasis on TETRA in health emergency services in Sardinia (Italy). According to the conclusions of the investigations, DMR technology had superior radio coverage, which was equal to -110 dBm for a DMR terminal and -105 dBm for TETRA. The report also discovered that DMR was the best option for cost savings, high coverage, spectrum efficiency and network configuration ease and was ideally suited to vast regions with low or medium traffic density.

[61] conducted an in-depth study examining the TETRA, DMR and LTE systems to identify the most suitable technology for mission-critical communications. Their findings indicated that DMR was the optimal solution for small to medium mission-critical applications. This conclusion was based on several advantages of DMR technology, including its cost-effectiveness, rapid deployment, minimal administrative training requirements and the provision of functionalities comparable to other digital technologies. The study highlighted DMR's capability to deliver reliable and efficient communication, making it a compelling choice for mission-critical scenarios.

[62] conducted a study to analyse the signal quality of the DMR Tier 3 trunking radio system along the Makassar - Pare-Pare railway route, which faced network coverage issues that posed safety risks. The research employed theoretical analysis using the link budget method, simulations with radio mobile software and field measurements with handheld transceivers (HT). The findings revealed that the average RSSI values from calculations, simulations and field measurements were -62.49 dBm, -62.61 dBm and -76.47 dBm, respectively. All RSSI values at all 36 measurement points met both ETSI and TAIT standards, demonstrating the theoretical and simulated results' alignment with field data, thus providing crucial insights for enhancing communication and ensuring the safety and security of train travel along this route.

These case studies collectively demonstrate the versatility and reliability of DMR technology across diverse mission-critical applications, including forest fire detection, public safety, railway communication, and health emergency services. The findings consistently highlight DMR's strengths in cost-effectiveness, scalability, energy efficiency, rapid deployment, and improved coverage compared to alternative technologies such as GSM-R and TETRA. By offering a practical migration path from analogue systems while ensuring robust and continuous communication, DMR emerges as a highly adaptable and sustainable solution for enhancing safety, efficiency, and resilience in critical communication infrastructures.

2.6 DMR Technical Specifications

Table 2-3 provides a comprehensive overview of the transmitter and receiver specifications for DMR Tier 2 radios, collating data from various authoritative sources, including the ETSI standards [4], Hytera communications RD985 repeater manual [5] and Tait communication TB9300 repeater manual [6]. Tait and Hytera provide DMR equipment aligned with ETSI DMR specifications, adhering to stringent standards and offering advanced features for enhanced performance.

Table 2-3- DMR Technical Specifications [4] [5] [6]

Specification	Value
Frequency Range	136-174, 400-480, 66-960 MHz (for VHF and UHF bands)
Channel Spacing	12.5(2x 6.25) kHz
Modulation	4FSK
Output Power	1-5 W (handheld), 1-25 W (mobile), 1-50/100 W (repeater)
Frequency Stability	± 0.5 ppm
Adjacent Channel Power	-60 dB, For 12.5 kHz channels
Transmitter Conducted Spurious Emissions	≤ -36 dBm
Receiver Sensitivity (Digital, 5% BER)	-120 to -117 dBm , Calculated from 0.22 to 0.3 μ V
Adjacent Channel Selectivity	60 dB (12.5 kHz), 70 dB (20/25 kHz) , for 12.5 kHz channels
Intermodulation Rejection	70 dB (12.5 kHz), 75 dB (20/25 kHz)
Spurious Response Rejection	70 dB (12.5 kHz), 75 dB (20/25 kHz)
Audio Output Power	1 dB (handheld/mobile), 3 dB(repeater) , at 5% distortion
Operating Voltage	7.4 V (handheld), 13.6 V(mobile/repeater)
Operating Temperature Range	-30 to +60 °C
Antenna Impedance	50 ohms

Most specifications are consistent across the sources. However, receiver sensitivity, a critical specification, shows slight variations. The Hytera RD985 documentation specifies a sensitivity level of -117 dBm, whereas the Tait TB9300 documentation indicates a sensitivity of -120 dBm, reflecting a slightly higher sensitivity at the lower end. To accommodate these variations, an average range of -120 to -117 dBm was taken. This outlined specification for sensitivity still outperforms the legacy analogue system, which was specified by ETSI to be -110 dBm, corresponding to a signal-to-noise ratio of 10 dB and a noise floor of -120 dBm [63].

These specifications will be utilised in the design section of the DMR project to ensure robust and reliable communication solutions, leveraging the latest repeaters such as the TB9300 Tait repeater. By incorporating these advanced specifications, the research design will focus on testing the performance of DMR against these standards using both simulated and real-world scenarios.

2.7 Future Railway Mobile Communication System (FRMCS)

Recent literature shows that railway communication is moving from narrowband voice systems toward broadband, IP-based and mission-critical service platforms. [64] explain that 4G and 5G systems are being investigated for railway critical signalling services, with performance assessment based on radio, network and application-layer indicators such as Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), Signal-to-Interference-plus-Noise Ratio (SINR), latency, jitter and signalling timeout. Similarly, [65] positions Fifth Generation Railway (5G-R) as a next-generation railway communication platform capable of supporting intelligent railway services, including higher-capacity data services, ultra-reliable low-latency communication and advanced operational applications. These developments indicate that future railway communication systems will not only support voice communication, but also broadband services, signalling data, monitoring, train-to-ground communication and intelligent transport applications.

FRMCS is also emerging as the long-term successor to GSM-R and is being developed to align railway communication with 5G-based mission-critical services. [66] describe FRMCS as the future 5G worldwide standard for railway operational communication, while the 5G RAIL project validates early FRMCS specifications through laboratory and field-based prototypes. In addition, interworking is an important consideration during railway communication migration because legacy radio systems cannot be replaced immediately in operational railway

environments. [67]explain that an Inter Working Function (IWF) can support communication between Long Term Evolution (LTE)-based mission-critical push-to-talk services and legacy Land Mobile Radio (LMR) systems. This indicates that future railway communication should allow DMR and other legacy mission-critical radio systems to interwork with LTE, 5G and FRMCS-based platforms so that operational voice, group communication and safety-related services remain available during gradual technology migration.

2.8 Summary

This chapter reviewed the literature on upgrading analogue radio communication systems to digital technologies, with particular emphasis on TETRA, LTE and DMR. The chapter highlighted that DMR is suitable for mission-critical railway voice communication because of its cost-effectiveness, improved audio quality, enhanced spectral efficiency and practical migration advantages over analogue systems. The reviewed case studies demonstrated successful DMR implementations in various mission-critical scenarios, including fire detection, public safety and railway communication, further supporting its relevance as a practical digital migration option.

The chapter also considered recent developments in railway communication, particularly FRMCS, LTE and 5G-based mission-critical communication systems. These technologies indicate the long-term direction of railway telecommunications toward broadband, IP-based and service-integrated platforms. However, within the scope of this study, DMR remains the focus as a near-term narrowband solution for mission-critical railway voice communication. The next chapter discusses the research design, simulation process and practical setup of the DMR communication system.

CHAPTER 3: RESEARCH DESIGN

3.1 Introduction

This chapter outlines the design and piloting of the DMR radio system for rail-bound communication. The previous chapter covered the literature on various technologies that could replace the PMR analogue radio communication and reviewed case studies on the success of DMR radio communication systems in different MCC applications. The research identified DMR networks as the most suitable solution within the defined pilot scope for a rail-bound mission-critical wireless communication system. The design and planning of the radio network are conducted using the Wireless Radio Access Planner (WRAP) software, a propagation modelling tool. A detailed explanation of the WRAP software is provided in the radio propagation model tuning section of this chapter.

The DMR specifications compiled in the previous section will assist in designing and testing the DMR system. The DMR pilot site will be installed and used to evaluate DMR technology by employing a Tait TB9300 repeater to simulate coverage from a single site and assess the DMR capabilities. A Hytera PD 785 handheld radio will be utilised to test different Receive Signal Strength (RSS) levels across the coverage area to support a comprehensive evaluation of the system's performance. The structured approach aims to provide a thorough assessment of DMR technology and its suitability for mission-critical communications in the railway industry.

The design consists of the following:

- Defining requirements
- Dimensioning the radio network
- Tuning the radio propagation model
- Conducting a pilot study (practical)

3.2 Defining Requirements

The first stage of the design process is to define the system requirements for the design. This involves surveying for an optimal solution and identifying the necessary tools and data to begin the design and planning process [68]. This section will outline all the requirements for the design. The requirements serve as the foundation against which all subsequent design decisions and evaluations will be measured. Formal permission to conduct the study and access the

company's operational environment was also obtained before the pilot study commenced, as presented in Annexure A.

3.2.1 Geographic Location

An important step in the design process is selecting the geographic area where the site will be installed [69]. In the design, a suitable location for both the simulation and piloting of the DMR radio site was identified. The design area included a railroad, as the intended coverage is along the railway. The Muiskraalkop site in Robertson, Western Cape (Figure 3-1), was chosen for the research design.

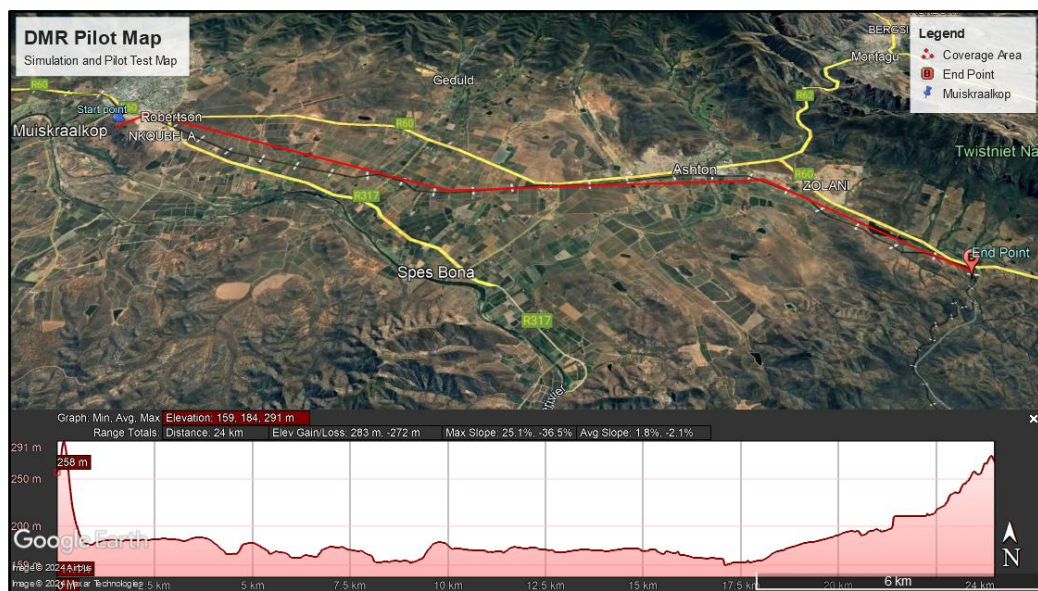


Figure 3-1- Muiskraalkop high site Google map

The chosen area for the radio coverage design, depicted in the Google map image (Figure 3-1), encompasses a section of the region extending from Muiskraalkop to the endpoint near Zolani. This area was specifically selected based on several key factors evaluated during a comprehensive terrain and landscape survey:

- Electricity availability: Reliable electricity supply for equipment.
- Suitable terrain: Favourable terrain for signal propagation.
- Existing infrastructure: Presence of facilities that simplify installation and maintenance.
- Proximity to major roads: Easy access for signal surveys.
- Geographical features: Analysis of natural and artificial elements that influence radio propagation.

- Elevation variations: An elevation profile ranging from 159 to 291 meters, providing a diverse testing environment.
- Potential obstacles: Identification and evaluation of hills or structures that could affect signal quality.
- Diverse terrain: Comprising urban and suburban areas with slopes and varied landscapes to assess signal performance under different topographical and environmental conditions.

The designated coverage area, marked in red (Figure 3-1), highlights the railway line where the coverage test was conducted. The study included both simulations and practical coverage tests along the railway line to evaluate the communication coverage. These tests assessed signal strength and quality, providing valuable data for optimising the radio coverage design along the route.

3.2.2 Design Project

The DMR design block diagram is illustrated in Figure 3-2. The block diagram consists of important components that make up a DMR radio site and were used in building the pilot site.

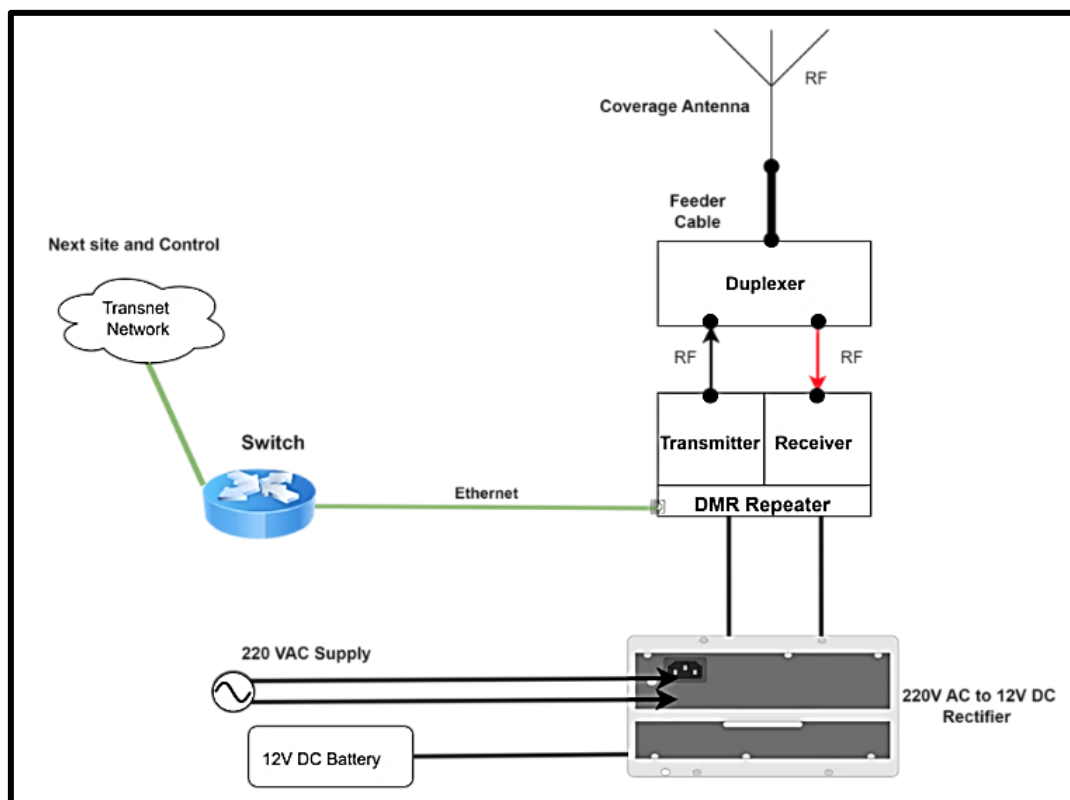


Figure 3-2- DMR design block diagram

The DMR radio sites include a duplexer, which is a device used in communication systems to allow simultaneous transmission and reception of signals through a single antenna, effectively separating the transmitted and received signals to avoid interference [70] [71]. A key component of the pilot site is the DMR repeater, which is the main radio equipment responsible for the modulation and demodulation of the radio signals. After developing the block diagram, the equipment to be used for the research was outlined. Table 3-1 lists the specifications of the equipment used in the DMR radio site design.

Table 3-1- Equipment Specifications

Equipment	Make and model	Specification
Site Equipment		
Antenna	Webb Corner Reflector (CR400)	9dBi
Repeater	Tait TB9300	Max 150W
Coaxial cable	LMR 400	Attenuation = 0.089 dB/m
Power supply	SOS Power Supply	230VAC to 13.6 VDC
Duplexer	Webb Duplexer	< 1.2dB insertion loss
End user equipment		
Handheld radio	Hytera PD785 U	Maximum 5W
Mobile radio	Hytera MD 785i	Maximum 25W
Test equipment		
Communication service monitor	Aeroflex 3350-R	Analogue and DMR
Vector network analyser	Rohde and Schwarz ZVL	9kHz – 3GHz
Power supply	TTi QPX1200S	1200-Watt DC power supply
Bird site analyser	SA-6000MHz	6000MHZ

The key components include the Webb CR400 corner reflector antenna with a gain of 9 dBi, the Tait TB9300 repeater with a maximum power output of 150 W and the LMR 400 coaxial cable with an attenuation rate of 0.089 dB/m. The power supply converts 230 VAC to 13.6 VDC to power the system, while the Webb duplexer ensures signal isolation with an insertion loss of less than 1.2 dB.

The Hytera PD785 U handheld radio (5 W) and the Hytera MD785i mobile radio (25 W) are the designated end-user devices for system testing. The handheld radio will be employed in the field to measure and verify signal strength at various test points, while the mobile radio will be

used on the workbench to assess the DMR system's power consumption under controlled conditions.

A range of specialised testing equipment has been included to ensure the system meets design requirements. The Aeroflex 3350-R Communication Service Monitor, compatible with both analogue and DMR systems, will perform comprehensive analysis and calibration of radio equipment. The Rohde & Schwarz ZVL Network Analyser (9 kHz – 3 GHz) will test and align the duplexer for optimal insertion loss. Additionally, the TTI QPX1200S 1200-Watt DC Power Supply will simulate power requirements during workshop testing and a site analyser will measure the antenna's VSWR to ensure proper impedance matching and minimal signal loss.

3.3 Radio Network Dimensioning

Network dimensioning is used for deploying a new network when the minimum capacity requirements for meeting the service agreement needs to be determined [72]. It involves performing calculations to determine the capacity and equipment specifications required to meet the network requirements. In the design, the equipment specifications obtained in Table 3-1 were used to calculate the requirements of the network design and simulations by performing link budget calculations.

3.3.1 Link Budget

Link budget calculation is the process of determining the power gain and losses from the transmitter to the receiver to establish the maximum allowable path loss while considering certain parameters [62] [69]. Link budget calculations were conducted to account for all gains and losses in a communication system from the transmitter to the receiver via the medium and they served as the input to the radio propagation modelling.

3.3.2 Effective Radiated Power (ERP)

ERP is a key component in the link budget calculation. It is determined by combining the transmit power of the antenna with the transmitter's antenna gain [73]. ERP can be calculated using Equation 1:

$$\text{ERP} = P_{\text{Tx}} - L_{\text{Tx}} + G_{\text{Tx}} \quad (1)$$

where:

- ERP: Effective radiated power (dBm)
- PTx : Maximum transmitter power (dB)
- LTx : Loss in the cable or connector at the transmitter (dB)
- GTx : Antenna gain at the transmitter (dBd)

A 20 W power level was selected for this research in accordance with Transnet's certification obligations with the Independent Communications Authority of South Africa (ICASA), the spectrum regulator. This requirement ensured that the research design limited the antenna's power output to a maximum of 20 W ERP.

To simulate this setup, the maximum power output from the antenna was configured in the WRAP software. However, a challenge arose because WRAP only accepts power input values in dBW (decibels relative to 1 W), not in Watts. As a result, the ERP had to be converted to dBW to ensure the simulation reflected the correct parameters. The following calculation was performed using Equation 2 to determine the ERP value in dBW for accurate use in the WRAP simulation:

$$\text{dBW} = \log_{10}(W) \quad (2)$$

$$\text{dBW} = \log_{10}(20) = 13\text{dBW}$$

Thus, 20 W was converted to 13 dBW for the simulation, enabling precise modelling of the antenna's power output within the software environment.

3.3.3 Free Space Loss (FSL)

Once the ERP is determined, the signal is radiated into free space, which serves as the medium. The next step in the research design was to calculate the losses that would be experienced in free space. FSL represents the phenomenon of radio wave power reduction as it propagates in free space. This attenuation depends on the signal frequency and the distance between the transmitter and receiver antennas. In this space, no obstacles are allowed because the transmission is Line of Sight (LoS) [12]. To calculate the FSL value, Equation 3 was used. This loss is represented by the Free Space Loss (FSL) model [74].

$$\text{FSL} = 32.45 + 20 \log f + 20 \log d \quad (3)$$

where:

- FSL: Free space loss (dB)
- f : Frequency used (MHz)
- d : Distance between transmitter and receiver (km)

3.3.4 RSSI (Receive Signal Strength Indicator)

Received Signal Strength Indicator (RSSI) measures the power level that a radio receiver detects from the transmitted signal, typically used to estimate the quality of a wireless communication link [75] [76] [77]. This measurement is crucial for understanding how radio waves propagate through different environments [78]. RSSI can be calculated using Equation 4.

$$\text{RSSI} = \text{ERP} - \text{FSL} + \text{GRx} - \text{LRx} \quad (4)$$

where:

- RSSI: Receive signal strength indicator (dBm)
- ERP: Effective radiated power (dBm)
- FSL: Free space loss (dB)
- GRx : Receiver antenna gain (dBd)
- LRx : Cable loss at the receiver antenna (dB)

3.3.5 Duplexer

The duplexer was used to combine the transmitter and the receiver to use one antenna for the research design. This is the important component of the design and since it is a passive device it has losses that need to be considered when doing link budget calculations. In the design, the Webb Industries Duplexer DU400/6 was used, which, according to the datasheet (see Table 3-2), has an insertion loss of less than 1.2 dB. To ensure conservative calculations, the maximum insertion loss of 1.2 dB was assumed as the acceptable attenuation limit.

The duplexer operates within a frequency range of 380–470 MHz, which is consistent with the requirements of the research design. For calibration and alignment purposes, a Vector Network Analyzer (VNA) was used to minimise the insertion loss and ensure that the duplexer is aligned

to operate on the research design frequency. The VNA is the most accurate instrument for such calibrations and verifications [79].

Table 3-2- Webb Industries Duplexer DU400/6 Specifications [7]

Category	Specification
Electrical Data	DU 400/6
Article Number	D10AA0003A
Frequency	380—470 MHz
Frequency Spacing	10 MHz
Continuous Input Power	40 W
Insertion Loss, Tx—Ant	< -1.2 dB
Rx Isolation @ Tx Freq	> - 80 dB
Return Loss @ Tx Freq	> -18 dB
Impedance	50 Ohm
Termination	N female
Mechanical Data	
Temperature Range	-10 to 60°C
Dimensions	L 250 mm x W 158 mm x H 33 mm
Packed Weight	1 kg
Packaged Volume	L 31 cm x W 19 cm x H 4.5 cm

3.3.6 Antenna Specification

The dBd (decibels relative to a dipole) was used for all antennae gain measurements because it provides a consistent and relevant basis for evaluating antenna performance in industrial environments. Some antenna suppliers provide antenna gain in their data sheets as dBi, which uses the isotropic antenna as the reference. The gain of a dipole antenna to the sides of the antenna is +2.14 dB. This means that the effective radiated power to the sides of the antenna is 2.14 dB more than the power from the transmitter. The difference between dBi and dBd is the intrinsic gain of a dipole, 2.14 dB as seen in Equation 5.

$$\text{dBd} = \text{dBi} - 2.14 \quad (5)$$

Table 3-3 provides a detailed overview of the specifications for the CR400 corner reflector antenna used in the research design. This table includes both the electrical and mechanical data essential for informing the design inputs and ensuring compatibility with the project's requirements. In the research design, the CR400 corner reflector was used, which is a dipole antenna with a specified gain of 9 dBi [8]. This gain value was converted to dBd, resulting in a gain of 6.86 dBd. The 6.86 dBd value was subsequently used in the calculations for the link

budget estimations. The CR400, which has frequency range of 406–470 MHz was chosen for the research design because the system’s operating frequency falls within this range.

Table 3-3- The CR400 Corner Reflector Specification [8]

Parameter	Value
Electrical Data	
Sales code	CR400
Article number	A10AA0061A
Frequency	406–470 MHz
Nominal gain	9 dBi
VSWR	$\leq 1.5:1$
Polarisation	Vertical or Horizontal
H-plane	54° @ 3 dB Beam Width
E-plane	72° @ 3 dB Beam Width
Front-to-back ratio	> 25 dB
Rated power	150 W
Impedance	50 Ω
Termination	N Female
Surge protection	All metal parts are directly grounded
Mechanical data	
Max. wind velocity	200 km/h
Wind load	11.7 kg @ 144 km/h
Flat plate area	0.110 m ²
Material	Aluminium with Moulded Dipole Cover
Mounting	To Ø 25 mm – Ø 50 mm Support Pipe, V-Bolts supplied
Antenna dimensions	H 0.5 m Vertically polarised H 1.2 m Horizontally polarised
Parcel dimensions	4.2 kg / 100 cm x 55 cm x 12 cm

3.3.7 Voltage Standing Wave (VSWR)

The duplexer, feeder, matching harness, and antenna employed in the research project are passive devices whose performance is determined by their impedance characteristics. A key parameter measured at the pilot site is the Voltage Standing Wave Ratio (VSWR), which represents the ratio between the amplifier’s output impedance and the connected device’s input impedance at a given frequency. An ideal impedance match of 50 Ω corresponds to a VSWR of 1:1 [80]. In this research design, a VSWR range up to 1:1.5 was considered acceptable, as this level is commonly adopted across industries, including Transnet [74], to ensure efficient power transfer and minimal signal reflection.

3.3.8 Feeder Cable Loss

The feeder cable used in the research project was an LMR 400 coaxial cable, with an attenuation rate of 0.089 dB/m. The cable loss is one of the components in the link budget and must be factored into the design of the radio system. The calculation below shows the total loss of the feeder cable over a length of 20 meters, with 10 meters of cable running from the pole to the high site and the remaining 10 meters accounting for the length of the pole. This represents where the antenna will be located.

$$L_{tx} = \text{Attenuation} \times \text{Cable Length} \quad (6)$$

$$L_{tx} = \frac{0.089\text{dB}}{\text{m}} \times 20 \text{ m} = 1.78\text{dB}$$

3.3.9 Radio Dimensioning Outputs

The radio dimensioning outputs section outlines the steps taken to calculate necessary parameters for the WRAP software simulation, ensuring that the simulation accurately reflects real-world conditions. To determine these specifications, the following link budget calculations were performed to obtain the values presented in Table 3-3.

The total loss was calculated based on the following component losses:

- L (cable): 0.89 dB
- L (duplexer): 1.2 dB
- L (matching harness): 3 dB

$$L_{Tx}(\text{total}) = L(\text{cable}) + L(\text{matching harness}) + L(\text{duplexer}) \quad (7)$$

$$L_{Tx}(\text{total}) = 1.78 + 3\text{dB} + 1.2\text{dB}$$

$$L_{Tx}(\text{total}) = 5.98 \text{ dB}$$

Given:

- ERP: 20 W
- $L_{Tx}(\text{total})$: 5.98 dB
- G_{Tx} : 6.86 dBd

First, convert ERP from dBW to dBm:

$$\text{ERP} = 13 \text{ dBW} + 30 \text{ dBm/dBW} = 43 \text{ dBm}$$

Using the ERP equation, the maximum transmitter power was calculated by rearranging Equation (1) to solve for PTx:

$$\text{PTx} = \text{ERP} + \text{LTx} - \text{GTx} \quad (8)$$

$$\text{PTx} = 43 + 5.98 - 6.86$$

$$\text{PTx} = 42.12 \text{ dBm}$$

To convert dBm to Watts, the following calculation was performed:

$$P_W = 10^{\left(\frac{P_{\text{dBm}}}{10}\right)} \times 1000 \quad (9)$$

$$P_W = 10^{\left(\frac{42.12}{10}\right)} \times 1000$$

$$P_W = 16.34 \text{ W}$$

For simulation purposes in WRAP, power is converted to dBW as follows:

$$P_{\text{dBW}} = 10 \times \log_{10}(P_W) \quad (10)$$

$$P_{\text{dBW}} = 10 \times \log_{10}(16.34) = 12.13 \text{ dBW}$$

Table 3-4 consolidates dimensioning results, presenting essential parameters such as ERP, component losses, antenna gain and maximum transmitter power.

Table 3-4- DMR network radio design dimensioning results

Parameter	Value
Effective Radiated Power	13 dBW / 43 dBm
Loss in Cable or Connector	1.78 dB
Duplexer Loss	1.2 dB
Matching Harness Loss	3 dB
Antenna Gain	6.86 dBd / 9dBi
Maximum Transmitter Power	16.34 W / 12.13 dBW

The parameters served as the essential input for the next stage of the research design, Radio propagation model tuning. These values were then used in the WRAP simulation to predict the system's performance within the research design.

3.4 Radio Propagation Model Tuning

This section presents the radio propagation model tuning carried out after the radio network dimensioning stage, with a focus on the DMR network planning using the WRAP software. Radio network planning is a crucial process in the design because it is used to determine and optimise the network coverage, whilst at the same time providing the desired capacity of the radio network [68] [81] [82].

3.4.1 WRAP Software

One of the most important decisions when designing a radio network is selecting the appropriate simulation software. The WRAP simulation software was chosen for the research design. WRAP is a comprehensive software tool used for radio network planning, spectrum management, interference analysis, frequency administration and network monitoring [83] [84].

The WRAP tool was selected for the research design due to its established reliability in WRAP's suite of planning and analysis tools for comprehensive maritime radio networks, covering surveillance, positioning, secure communication, railway communication and vessel tracking at sea [83]. For railway communication networks, WRAP provides integrated tools enabling users to plan coverage, manage interference and ensure redundancy even in cases of base station failures [83] [84]. In the research design, the WRAP software was used for antenna configuration, radiation pattern setup, repeater configuration and overall system design. The software ensures precise antenna placement, optimised radiation patterns to enhance coverage and minimise interference and configure repeaters.

3.4.2 Antenna Configuration

In the research, two back-to-back corner reflector antennas, each with a gain of 9 dBi, were used as specified in the previous section on antenna specifications. When these antennas were combined using a matching harness to ensure proper impedance matching, the signal was

divided between them. This division introduced a 3 dB loss into the antenna system due to the inherent nature of splitting the signal. As a result, the effective gain of the antenna system was reduced by 3 dB. This resulted in the input gain being 6 dBi, reflecting the combined effect of using two corner reflector antennas back-to-back with the associated splitter loss. Figure 3-3 illustrates the WRAP antenna configuration.

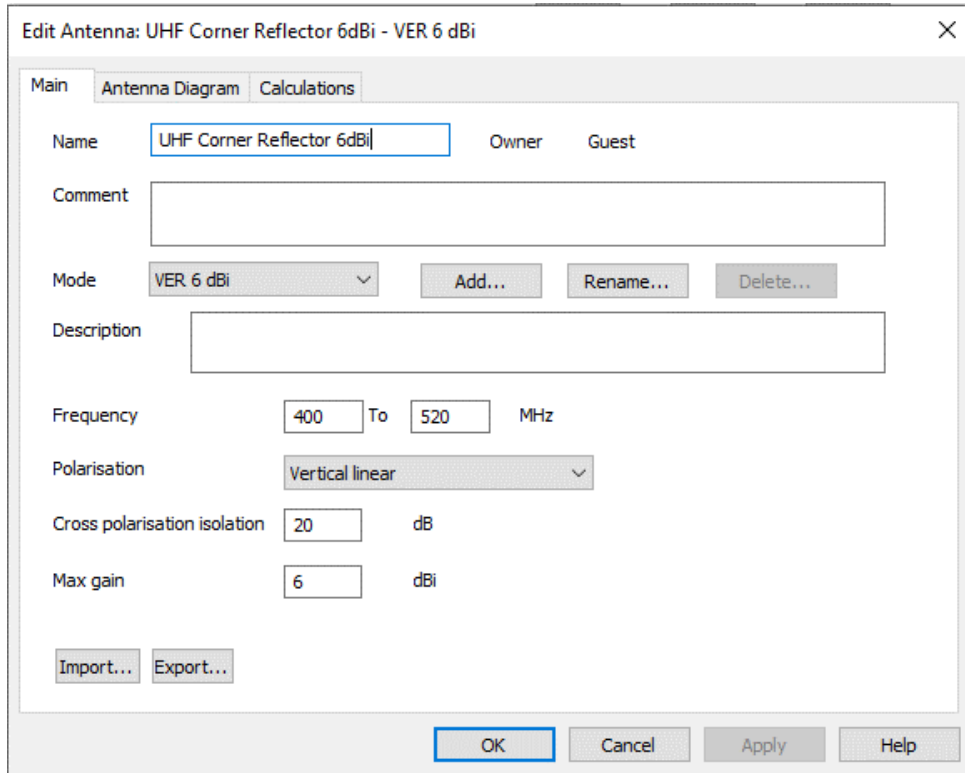


Figure 3-3- Antenna gain configuration

3.4.3 Antenna Radiation Pattern Configuration

The radiation pattern for the CR400 corner reflector antenna was imported into the WRAP simulation software to provide a detailed visualisation of its radiation characteristics, as shown in Figure 3-4 and Figure 3-5. This radiation pattern data was extracted from the CR400 manufacturer's manual, with specifications outlined in Table 3-2, ensuring that the simulation accurately reflected the antenna's real-world performance.

The imported radiation patterns are displayed in a polar plot format, showing the directional properties of the antenna with measurements taken at various horizontal and vertical angles. The dB levels indicate the relative signal strength at each angle, with a clear representation of the main lobe and side lobes. It is important for the radiation pattern to match the practical characteristics of the antenna to ensure that the simulation closely approximated the practical

results. Figure 3-4 illustrates the horizontal pattern that was obtained from the WRAP software, which was optimised to match the expected performance parameters for accurate analysis.

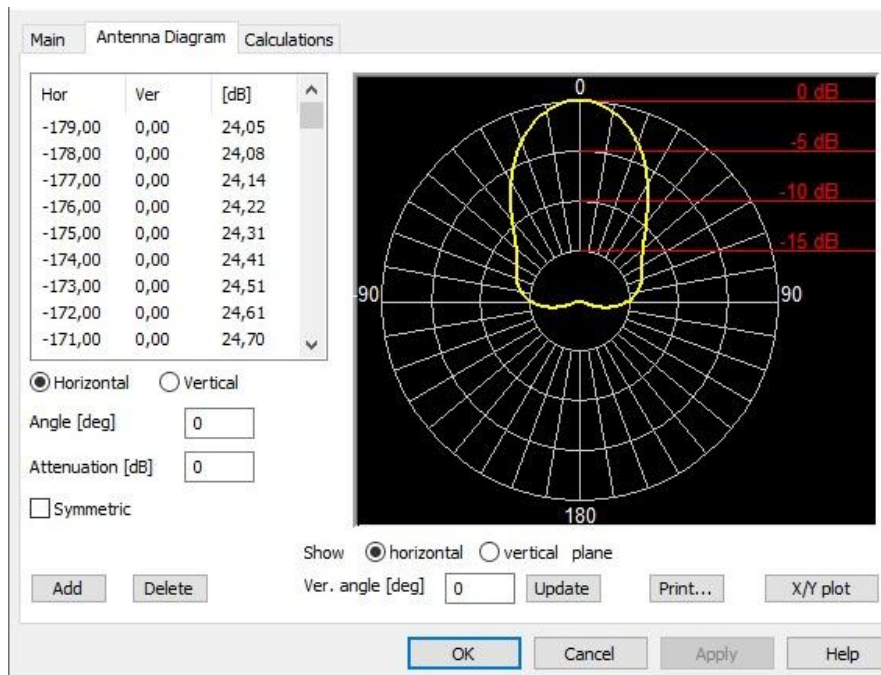


Figure 3-4- Antenna horizontal pattern

Figure 3-5 illustrates the vertical pattern for the CR400 corner reflector, configured using WRAP software. This pattern provides insight into the antenna's performance in the vertical plane, highlighting its capacity to focus signal strength at specific angles above and below the horizontal axis.

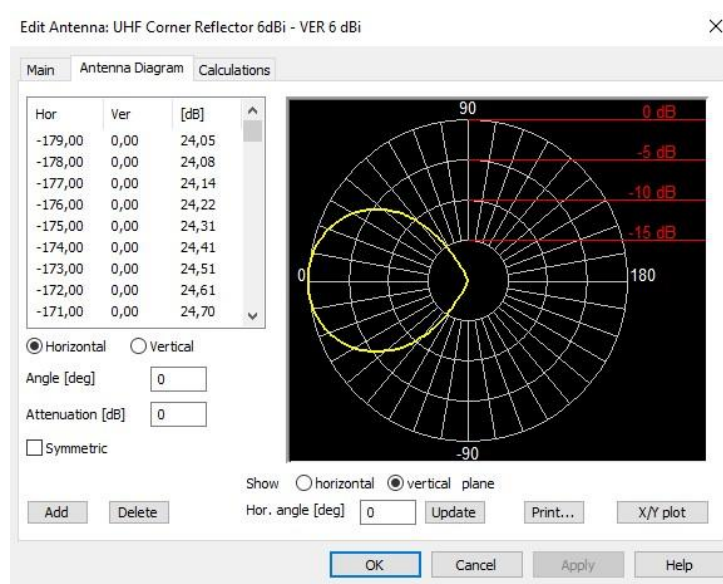
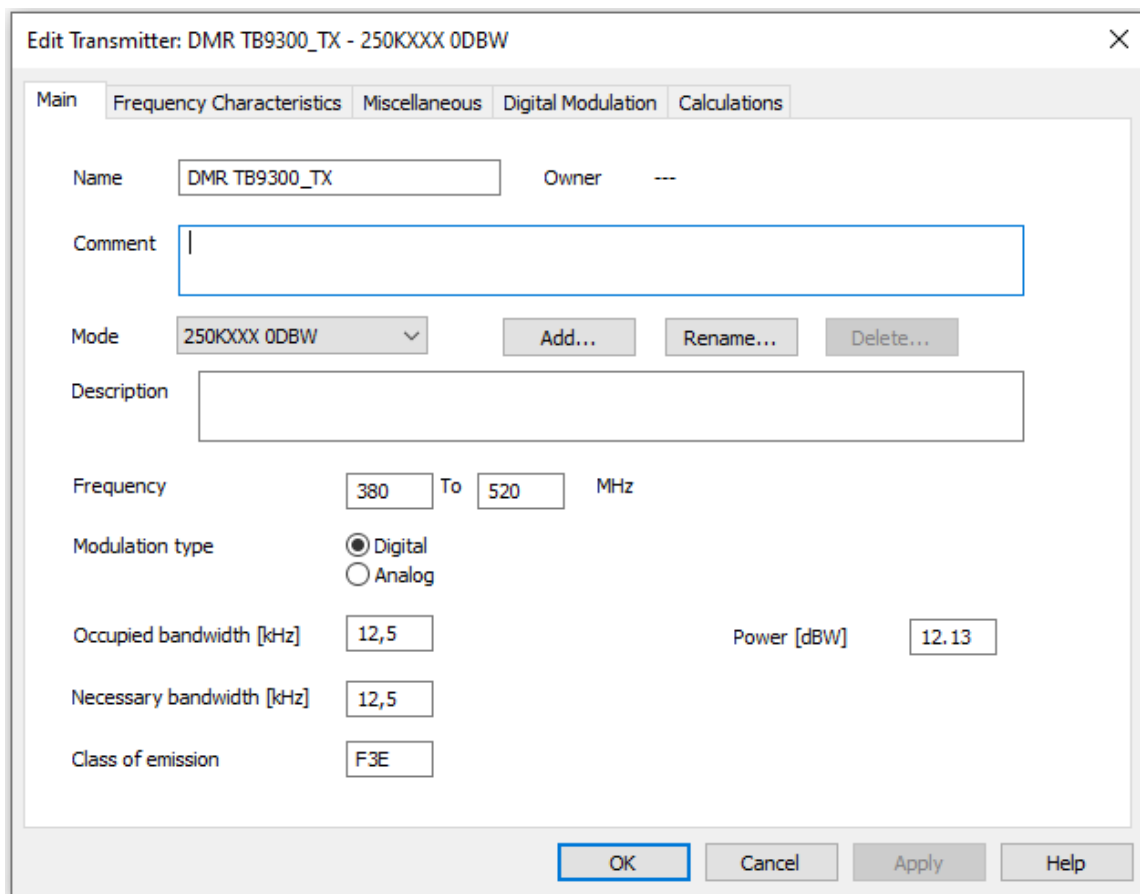


Figure 3-5- Antenna vertical radiation pattern

3.4.4 Repeater Configuration

The DMR repeater is one of the most critical components of the research design, responsible for all radio frequency intelligence within the DMR radio system. As part of the transmitter equipment, the repeater is installed at a high site within the radio network. Figure 3-6 illustrates the repeater configuration in the WRAP software. The configuration of the transmitter power for the repeater was based on the parameters listed in Table 3-4. These specifications were entered into the WRAP simulation software to ensure accurate modelling of the system. Since the WRAP software requires power values to be entered in decibels relative to one watt (dBW), the maximum transmitter power, initially calculated as 16.34 W, was converted to 12.13 dBW. This conversion ensures that the simulation accurately reflects the power levels used in the actual system design.



Edit Transmitter: DMR TB9300_TX - 250KXXX 0DBW

Main | Frequency Characteristics | Miscellaneous | Digital Modulation | Calculations

Name: DMR TB9300_TX Owner: ---

Comment:

Mode: 250KXXX 0DBW Add... Rename... Delete...

Description:

Frequency: 380 To 520 MHz

Modulation type: ☒ Digital ☐ Analog

Occupied bandwidth [kHz]: 12,5 Power [dBW]: 12.13

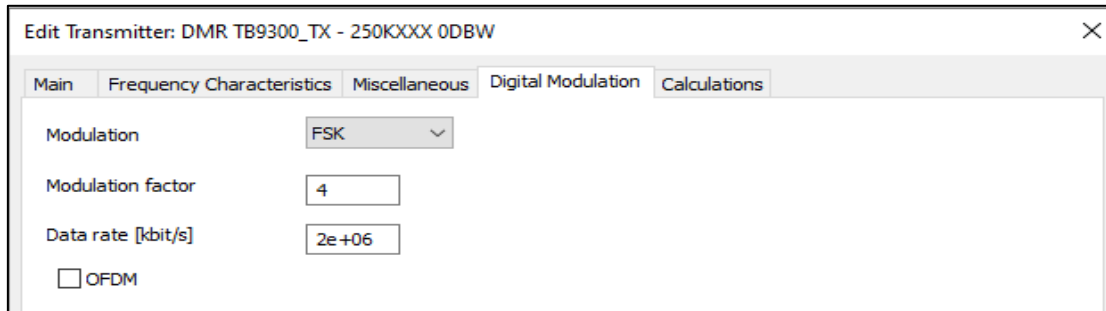
Necessary bandwidth [kHz]: 12,5

Class of emission: F3E

OK Cancel Apply Help

Figure 3-6- DMR repeater transmitter configuration

The power values were first entered, followed by configuring the modulation type for the DMR repeater in the WRAP software. As specified in Table 2-3, the DMR system utilises 4FSK modulation, which was accordingly set up in Figure 3-7.



Edit Transmitter: DMR TB9300_TX - 250KXXX 0DBW

Modulation: FSK

Modulation factor: 4

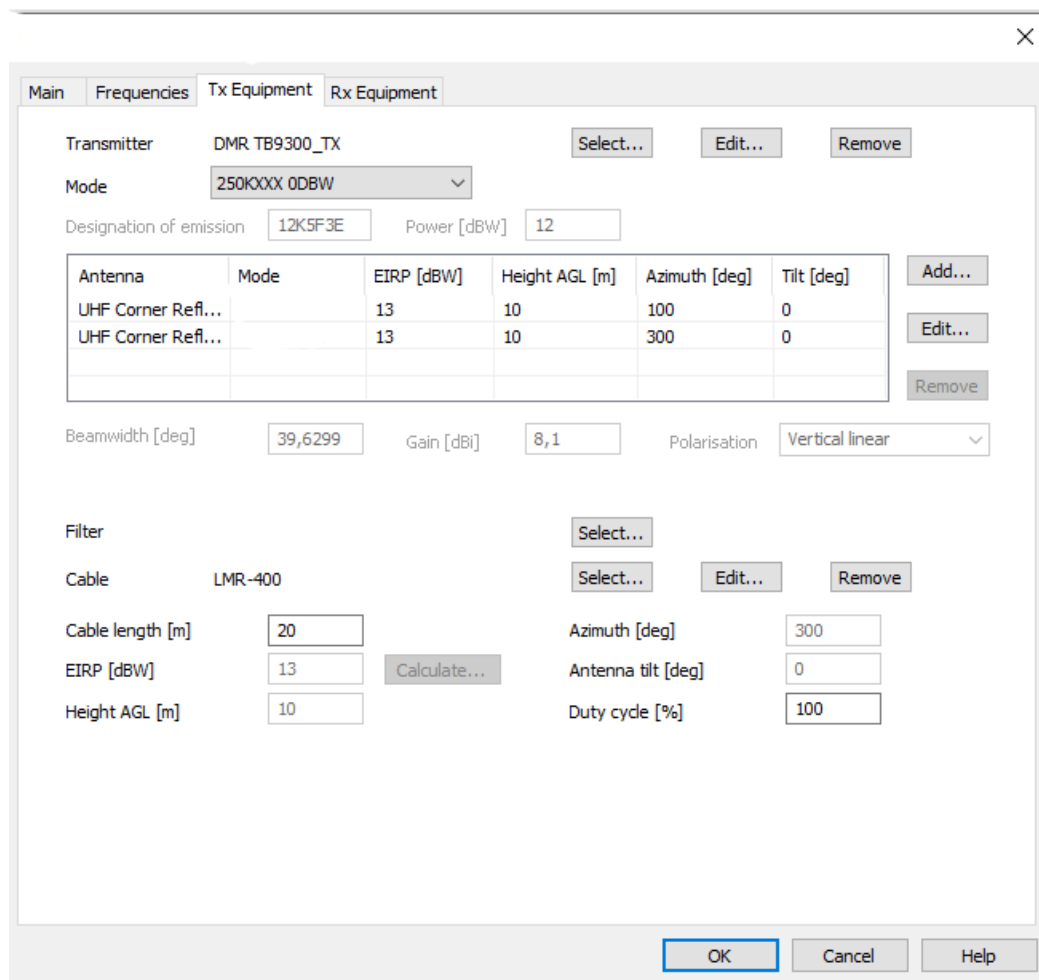
Data rate [kbit/s]: 2e+06

☐ OFDM

Figure 3-7- DMR repeater modulation configuration

3.4.5 System Configuration

The final step in the WRAP simulation setup was configuring the transmit system to ensure accurate representation of the real-world deployment. Figure 3-8 illustrates the system configuration, specifically the transmitter equipment setup, which is important since the research design uses the transmitter to measure the transmitted signal from the high site.



WRAP system configuration

Transmitter: DMR TB9300_TX

Mode: 250KXXX 0DBW

Designation of emission: 12K5F3E

Power [dBW]: 12

Antenna	Mode	EIRP [dBW]	Height AGL [m]	Azimuth [deg]	Tilt [deg]
UHF Corner Refl...		13	10	100	0
UHF Corner Refl...		13	10	300	0

Beamwidth [deg]: 39,6299

Gain [dBi]: 8,1

Polarisation: Vertical linear

Filter: [Select...]

Cable: LMR-400

Cable length [m]: 20

EIRP [dBW]: 13

Height AGL [m]: 10

Azimuth [deg]: 300

Antenna tilt [deg]: 0

Duty cycle [%]: 100

OK Cancel Help

Figure 3-8- WRAP system configuration

The system configuration included selecting an LMR-400 coaxial cable with a length of 20 m. The ERP, representing the power radiated by the antenna, was set to 13 dBW, corresponding to the calculated conversion from 20 W to dBW. ERP was a critical parameter in the communication system study as it determined the effective strength of the signal radiated by the antenna, considering both the transmitter power and antenna gain. Ensuring that the ERP was accurately calculated and set was essential for achieving the desired coverage and performance. The antenna height was set at 10 meters above ground level in this simulation, which significantly influenced line-of-sight range and signal propagation.

3.5 DMR Network Pilot

The pilot study for the research was conducted after the completion of the simulation phase, which had modelled and predicted the system's behaviour under various scenarios. With the simulations complete, the pilot study was essential for validating the research design through practical implementation. The study included workshop testing and field installation, ensuring that all equipment was thoroughly tested in the workshop before being installed and deployed in the field.

During the workshop testing phase, the focus was on aligning and verifying the equipment components that would be used in the installation. This phase also included programming the repeater and handheld radios that were essential for the field testing. These steps ensured that all equipment was fully operational and met the necessary standards for deployment.

The next phase involved the field installation and testing of a single pilot site. This on-site installation provided an opportunity to observe and measure the system's performance in a real-world setting. The results from this field testing were then compared to the simulated outcomes from the earlier phase. This comparison was crucial in validating the research design and ensuring that the system would perform as expected in actual conditions.

3.5.1 Workshop Testing

In the workshop testing and configuration, the components that make up the DMR radio network pilot site were configured and tested separately to ensure that they conform to the technical specifications. The repeater was the most important component of the research design and was configured and tested first.

3.5.1.1 Repeater Practical Configuration

The setup of the TB9300 Tait repeater was a crucial step in establishing the DMR radio network, as it functions as both the transmitter and receiver, ensuring reliable communication within the system. The configuration was conducted using the Tait Service Kit software, which enabled precise setup of the repeater used in the research design.

The transmitter was programmed first, beginning with its frequency. The test frequency was set on the transmitter and its power was configured to align with the link budget analysis conducted during the simulation phase. The repeater was programmed for 16 W instead of the calculated 16.34 W. This adjustment was necessary because the software accepts only whole numbers, requiring the power level to be rounded down to 16 W. Figure 3-9 illustrates the software setup of the repeater, showing the programmed power level.

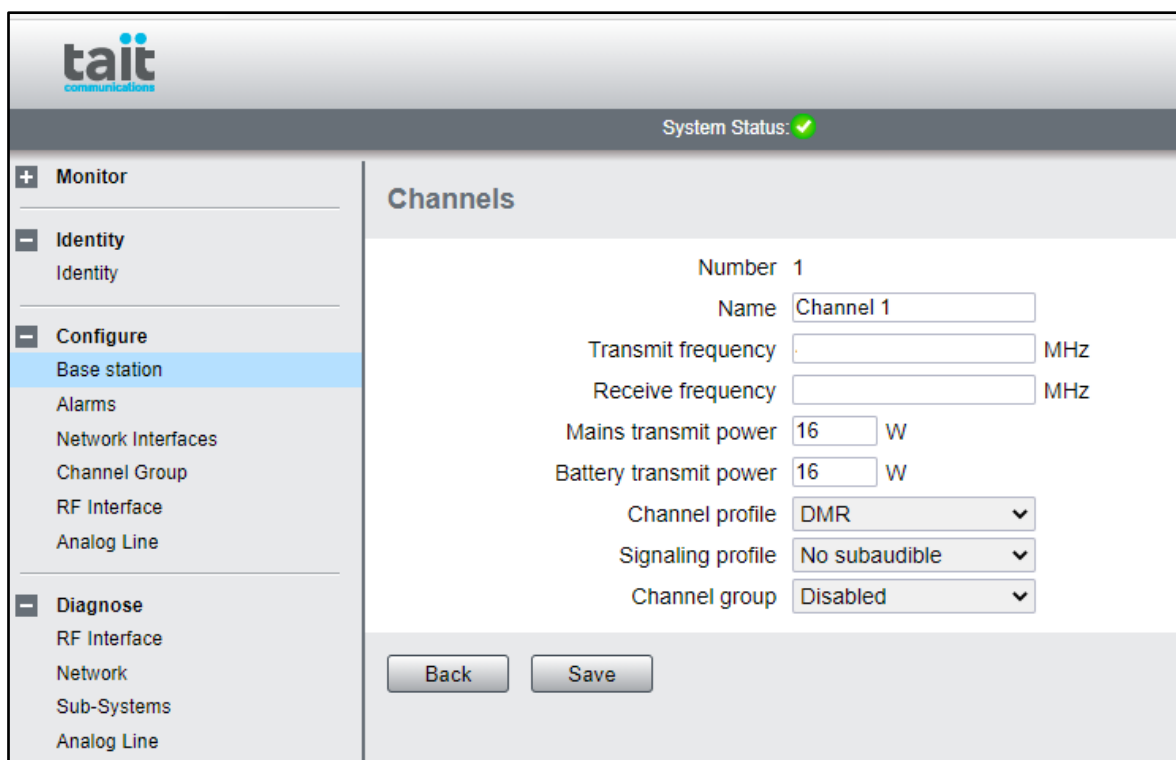


Figure 3-9- Repeater software setup

To validate the repeater's configuration, a workshop test was conducted using the Aeroflex 3550-R Communication Service Monitor and a power supply. The power supply was set to 13.4 VDC to provide the power to the repeater. Since the research design focuses on the transmit signal from the repeater, the transmitter port of the repeater was connected to the service monitor to measure key transmission parameters, including output power and frequency

accuracy. Figure 3-10 illustrates the testing setup, showing the connection between the repeater, service monitor and power supply.

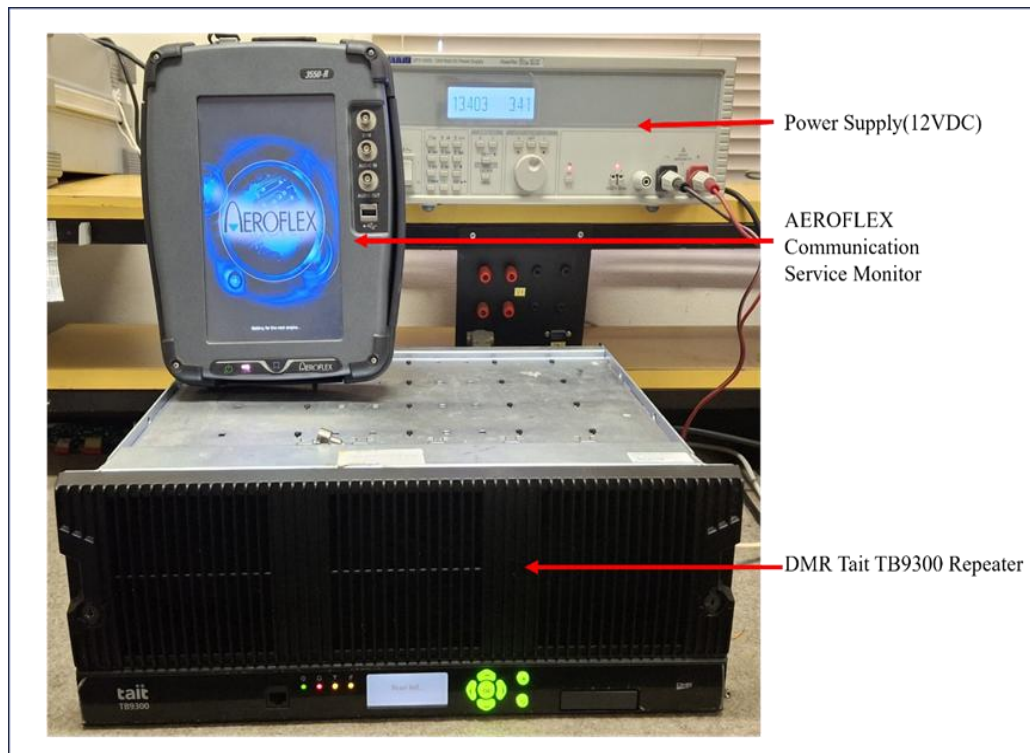


Figure 3-10- Repeater workshop setup

Figure 3-11 shows the readings captured during the test, displaying the transmitter power and frequency error. By analysing these values, potential deviations from expected transmission parameters were identified, allowing for necessary adjustments.



Figure 3-11- Communication service monitor readings

The results from the service monitor showed a transmit power of 15.986 W, which is slightly lower than the programmed power of 16 W. This small difference can be attributed to factors such as the tolerances of the test equipment and the repeater's internal components. Additionally, the accuracy of the test equipment itself plays a role. Measuring instruments like the Aeroflex 3550-R Communication Service Monitor have their own calibration tolerances, which may introduce minor measurement variations.

The transmitter frequency error was measured at -18 Hz using the Communication Service Monitor. This measurement indicates the difference between the intended transmission frequency and the actual transmitted frequency. When compared to the DMR technical specifications in Table 2-3, which specify a frequency stability requirement of ± 0.5 ppm, the measured frequency error falls well within the acceptable range. For the test frequency of 446 MHz, the allowed frequency deviation can be calculated as follows:

Given:

- Frequency stability: ± 0.5 ppm
- Test frequency: 446 MHz.

$$\text{Max frequency error} = \pm (\text{ppm} \times \text{Operating frequency}) \quad (11)$$

$$\text{Max frequency error} = \pm (0.5 \times 10^{-6} \times 446 \times 10^6)$$

$$\text{Max frequency error} = \pm 223 \text{ Hz}$$

This means the repeater's frequency can vary by up to ± 223 Hz while still meeting the standard. The observed frequency error of -18 Hz is significantly lower than this limit, demonstrating that the repeater maintains high frequency accuracy. This level of precision ensures minimal signal drift and reliable communication within the DMR network.

3.5.1.2 Duplexer Configuration

The duplexer was tested in the workshop using the Rohde & Schwarz ZVL Network Analyzer with the setup shown in Figure 3-12. In this configuration, Port 1 was connected to the transmitter, while Port 2 was connected to the antenna port of the duplexer. This setup was used to measure the insertion loss of the duplexer by feeding a signal from the transmitter into the duplexer and observing how much of the signal was passed through to the antenna.

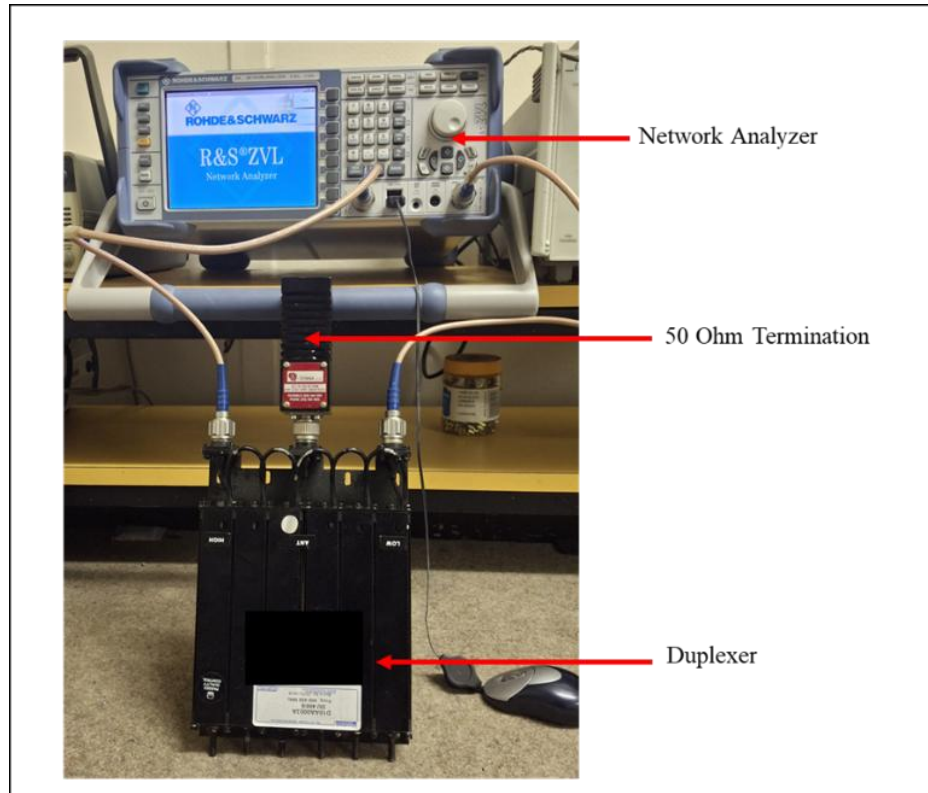


Figure 3-12 - Duplexer configuration

Figure 3-13 presents the insertion loss measurement results for the duplexer, illustrating its performance at key operating frequencies. The duplexer was adjusted to ensure optimal alignment, achieving minimal insertion loss at the design frequency and excellent isolation at the receive path frequency.

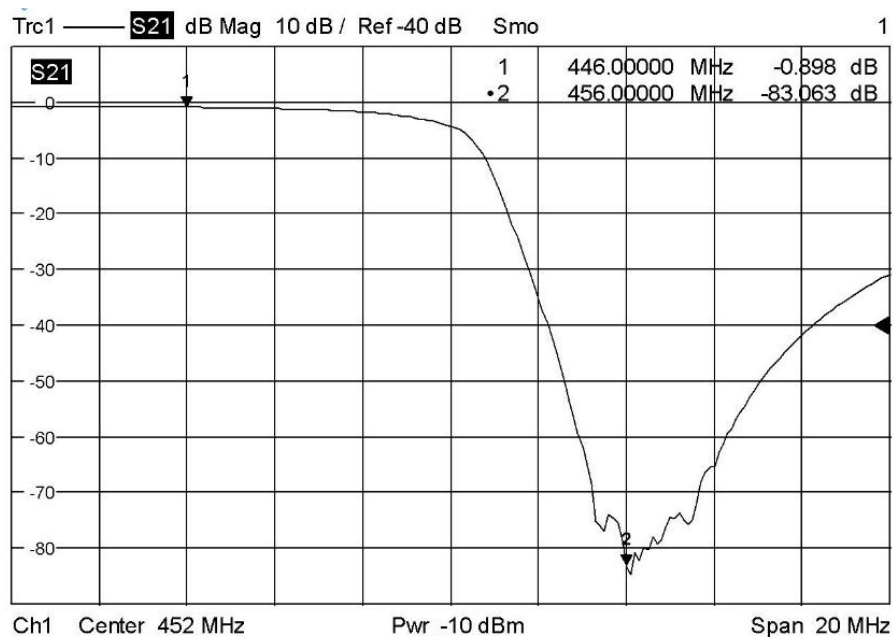


Figure 3-13- Insertion loss measurement results for the duplexer

The measurement was conducted across a frequency span of 20 MHz, centred at 452 MHz, with the input power level set to -10 dBm. The graph displays the S21 parameter in dB, which represents the forward transmission coefficient (insertion loss) from the transmitter to the antenna port.

In this test, 446.000 MHz was used as the design transmitter frequency. At this frequency, the measured insertion loss was approximately -0.898 dB. This result is within the manufacturer's specified limit of less than -1.2 dB, indicating that the duplexer introduces minimal signal attenuation between the transmitter and the antenna. Additionally, the isolation performance at the receive frequency of 456.000 MHz was measured at -83.063 dB, which exceeds the required minimum of -80 dB. This high level of isolation ensures that the receiver is effectively protected from strong transmit signals, thus preserving receiver sensitivity and minimising distortion.

3.5.1.3 Antenna configuration

The VSWR for the antenna was measured using the SA-6000MHz Bird Site Analyzer. The VSWR is a critical indicator of how well the antenna is impedance-matched to the transmission lines. Figure 3-14 shows the antenna VSWR workshop test setup.

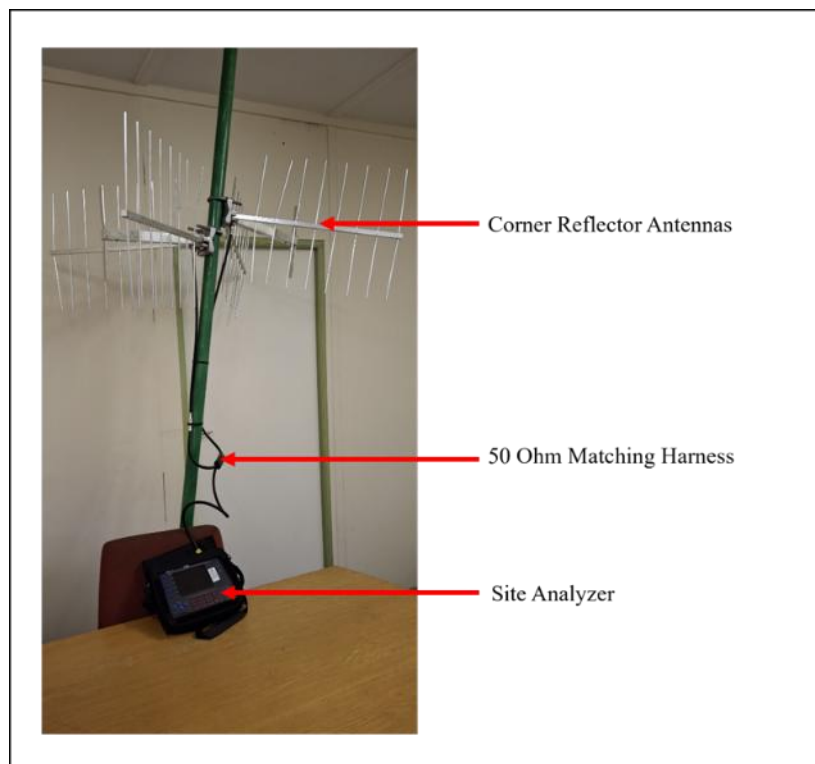


Figure 3-14- Antenna VSWR measurement

The setup involved connecting the analyser to the antenna via a coaxial cable. The analyser then transmitted a signal through the cable to the antenna and measured how much of the transmitted signal was reflected due to any impedance mismatch. The VSWR value was directly measured based on the ratio of the reflected signal to the transmitted signal with the results displayed in Figure 3-14.

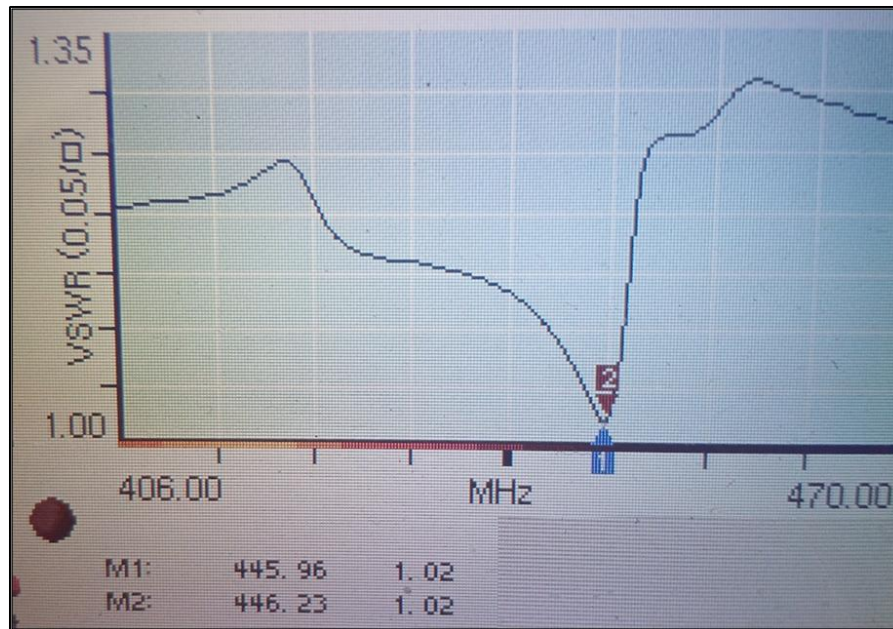


Figure 3-15- Bird analyser VSWR measurement

The test was conducted at a frequency of 446 MHz, as specified for the system. The expected result based on the antenna specification is a VSWR value $\leq 1.5:1$, indicating that the impedance mismatch should be minimal and within acceptable limits. During the measurement, the analyser displayed a VSWR of 1.02, which is excellent, well below the specified maximum value of 1.5:1. To accurately capture the VSWR at 446 MHz, the spectrum analyser markers were adjusted to 445.96 MHz (Marker 1) and 446.23 MHz (Marker 2), since the marker was not precisely aligning with 446.00 MHz.

3.6 Radio Site Installation

The installation of the DMR pilot site involved several critical steps to ensure that all components functioned correctly together as a complete communication system. Initially, individual components such as the antenna, duplexer, repeater and power supply were tested separately. The power supply unit, which converts 220 VAC to 12 VDC, was measured and the output was recorded as 13.4 V, confirming its proper operation. Once each component was

verified, they were integrated into the system. Figure 3-16 illustrates the complete site setup, illustrating the configuration and interconnection of each system component.

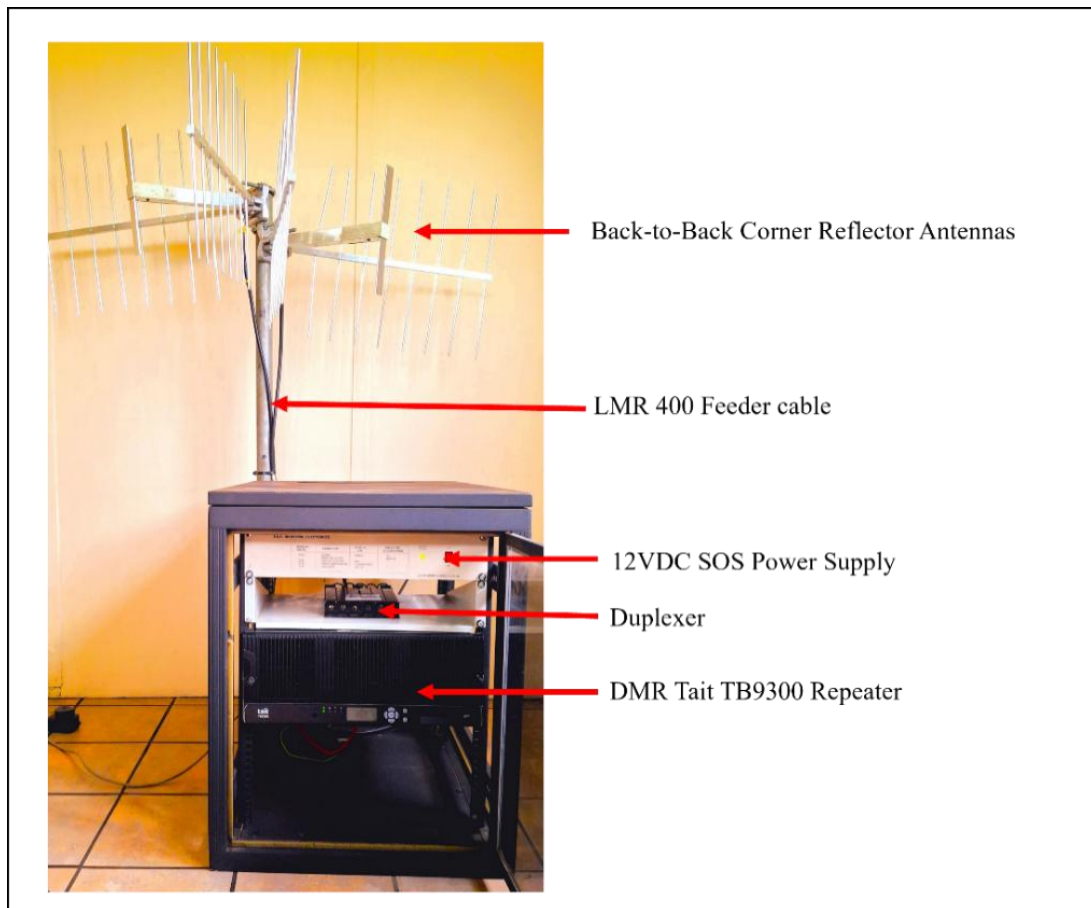


Figure 3-16- Complete DMR radio site

After assembling the system at the workshop, testing was conducted to verify its full functionality and voice quality using a handheld radio. Additionally, harmonic testing was performed using a spectrum analyser to ensure the system met the necessary signal integrity standards. Harmonic distortion occurs when nonlinearities in devices, such as the transmitter or amplifier, generate unwanted frequency components. These harmonics are integer multiples of the original signal's frequency and can cause interference with nearby channels, leading to degraded system performance [85].

The spectrum analyser was used to measure the presence and amplitude of harmonics across the frequency spectrum, with the results presented in Chapter 4. By analysing the harmonic distortion, it is possible to determine whether the system operates within the acceptable limits of signal purity. Excessive harmonics can affect not only the performance of the radio system but also neighbouring communication systems, which is why their suppression is essential.

Ensuring that the system operates within these standards guarantees that the transmission is clean and does not interfere with other channels. After the workshop testing, the system was carefully transported to the high site location for final installation, ensuring all components were verified for optimal performance.

3.7 Summary

Chapter 3 outlined the research design and pilot implementation of a DMR system for rail-bound communication, encompassing critical stages such as requirement definition, radio network dimensioning, and equipment configuration and testing. The design utilised WRAP software for propagation modelling and involved calculating key parameters, including ERP and FSL. This design phase was crucial as it laid the groundwork for both practical implementation and simulated results, setting the stage for subsequent stages of the research project. The following chapter presents the results and discussion of the research design. The section will compare the simulated results and practical results of the research design.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

In Chapter 3, the research design and pilot implementation of the DMR system for rail-bound communication were discussed. The chapter outlined the selection and configuration of DMR technology, emphasising its suitability for mission-critical railway communication. The design process included defining requirements, radio network dimensioning and propagation model tuning using WRAP software. To ensure real-life applicability, the chapter also detailed the workshop testing and field installation of the pilot site, aimed at validating the simulation results by comparing them with practical measurements.

This chapter presents the results of the research design by evaluating the performance of the DMR system. The analysis begins with the simulated outcomes, focusing on the predicted RSSI values across the defined experimental area. These results are then compared to practical RSSI results obtained from the pilot study to assess the alignment between simulated and practical performance. In addition to signal strength evaluation, the chapter also examines the results of a spectrum sweep to identify potential interference and ensure spectral compliance, as well as measurements of power consumption performance of the DMR system. The chapter covers the following key areas:

- Simulated results
- Practical results
- Spectrum analyser sweep
- DMR power consumption.

4.2 Simulated Results

The simulation of the DMR research design was executed using WRAP simulation software which allowed for a comprehensive analysis of the radio coverage and performance. The signal coverage map generated from the simulation is crucial for understanding how various parameters affect the RSSI across the designated coverage area. Since the RSSI is the key indicator of the coverage performance it was important to colour-code different signal levels throughout the coverage area before running the simulation. These colour codes were configured within the WRAP simulation software. Table 4-1 provides a colour code that was

chosen for the simulation for visualising signal strength based on RSS values. Each colour corresponds to a specific dBm range, enabling quick identification of signal strength across different points.

Table 4-1- RSSI level colour codes

Signal Strength	Colour	Description
Signal $\geq$ -100 dBm	Green	Strong Signal
-110 dBm $\leq$ Signal < -100 dBm	Yellow	Moderate Signal
-115 dBm $\leq$ Signal < -110 dBm	Orange	Weak Signal
-120 dBm $\leq$ Signal < -115 dBm	Red	Very Weak

Figure 4-1 shows the simulation result from the Muiskraalkop high site, visually displaying signal coverage and its distribution. The green zones are concentrated around the Transceiver High Site (between 6230 and 6240, indicating a strong signal) covering the central operational area. In contrast, the red zones are prominent along the southern and southwestern edges of the coverage area (between 6220 and 6230, indicating a very weak signal) where signal performance drops sharply, reflecting areas of poor coverage due to terrain shadowing or distance.

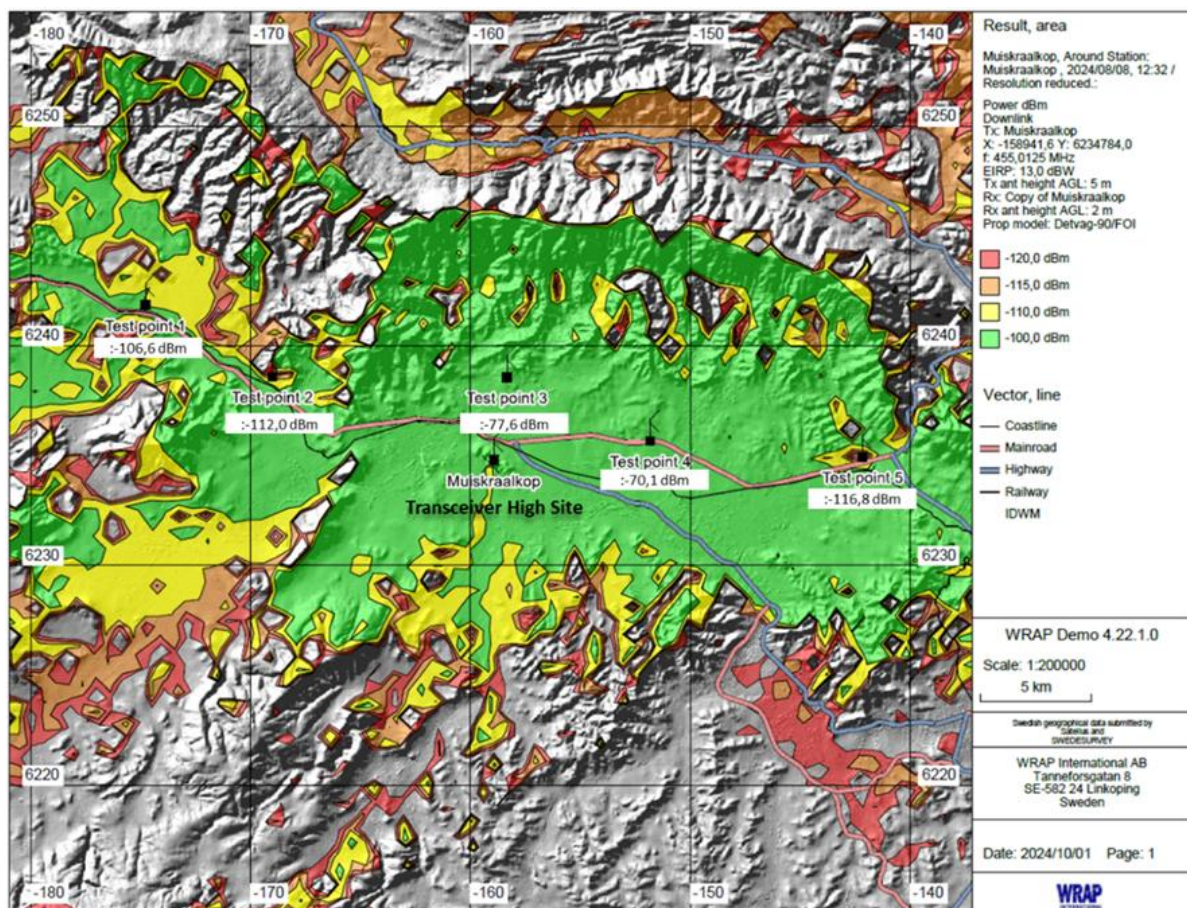


Figure 4-1- DMR WRAP coverage simulated results

To facilitate a comprehensive coverage analysis, test points were strategically selected to represent a range of signal strength scenarios from strong to weak RSSI levels. These points, identified as Points 1 through 5, were mapped in the WRAP simulation and their coordinates were recorded accordingly. The DMR handheld radio was used during the practical testing at these locations to capture real-world signal strength measurements. This meant that the points needed to be accessible by road for the practical test.

The simulated results from WRAP demonstrated effective coverage across the railway, with RSSI levels that varied based on terrain and propagation conditions. This is evidenced by the WRAP-generated coverage map, highlighting predominantly green areas, representing RSSI levels greater than -100 dBm along the intended railway line. Table 4-2 presents the simulated RSSI values at each test point derived from Figure 4-1.

Table 4-2- WRAP test points simulated RSSI level

Test Point	Simulated RSSI (dBm)
Point 1	-106.6
Point 2	-112
Point 3	-77.6
Point 4	-70.1
Point 5	-116.8

The table indicates that Test Points 3 and 4 (-77.6 dBm and -70.1 dBm, respectively) recorded strong signal levels, which can be attributed to their direct line-of-sight to the high site located at the Muiskraalkop. Conversely, Test Points 2 (-112.0 dBm) and 5 (-116.8 dBm) registered considerably weaker signal levels, primarily due to terrain-induced obstructions, such as hills or dense vegetation that hinder radio wave transmission. Test Point 1, with an RSSI of -106.6 dBm, falls within the moderate range, suggesting partial obstruction in the signal path that caused some degree of signal loss.

The propagation results highlight the influence of terrain variations, where obstructions contribute to signal degradation, whereas open landscapes with minimal interference provide better communication reliability. The results from Test Points 1 to 5, along with observed signal levels along the railway, indicate that the coverage meets the DMR Tait TB9300 repeater specifications. With an acceptable RSSI limit of -119 dBm, all measured test points fall within this range, confirming adequate coverage across the railway.

4.3 Practical Results

This section presents the practical measurements obtained during field testing, which are essential for validating the simulated results and confirming the real-world applicability of the DMR research design. The field test was conducted using the coordinates derived from the WRAP simulation, ensuring alignment between simulated receiver locations and actual test points. All technical preparations, including configuration and verification of the system components, were completed in the workshop prior to the on-site deployment at the Muiskraalkop high site. The DMR equipment was then installed and field testing commenced using a Hytera PD785 DMR handheld radio to record RSSI values at each of the five designated test points.

A technician was stationed at the Muiskraalkop high site to monitor and ensure that the repeater was actively transmitting during testing at each of the designated test points. In addition to signal strength measurements, voice quality was also evaluated between the high site and the respective test points to assess communication clarity under real operating conditions. The recorded practical RSSI values are presented in Table 4-3.

Table 4-3- Practical test points RSSI level results

Test Point	Practical RSSI (dBm)
Point 1	-109
Point 2	-114
Point 3	-81
Point 4	-72
Point 5	-119

Point 4 recorded the strongest signal at -72.00 dBm, attributed to clear line-of-sight and open terrain. Point 3 followed with -81.00 dBm, also benefiting from unobstructed conditions. Point 1 measured an RSSI of -109.00 dBm, due to partial obstructions along the path. Point 2 recorded -114.00 dBm, while Point 5, with the lowest signal strength at -119.00 dBm, was in an area affected by elevated terrain and dense vegetation. These practical measurements reflect the actual performance of the DMR system in field conditions and form the basis for assessing coverage effectiveness.

After recording the RSSI values at the various test points, the practical results were plotted on Google Earth to provide a clearer spatial representation and to facilitate comparison with the

simulated coverage results. The practical result map, displaying the measured RSSI levels at each location, is illustrated in Figure 4-2.

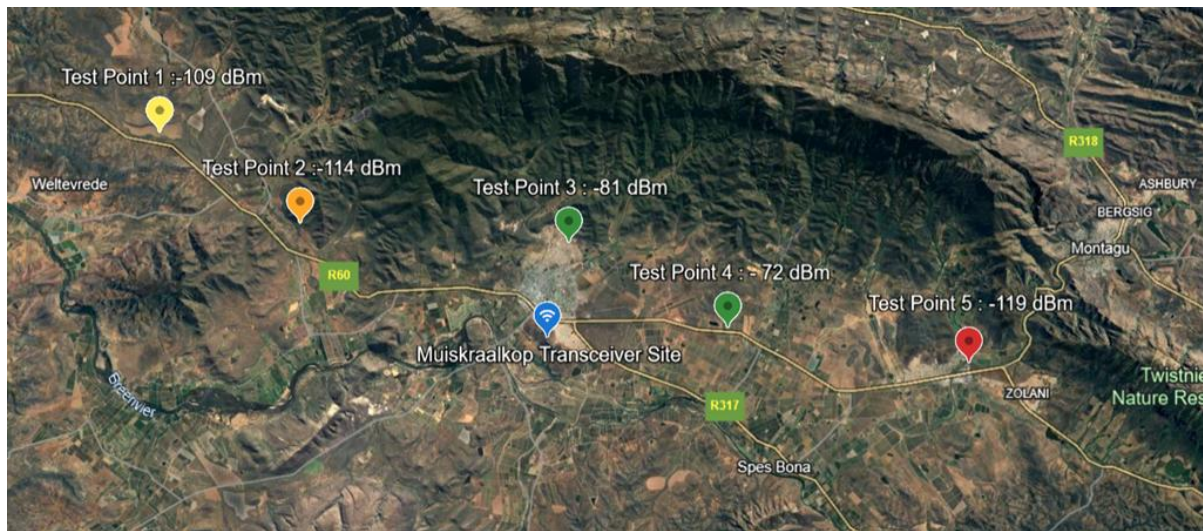


Figure 4-2- DMR Google map coverage practical results

4.4 Design Simulation and Practical Results Comparison

The comparison of simulated and practical results is critical to the research design, as it serves to validate the simulation model by benchmarking it against real-world measurements. In this study, such a comparison was essential in providing proof of concept and in guiding the formulation of evidence-based recommendations. Moreover, it supports the scalability of the project, given that the system's practical performance was empirically tested. Figure 4-3 presents the bar chart plotted in MS Excel, illustrating the comparative analysis between simulated and practical results across the designated test points.

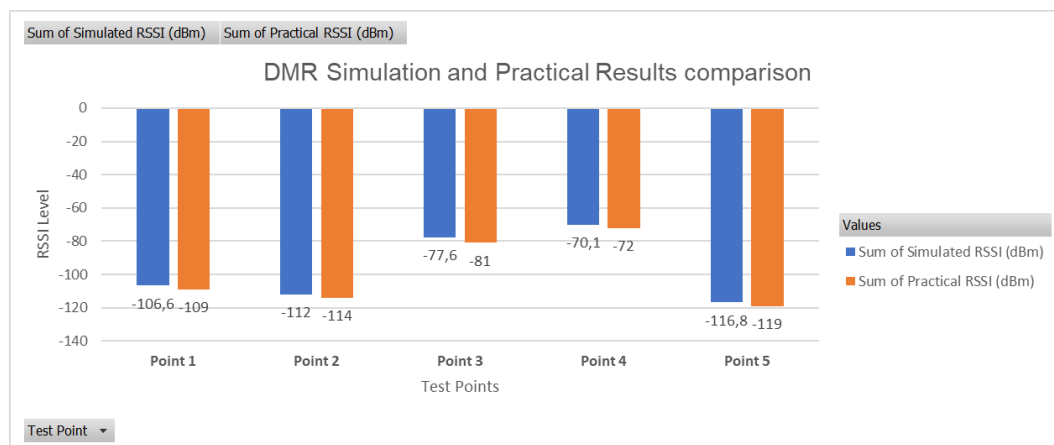


Figure 4-3- Comparison of simulated and practical RSSI results at test points

To determine the accuracy of the research design, the Mean Absolute Percentage Error (MAPE) was calculated. MAPE is a statistical metric used to evaluate the percentage deviation between simulated and practical results. It quantifies the average absolute difference between predicted and actual values, expressed as a percentage of the actual values [86].

The calculation process began by determining the absolute error at each test point, which represents the magnitude of deviation between the simulated and practical RSSI values. These absolute errors were then aggregated to compute the MAPE, as shown in Equation 14, thereby quantifying the overall accuracy of the research design. The following equation illustrates the computation of MAPE:

- Step 1: Absolute error

The absolute error is calculated using the following formula:

$$\text{Absolute error} = |\text{Simulated RSSI} - \text{Practical RSSI}| \quad (12)$$

$$\text{Point 1: } |-106.6 - (-109)| = 2.4 \text{ dBm}$$

$$\text{Point 2: } |-112 - (-114)| = 2 \text{ dBm}$$

$$\text{Point 3: } |-77.60 - (-81)| = 3.4 \text{ dBm}$$

$$\text{Point 4: } |-70.10 - (-72)| = 1.9 \text{ dBm}$$

$$\text{Point 5: } |-116.80 - (-119)| = 2.2 \text{ dBm}$$

- Step 2: Percentage Error

The percentage error was calculated using the following formula:

$$\text{Percentage error} = \left(\frac{\text{Absolute Error}}{|\text{Practical RSSI}|} \right) \times 100 \quad (13)$$

$$\text{Point 1: } (2.40 / 109) \times 100 = 2.2\%$$

$$\text{Point 2: } (2.00 / 114) \times 100 = 1.75\%$$

$$\text{Point 3: } (3.40 / 81) \times 100 = 4.2\%$$

$$\text{Point 4: } (1.90 / 72) \times 100 = 2.64\%$$

$$\text{Point 5: } (2.20 / 119) \times 100 = 1.85\%$$

- Step 3: Mean absolute percentage error (MAPE)

MAPE was calculated using the following formula:

$$\text{MAPE} = \frac{1}{n} \sum_{i=0}^n \left| \frac{A_i - F_i}{A_i} \right| \times 100 \quad (14)$$

where:

- A_i is the practical RSSI value
- F_i is the simulated RSSI value
- n is number of test points.

Substituting the calculated values:

$$\text{MAPE} = \frac{1}{5} \times (2.2 + 1.75 + 4.2 + 2.64 + 1.85)$$

$$\text{MAPE} = \frac{12.64}{5} = 2.53\%$$

The MAPE result of 2.53% signifies that the deviation between simulated and practical RSSI values is minimal, indicating a high level of accuracy in the simulation model. For the research design, this outcome validates the methodology used for system modelling, confirms the effectiveness of the radio propagation assumptions used in the simulation model and supports the practical applicability of the proposed DMR solution.

It is important to note that practical results were influenced by several factors present in the RF environment, such as weather conditions, component tolerances and atmospheric impurities. Therefore, achieving a MAPE of 2.53% despite these real-world influences justifies the reliability of the simulation model and highlights its robustness in accurately representing RF propagation under practical deployment conditions.

The findings of this study were presented in the paper titled “Design of a Digital Mobile Radio Network for Mission-Critical Communication” at RTCSE 2025. The paper reports the key technical results obtained from the simulation and practical field-testing activities conducted as part of this study and is included in Annexure B. Its presentation provided an opportunity for the research methodology, network design and validation results to be communicated within an academic and engineering forum.

4.5 Analysis of Harmonic Distortion in the DMR System

In the previous chapter, harmonic distortion was defined as a phenomenon that occurs in communication systems when nonlinearities within RF components generate unwanted frequency components known as harmonics. As part of the research design, one of the workshop tests included evaluating harmonic distortion in the system. The results of the spectrum analysis are presented in Figure 4-4, which illustrates the fundamental and harmonic components of the transmitted signal.

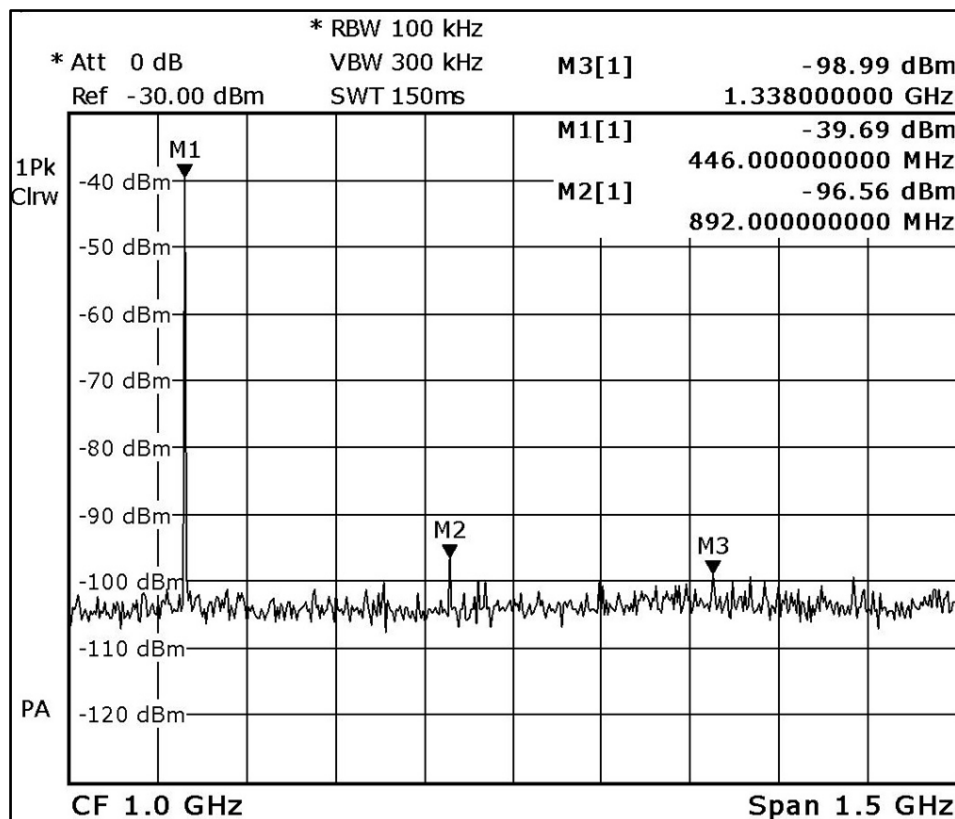


Figure 4-4- DMR harmonic spectrum analysis

The transmitter was not directly connected to the spectrum analyser to evaluate its harmonic performance. Instead, the signal was transmitted via an antenna and the spectrum analyser was placed in proximity to capture the radiated signal. This over-the-air transmission introduced natural attenuation, which helped ensure that the input signal into the spectrum analyser remained within safe power limits for accurate measurement.

The spectrum analyser was configured with a span of 1.5 GHz to observe the second- and third-order harmonics, with the fundamental frequency (marked as M1) at 446 MHz, representing the first-order harmonic and the system's design frequency. This setup ensured precise

detection and accurate measurement of harmonic distortions. The harmonic frequencies were calculated as follows:

- Second harmonic (M2)

$$f_2 = 2 \times f_1 = 2 \times 446 \text{ MHz} = 892 \text{ MHz}$$

- Third harmonic (M3)

$$f_3 = 3 \times f_1 = 3 \times 446 \text{ MHz} = 1.338 \text{ GHz}$$

Markers were placed at these key frequencies M1 at 446 MHz, M2 at 892 MHz and M3 at 1.338 GHz, to enable clear identification of harmonic levels. The measured power levels at the markers were:

- Fundamental (f_1): -39.69 dBm
- Second harmonic (f_2): -96.56 dBm
- Third harmonic (f_3): -98.99 dBm

The suppression levels were calculated using Equation 15.

$$\Delta P = P_{f1} - P_{fn} \quad (15)$$

- Second Harmonic Suppression:

$$\Delta P_2 = -39.69 \text{ dBm} - (-96.56 \text{ dBm}) = 56.87 \text{ dB}$$

- Third Harmonic Suppression:

$$\Delta P_3 = -39.69 \text{ dBm} - (-98.99 \text{ dBm}) = 59.30 \text{ dB}$$

The recorded suppression levels of 56.87 dB and 59.30 dB for the second and third harmonics, respectively, demonstrate strong attenuation of unwanted emissions relative to the fundamental carrier. This indicates that the transmitter effectively limits harmonic radiation, a critical requirement for ensuring spectral efficiency and preventing interference with adjacent services.

According to the regulatory requirements set out in ICASA for the 440 MHz to 450 MHz band, repeaters must meet specific emission limits, including a minimum of 40 dB intermodulation attenuation and a spurious emission limit of -36 dBm for frequencies below 1 GHz during operation [87]. When compared to these benchmarks, the measured harmonic suppression levels clearly satisfy and surpass the required standards.

4.6 Power Consumption

To further evaluate the operational advantages of DMR systems, it is essential to examine their power consumption characteristics, especially in comparison to analogue systems. Section 2.3.3.1 highlighted that DMR radios are claimed to offer up to 40% improved power efficiency over analogue counterparts, thereby extending the time between battery charges.

The test was conducted using a regulated DC power supply set to 13.4 V to simulate the operational voltage. A Hytera mobile radio was tested in both DMR and analogue modes. The current draw was monitored using the power supply's digital display. The experiment lasted 2 hours, aiming to obtain the most accurate power consumption reading. Samples were taken using the mobile radio in DMR mode by slowing down a camera to capture current values at 30 ms intervals. The maximum current was then observed and shown in Figure 4-5.

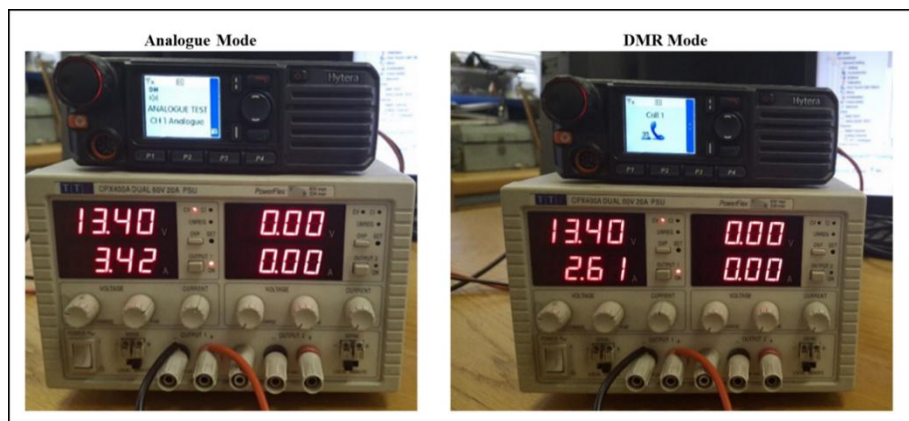


Figure 4-5- DMR and analogue current measurement

The radio standby current was recorded to be 0.33 A for both analogue and DMR modes. During standby, both systems drew 0.33 A consistently. However, during transmission, the DMR mode drew 2.61 A every 30 seconds before returning to standby, while the analogue mode consistently drew 3.42 A. The following calculations were performed to determine the average current consumption.

For the DMR mode:

- Standby current: 0.33 A
- Transmit current: 2.61 A (for 50% of the time)
- Voltage: 13.4 V

Accounting for the 50% transmit duty cycle, Equation 16 was used to calculate the current:

$$I_{DMR} = \frac{I_{tx} + I_{standby}}{2} \quad (16)$$

$$I_{DMR} = \frac{2.61 + 0.33}{2} = 1.47 \text{ A}$$

For the analogue mode, the constant measured current was used.

- Active consumption: 3.42 A (constant)

$$I_{analogue} = 3.42 \text{ A}$$

The percentage improvement in current consumption was calculated as follows:

$$\text{Percentage improvement} = \frac{I_{analogue} - I_{DMR}}{I_{analogue}} \times 100 \quad (17)$$

$$\text{Percentage improvement} = \frac{3.42 - 1.47}{3.42} \times 100 = 57\%$$

The experimental results demonstrate a significant improvement in battery consumption for DMR mode, with a 57% reduction in average current consumption compared to analogue mode. This improvement not only supports but also exceeds the literature claims of a 40% increase in battery life, showcasing the efficiency and effectiveness of DMR technology in enhancing battery performance [48][49].

4.7 Summary

Chapter 4 presents the results of the DMR system implementation, focusing on simulated and practical signal coverage, spectrum performance and power consumption. Simulated RSSI values generated using WRAP software were compared to field measurements taken at five designated test points. The results showed strong alignment, with a MAPE of 2.53%, confirming the accuracy and reliability of the simulation model. Spectrum analysis further demonstrated effective harmonic suppression, with second and third harmonics attenuated by more than 56 dB, exceeding ICASA regulatory requirements.

The chapter also highlights the energy efficiency of the DMR system. Power consumption tests revealed that DMR significantly reduces average current draw compared to analogue systems (1.47 A versus 3.42 A), resulting in a 57% improvement, surpassing the 40% efficiency gain cited in the literature. The following chapter discusses the overall outcome of the research and presents final conclusions and recommendations.

CHAPTER 5: DISCUSSIONS, IMPLICATIONS AND CONCLUSION

5.1 Introduction

This chapter presents a critical discussion and synthesis of the research findings in relation to the study's aims, objectives and research questions. The purpose is to interpret the outcomes from the design, simulation and pilot testing of the DMR communication system and to provide a reflective evaluation of the study. The chapter also highlights the significance of the study and the implications for future development and implementation of DMR systems in mission-critical railway communication environments.

The chapter is structured to first revisit the previous chapters and summarise the key outcomes. This is followed by a detailed commentary on how the research questions were addressed and a review of the research objectives and the extent to which they were achieved. The chapter concludes with recommendations for future research and potential improvements in the application and scalability of the proposed DMR system.

5.2 Reflection on Previous Chapters

Chapter 1 presented the introduction of the research by outlining the critical background, identifying the challenges posed by Transnet's ageing analogue radio systems and articulating the problem statement, research aims, objectives and questions. It emphasised the growing urgency for modernising mission-critical railway communication systems, not only to improve operational efficiency but also to meet regulatory and safety demands. The chapter firmly positioned the research within the context of global spectrum scarcity and technological evolution, introducing the idea that Digital Mobile Radio (DMR) may serve as the most effective replacement. By establishing clear research questions and objectives, it created a structured path that logically framed the exploration, evaluation and testing phases described in the chapters that followed.

Chapter 2 presented the literature review, providing a comprehensive analysis of analogue and digital communication systems relevant to mission-critical environments. It carefully examined the technical, operational and economic aspects of TETRA, LTE and DMR, using case studies and scholarly references to demonstrate their respective strengths and limitations. DMR emerged as the most promising candidate due to its superior spectrum efficiency, reliable voice quality, power efficiency and cost-effectiveness compared to both analogue systems and other

digital alternatives. The chapter not only build the theoretical foundation but also provided the technical benchmarks and design principles that directly informed the practical implementation detailed in Chapter 3, ensuring a well-grounded transition from literature to application.

Chapter 3 presented the research design by translating the theoretical insights from Chapter 2 into a structured and detailed system implementation plan. It covered the definition of system requirements, link budget calculations, equipment specifications and propagation modelling using WRAP software, all tailored to the specific needs of railway communication. The chapter described the step-by-step approach used to design, configure and simulate the DMR system, ensuring that it adhered to both regulatory standards and operational expectations. Importantly, it culminated in the deployment of a pilot site, demonstrating how the theoretical models and simulations were applied in a real-world setting. This formed the critical bridge between conceptual planning and empirical testing, Chapter 4 explored in detail.

Chapter 4 presented the results and discussion, delivering a detailed comparison between the simulated RSSI coverage predictions and the practical field measurements obtained from the pilot DMR site. The chapter aimed to confirm the accuracy of the simulation models developed in Chapter 3 by calculating the MAPE. Beyond coverage, the chapter also examined harmonic distortion and power consumption to determine whether the design met regulatory compliance standards, demonstrating the clear technical and operational advantages of the DMR system over legacy analogue systems. By connecting these empirical findings back to the research questions and objectives defined in Chapter 1, the chapter aimed to validate the entire research process and confirm the feasibility and robustness of DMR as the preferred solution for future mission-critical railway communications. Furthermore, this chapter formed the critical analytical stage of the research, setting the stage for interpreting findings, addressing research questions and reflecting on research objectives, all of which were fully explored in Chapter 5.

5.3 Research Questions

- Research Question 1: What are the multiple digital radio systems' key characteristics and capabilities that could potentially replace Transnet's PMR analogue radio communication network?

The literature review explored several digital radio technologies, including TETRA, LTE and DMR, each offering various technical and operational advantages over analogue systems. TETRA, while offering strong encryption and support for direct mode operation, has high

operational costs and consumes significant power. LTE provides high data throughput and network scalability but poses deployment challenges in terms of cost and coverage for mission-critical systems. In contrast, DMR emerged as the most balanced option, offering a compromise between cost-effectiveness, spectrum efficiency, backward compatibility and voice quality. Its use of 2-slot TDMA in a 12.5 kHz channel, combined with superior power efficiency and ease of implementation, positions DMR as the most suitable candidate to replace Transnet's legacy PMR systems.

- Research Question 2: Among the evaluated options, which digital radio system demonstrates the most promising performance improvements compared to the existing analogue radio system?

DMR was shown to offer clear performance enhancements over analogue systems, particularly in terms of voice quality, signal reliability and network scalability. The integration of AMBE vocoder technology ensures consistent and intelligible voice transmission even under degraded signal conditions. Additionally, the system's digital nature allows for better spectrum utilisation and encryption, addressing several shortcomings of the analogue PMR system. This marked improvement in performance underpins the recommendation of DMR for deployment in mission-critical railway communication environments.

- Research Question 3: How does the tested Received Signal Strength Indicator (RSSI) and the overall coverage performance of the pilot digital radio high site compare to the mission-critical communication requirements in Transnet's operations?

The coverage performance of the pilot digital radio high site was evaluated through simulated and practical field testing at Muiskraalkop in Robertson, Western Cape. The field pilot focused on RSSI measurements at designated test points, comparing practical readings with WRAP-simulated results. The practical RSSI levels met the ETSI standards sensitivity threshold of -117 dBm, with most points exceeding -100 dBm, confirming that the deployed pilot met the operational requirements of MCC application in the railway environment.

- Research Question 4: What is the radio spectral efficiency of the selected digital radio system and how does it compare to the analogue system, as determined through spectrum analysis?

The spectral analysis confirmed that the DMR system provides higher efficiency than analogue systems. The 2-slot TDMA structure within a 12.5 kHz bandwidth doubles user capacity

compared to traditional FDMA systems. Spectrum sweep tests showed minimal harmonic interference, confirming ICASA and ITU-R compliance. These characteristics ensure better utilisation of limited frequency spectrum, which is vital for modern railway communication needs.

5.4 Research Objectives

- Objective 1: Evaluate multiple digital radio systems capable of replacing Transnet's analogue radio systems to determine the most suitable option.

This objective was addressed by conducting a comprehensive literature review and comparative analysis of digital radio technologies. Several digital systems, namely TETRA, LTE and DMR were evaluated in terms of technical specifications, operational performance and deployment feasibility. The literature review drew upon case studies including [3], [13], [59], [60], [61] and [62], which confirmed DMRs practical advantages, such as wide coverage, flexibility, cost-effectiveness and compliance with international standards. For instance, [3] reported a DMR trunked system in Corfu achieving 98% land and 99.8% sea coverage, further improving to 99% land coverage with additional base stations. These findings substantiated the conclusion that DMR presents the most practical and technically suitable solution for replacing Transnet's analogue communication infrastructure.

- Objective 2: Design and simulate the digital radio communication system to assess its performance improvements over the existing analogue radio system.

The digital radio communication system was designed using WRAP (Wireless Radio Access Planning) software to simulate coverage along the Robertson–Zolani railway corridor. The design process incorporated key engineering parameters such as a measured Effective Radiated Power (ERP) of 42.3 dBm, feeder cable loss of 0.89 dB (LMR 400), duplexer insertion loss of 1.2 dB and an antenna gain of 9 dBd. These values were entered into the WRAP link budget and terrain-based propagation model to simulate expected signal strength levels at ground level.

Simulation outputs showed strong coverage throughout the test corridor, with RSSI values consistently predicted above -100 dBm at designated test points. The system was modelled using a Tait TB9300 repeater and a Webb CR400 corner reflector antenna placed at Muiskraalkop. The WRAP-generated coverage map confirmed wide-area service suitable for mission-critical communication. The simulation process, supported by quantitative link budget analysis and terrain profiling, demonstrated that the proposed DMR system would offer

improved performance over the analogue system by providing higher signal reliability, expanded coverage and better spectral efficiency under operational conditions relevant to Transnet's environment.

- Objective 3: Test the Received Signal Strength Indicator (RSSI) and overall coverage performance by deploying a pilot digital radio high site.

To validate the WRAP simulation results, a pilot DMR site was deployed at Muiskraalkop, a high-altitude location along the Robertson–Zolani railway corridor. This site was selected due to its line-of-sight advantages and existing telecom infrastructure. Field testing involved collecting RSSI measurements at predefined points along the railway using a Hytera PD785 handheld radio. These tests were conducted under actual environmental conditions to determine whether the deployed system could maintain reliable communication throughout the corridor.

The field results closely aligned with the simulated coverage, confirming the accuracy of the WRAP model. Most test points recorded RSSI values above -100 dBm, exceeding the ETSI minimum receiver sensitivity threshold. The Mean Absolute Percentage Error (MAPE) between measured and simulated RSSI values was 2.53%, indicating strong consistency. This confirmed that a single DMR high site could deliver stable, mission-critical communication over the intended rail segment, addressing the limitations of the legacy analogue system and supporting Transnet's operational safety and coordination requirements.

- Objective 4: Evaluate the radio spectral efficiency of the digital radio system through spectrum analysis.

The DMR system uses 2-slot TDMA within a single 12.5 kHz channel, allowing two simultaneous voice or data streams on the same frequency allocation. To demonstrate this in the study, both voice channels were programmed into one 12.5 kHz frequency on the Hytera PD785 handheld radio during testing. This confirmed the ability to deliver dual-channel voice services over a narrowband allocation, effectively doubling channel efficiency compared to traditional analogue systems.

5.5 Recommendations

Technology is a fast-growing domain, particularly in mission-critical communication systems. As operational requirements evolve, it becomes necessary to ensure that deployed technologies

can adapt, scale and integrate with emerging solutions. The following are the final recommendations from this study:

- Integration with emerging technologies: Organisations such as Transnet should explore the interoperability of DMR systems with broadband technologies, including LTE and 5G. This includes evaluating interworking functions, gateway solutions and hybrid architectures that can facilitate seamless communication between narrowband voice (DMR) and broadband data (LTE/5G) systems, particularly in environments requiring high data throughput and real-time situational awareness.
- Scalability and future expansion: The single-site pilot provides a baseline for modular expansion through IP-linked DMR sites. In a larger deployment, performance would depend on frequency reuse, overlapping coverage, roaming, backhaul resilience, channel capacity, peak-hour call blocking, redundancy and interference coordination. Capacity should be dimensioned from expected talk groups, busy-hour calls and simultaneous calls rather than assuming that two time slots are sufficient. These parameters were not tested and should be validated through a multi-site trial with traffic-loading, failure and roaming tests
- Companies such as Transnet could adopt a long-term roadmap extending beyond the current DMR deployment, positioning the organisation for future broadband-based MCC technologies such as LTE-based MCPTT (Mission Critical Push-to-Talk) and 5G-based MCC systems:

REFERENCES

- [1] T. Onali, M. Sole and D. D. Giusto, “DMR Networks for Health Emergency Management: A Case Study,” in *Proceedings of the 7th International Wireless Communications and Mobile Computing Conference (IWCMC 2011)*, Istanbul, 2011.
- [2] A. Qaddus, “Real Time Performance Analysis of Digital Mobile Radio (DMR) and APCO Project 25 (P 25) Radio Systems in Land Mobile Radio (LMR) Systems,” *International Journal of Computer Engineering and Information Technology (IJCEIT)*, vol. 8, no. 3, pp. 49-55, 2016.
- [3] DMR Association, “Benefits and Feature of DMR White Paper,” 12 May 2016. [Online]. Available: https://www.dmrassociation.org/public-downloads/documents/White-Papers/DMR-Association-White-Paper_Benefits-and-Features-of-DMR_160512.pdf. [Accessed 30 August 2022].
- [4] European Telecommunications Standards Institute (ETSI), “ETSI TS 102 361-2 V2.4.1 (2017-10) Technical Specification: Electromagnetic Compatibility and Radio Spectrum Matters (ERM); Digital Mobile Radio (DMR) Systems; Part 2: DMR Voice and Generic Services and Facilities,” ETSI, Sophia Antipolis, 2017.
- [5] Hytera Communications , “RD985 / RD985S DMR Repeaters,” Hytera Communications , Slough, 2017.
- [6] T. I. Limited, “Tait TB9300 Specifications: Ultra-Narrowband Solutions for Mission-Critical Networks,” Tait International Limited, Christchurch, 2021.
- [7] Webb Industries , “Duplexer 380-470MHz UHF DU400/6,” 05 October 2021. [Online]. Available: https://www.webb.co.za/wp-content/uploads/2021/10/A00056_01.pdf. [Accessed 25 July 2024].
- [8] Webb Industries, “Corner Reflector 9 dB 406 ... 700 MHz,” 16 February 2024. [Online]. Available: https://www.webb.co.za/product/corner-reflector-9-db-406-700-mhz/?srsltid=AfmBOorCyUAiGYAYKwBlHUYuz_HwSyi2bZ82Rk_x-KECydEg_mK0fGMq. [Accessed 25 July 2024].

- [9] J. Hu, G. Liu, Y. Li, Z. Ma, W. Wang, C. Liang, F. R. Yu and P. Fan, “Off-Network Communications for Future Railway Mobile Communication Systems: Challenges and Opportunities,” *IEEE Communications Magazine (CM)*, vol. 60, no. 10, pp. 64 - 70, 2022.
- [10] A. Kouwen, M. Scanlon, K.-K. R. Choo and N.-A. Le-Khac, “Digital Forensic Investigation of Two-Way Radio Communication Equipment and Services,” *Digital Investigation (DI)*, vol. 26, no. 1, pp. 77-86, 2018.
- [11] T. D. Katsilieris and T. E. Karafasoulis, “A Digital Radio Network of DMR Trunked Technology for All Safety Services: A Use Case in Corfu Island,” in *Proceedings of the 6th International Conference on Civil Protection and New Technologies (SafeCorfu 2019)*, Corfu, 2019.
- [12] P. Jie, “Current Situation and Solutions of High Speed Railway Communication,” in *Proceedings of the 8th International Conference on Education, Management, Computer and Society (EMCS 2018)*, Shenyang, 2018.
- [13] J. Burke, “Leveraging Mission Critical Communications as a Managed Service,” WU Executive Academy, Vienna, 2019.
- [14] M. Ulema, *Fundamentals of Public Safety Networks and Critical Communications Systems*, Piscataway: Wiley- IEE Press, 2018.
- [15] K. O. Olasupo, I. Kostanic and O. E. Olasupo, “Investigation of the Impact of Heterogeneous Traffic on Performance of LTE-based Mission Critical Communication Networks,” in *Proceedings of the 8th IEEE Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON 2017)*, Vancouver, 2017.
- [16] T. D. Katsilieris and T. E. Karafasoulis, “Capacity and Coverage Planning of DMR Trunking Radio Network for PPDR Services,” in *Proceedings of the 24th International Conference on Circuits, Systems, Communications and Computers (CSCC 2020)*, Chania, 2020.
- [17] M. Dolfi, S. Morosi, P. Piunti and E. Del Re, “Energy efficiency perspectives of PMR Network,” in *10th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, Larnaca, 2016.

- [18] A. Kumbhar, F. Koohifar, I. Güvenç and B. Mueller, “A Survey on Legacy and Emerging Technologies for Public Safety Communications,” *IEEE Communications Surveys and Tutorials (CST)*, vol. 19, no. 1, pp. 97-124, 2017.
- [19] V. K. Joshi and T. Kavitha, “Efficient Methods to Improve Power Bandwidth Measurement of ETSI Low Bandwidth Digital Mobile Radio,” *Measurement: Sensors (MS)*, vol. 27, no. 1, pp. 1-7, 2023.
- [20] M. Hanchate, R. Patil, T. Marathe, S. Srivastava, P. Dhivare and S. Singh, “Terrestrial Trunked Radio,” *Elixir International Journal (EIJ)*, vol. 93, no. 1, pp. 39668-39671, 2016.
- [21] K. Kunavut, “An Overview of Digital Trunked Radio: Technologies and Standards,” *Journal of Industrial Technology (JIT)*, vol. 10, no. 2, pp. 111-121, 2014.
- [22] J. C. C. Tesolin, M. A. A. da Silva, M. L. M. Campos, D. F. C. Moura and M. C. Cavalcanti, “Critical Communication Scenarios Description Based on Ontological Analysis,” in *Proceedings of the 13th Seminar on Ontology Research in Brazil (ONTOBRAS 2020)*, Rio de Janeiro, 2020.
- [23] A. U. Chaudhry and R. H. Hafez, “LMR and LTE for Public Safety in 700 MHz Spectrum,” *Wireless Communications and Mobile Computing (WCMC)*, vol. 2019, no. 1, pp. 1-17, 2019.
- [24] A. Yarali, *Public Safety Networks from LTE to 5G*, Chichester: John Wiley & Sons, 2020.
- [25] Q. Wang, W. Li, Z. Yu, Q. Abbasi, M. Imran, S. Ansari, Y. Sambo, L. Wu, Q. Li and T. Zhu, “An Overview of Emergency Communication Networks,” *Remote Sensing (RS)*, vol. 15, no. 6, pp. 1-36, 2023.
- [26] C. Gruet, X. Pons-Masbernard and P. Force, “The LTE Evolution: Private Mobile Radio Networks,” *IEEE Vehicular Technology Magazine (VTM)*, vol. 8, no. 2, p. 64 70, 2013.

- [27] R. Ferrus, O. Sallent, G. Baldini and L. Goratti, “LTE: The Technology Driver for Future Public Safety Communications,” *IEEE Communications Magazine (ICM)*, vol. 51, no. 10, pp. 154-161, 2013.
- [28] T.-T. Nguyen, C. Bonnet and N.-D. Nguyen, “9 - LTE Broadcast for Public Safety,” in *Wireless Public Safety Networks 2 -A Systematic Approach*, London, Elsevier, 2016, pp. 263-293.
- [29] A. Jarwan, A. Sabbah, M. Ibnkahla and O. Issa, “LTE-Based Public Safety Networks: A Survey,” *IEEE Communications Surveys & Tutorials (CST)*, vol. 21, no. 2, pp. 1165-1187, 2019.
- [30] H. Mousavi , I. S. Amiri , M. A. Mostafavi and C. Y. Choon , “LTE Physical Layer: Performance Analysis and Evaluation,” *Applied Computing and Informatics (ACI)*, vol. 15, no. 1, pp. 34-44, 2019.
- [31] F. D. Alotaibi and A. A. Ali, “TETRA Outdoor Large-scale Received Signal Prediction Model Based on Recent RF Measurements in Riyadh Urban Area,” *Journal of King Saud University - Engineering Sciences (JKSUES)*, vol. 21, no. 1, pp. 23-30, 2009.
- [32] European Telecommunications Standards Institute (ETSI), “ETSI EN 300 392-2 V3.8.1 (2016-08) European Standard: Terrestrial Trunked Radio (TETRA); Voice Plus Data; Part 2: Air Interface (AI),” ETSI, Sophia Antipolis, 2016.
- [33] T. Köhler , M. Wölfel and M. Ciba , “Terrestrial Trunked Radio (TETRA) Exposure of Neuronal In Vitro Networks,” *Environmental Research (ER)*, vol. 162, no. 1, pp. 1-7, 2018.
- [34] L.-S. Hsiao and I.-L. Lin, “Integrating 5G and Terrestrial Trunked Radio into Railway Communication System for Railway Safety and Information Security,” *Sensors and Materials (SM)*, vol. 36, no. 3, pp. 1275-1285, 2024.
- [35] D. d.-R. Carrión, L. Juan-Llácer and J.-V. Rodríguez, “Radio Planning Considerations in TETRA to LTE Migration for PPDR Systems: A Radioelectric Coverage Case Study,” *Applied Sciences (AC)*, vol. 9, no. 2, pp. 1-12, 2019.

- [36] T. Eggert , H. Dorn , C. Sauter, A. Marasanov , M.-L. Hansen, A. Peter, G. Schmid , T. Bolz and H. Danker-Hopfe, “Terrestrial Trunked Radio (TETRA) Exposure And Its Impact On Slow Cortical Potentials,” *Environmental Research (ER)*, vol. 143, no. 1, pp. 112-122, 2015.
- [37] P. Elliott , M. Aresu , H. Gao , A.-C. Vergnaud , A. Heard , D. McRobie, J. Spear , D. Singh, H. W. Kongsgård , C. Mbema and D. C. Muller , “Use of TETRA Personal Radios and Sickness Absence in the Airwave Health Monitoring Study of the British Police Forces,” *Environmental Research (ER)*, vol. 175, no. 1, pp. 148-155, 2019.
- [38] R.-G. Bartusica, M. Madalin , S. Halunga and F. Octavian , “Radio Frequency Over Fibre Optics Repeater for Mission-Critical Communications: Design, Execution and Test,” *Sensors (MDPI)*, vol. 22, no. 1, pp. 1-23, 2022.
- [39] A. Fongen, “Integration of Digital Mobile Radio in a Sensor Network,” in *Proceedings of the 16th International Conference on Sensor Technologies and Applications (SENSORCOMM 2022)*, Lisbon, 2022.
- [40] S. M. Svrzić and P. Jovanoski, “Description of the TETRA 1 Technology and Standard for Modern Digital Trunking Systems of Functional Mobile Radio Communications,” *Vojnotehnicki Glasnik/Military Technical Courier (VG/MTC)*, vol. 69, no. 3, pp. 687-726, 2021.
- [41] A. Goeritno, N. Andriana , Indriya, I. Setyawibawa and D. Suhartono, “Application-Based Simulation on the Digital Trunking Radio Communication System to Predict the Area Coverage,” *Jurnal Ilmiah Teknik Elektro Komputer dan Informatika (JITEKI)*, vol. 8, no. 2, pp. 256-268, 2022.
- [42] P. G. Arun, “State Diagram Representation of Individual Voice Call in Digital Mobile Radio (DMR) Tier-3,” *International Journal of Electronics, Communication and Soft Computing Science & Engineering (IJECSCE)*, vol. 3, no. 4, pp. 2277-9477, 2014.
- [43] P. Yang, X. Dang and X. Yu, “Multi-Symbol Detection for ETSI DMR Signals,” in *Proceedings of the 12th International Bhurban Conference on Applied Sciences & Technology (IBCAST 2014)*, Islamabad, 2014.

- [44] European Telecommunications Standards Institute (ETSI), “ETSI TS 102 361-1 V2.5.1 (2017-10) Technical Specification: Electromagnetic Compatibility and Radio Spectrum Matters (ERM); Digital Mobile Radio (DMR) Systems; Part 1: DMR Air Interface (AI) Protocol,” ETSI, Sophia Antipolis, 2017.
- [45] European Telecommunications Standards Institute (ETSI), “ETSI TS 102 361-3 V1.3.1 (2017-10) Technical Specification: Electromagnetic Compatibility and Radio Spectrum Matters (ERM)); Digital Mobile Radio (DMR) Systems; Part 3: DMR data protocol,” ETSI, Sophia Antipolis, 2017.
- [46] A. B. Nikitin, I. V. Kushpil, J. M. Kokurin and V. A. Sharov, “New Method of Trains Movement for Low-Density Railway Lines of JSC Russian Railways,” *Transport Automation Research (TAR)*, vol. 4, no. 4, pp. 561-579, 2018.
- [47] J. Wang, B. Cai, C. M. Jin and J. Liu, “A train control system for low density line in China,” *Journal of the China society (JCS)*, vol. 37, no. 12, pp. 46-52, 2015.
- [48] H. Ghannadrezaii, J.-F. Bousquet and J. Craig, “Outage Probability Analysis to Address Interference Vulnerabilities in Digital Mobile Radio Networks,” in *Proceedings of the IEEE Communications Quality and Reliability Workshop (CQR 2021)*, Naples, 2021.
- [49] S. Faruque , “Frequency Division Multiple Access (FDMA),” in *Radio Frequency Multiple Access Techniques Made Easy* , Cham, Springer, 2018, pp. 21-33.
- [50] A. Grami, “Chapter 11 - Communication Networks,” in *Introduction to Digital Communications*, Amsterdam, Academic Press, 2016, pp. 457-491.
- [51] Tait Radio Academy, “Introduction to DMR Study Guide (Issue 1.00.04),” Tait Limited, Christchurch, 2015.
- [52] Hytera Communications Co, “PD782G/PD702G (UL913) Intrinsically Safe Full Power Digital Radio.,” Hytera , Miramar, 2018.
- [53] L. Yang and F. Luo, “Generation and Transmission Analysis of 4-Ary Frequency Shift Keying Based on Dual-Parallel Mach-Zehnder Modulator,” *Frontiers of Optoelectronics (FO)*, vol. 10, no. 2, pp. 160-165, 2017.

- [54] K. Jin-Guk, S. Kwang-Bok, . S. Chol-Uk and K. Man-Ho, “Simultaneous Wireless Power and Data Transfer Based on 4FSK Modulation Using the Four Splitting Frequencies of Series–Parallel Combined Resonant Circuit-Based System,” *Electrical Engineering (EE)*, vol. 105, no. 1, pp. 1307-1315, 2023.
- [55] M. Fortna and R. Barden, “Optimising Digital RF Communication Systems:,” Vicom Australia Pty Ltd, 24 June 2019. [Online]. Available: <https://www.criticalcomms.com.au/content/test-measure/article/optimising-digital-rf-communication-systems-1488055804>. [Accessed 04 July 2024].
- [56] D. Athow, “Professional Radio With DMR Test and Technology,” TechRadar Pro, 28 January 2017. [Online]. Available: <https://www.techradar.com/news/professional-radio-with-dmr-test-and-technology>. [Accessed 04 July 2024].
- [57] A. Ekşim and H. Yetik, “Performance Improvement of AMBE 3600 bps Vocoder with Improved FEC,” in *Proceedings of the 13th Advanced International Conference on Telecommunications (AICT 2017)*, Venice, 2017.
- [58] J. S, K. R. Ahmed, R. A. Rahiman, S. R, A. G. Anil and V. V. P, “A Robust Algorithm to Decode Trellis Coded Modulation in DMR Systems,” *International Journal of Scientific & Engineering Research (IJSER)*, vol. 7, no. 4, pp. 357-361, 2016.
- [59] G. Pettorru, M. Fadda, R. Girau, M. Sole, M. Anedda and D. Giusto, “Using Artificial Intelligence and IoT Solution for Forest Fire Prevention,” in *Proceedings of the 2023 International Conference on Computing, Networking and Communications (ICNC 2023)*, Honolulu, 2023.
- [60] A. Nikitin, A. Manakov, I. Kushpil, A. Kostrominov and A. Osminin, “On the Issue of Using Digital Radio Communications of the DMR Standard to Control the Train Traffic on Russian Railways,” in *Proceedings of the East-West Design & Test Symposium (EWDTS 2020)*, Rostov-on-Don, 2020.
- [61] G. Đukanović, and D. Popović, “Mission critical ICT,” *Journal of Information Technology & Applications (JITA)*, vol. 9, no. 2, pp. 60-66, 2019.

- [62] M. A. S. Firmansyah, D. A. Feryando and A. P. E. Wibowo, “Comparative Analysis of DMR (Digital Mobile Radio) Tier 3 Performance Based on RSSI Parameters at the Rammang-Rammang Site,” in *Proceedings of the 2nd International Conference on Railway and Transportation (ICORT 2023)*,, Makassar, 2023.
- [63] European Telecommunications Standards Institute (ETSI), “Radio Equipment and Systems (RES); Radio Site Engineering for Radio Equipment and Systems in the Mobile Service.,” ETSI, Sophia Antipolis, 1996.
- [64] A. G. Plaza, R. G. Cantarero, R. B. A. Banda and C. B. Rodríguez , “5G Based on MNOs for Critical Railway Signalling Services,” *Applied Sciences*, vol. 12, no. 18, pp. 1-12, 2022.
- [65] R. He, B. Ai, Z. Zhong, M. Yang, R. Chen and J. Ding , “5G for Railways: Next Generation Railway Dedicated Communications,” *IEEE Communications Magazine*, vol. 60, no. 12, pp. 130-136, 2022.
- [66] V. Nikolopoulou, D. Mandoc and S. Gogos, “5GRAIL paves the way to the Future Railway Mobile Communication System Introduction,” *Transportation Research Procedia*, vol. 1, no. 72, pp. 2197-2204, 2023.
- [67] C.-C. Tseng, S.-Y. Lien, C.-X. Zhuang and F.-C. Kuo, “InterWorking Function for Mission Critical Push to Talk Services,” in *Smart Grid and Internet of Things*, Cham, Springer, 2022, pp. 53-68.
- [68] S. Tarapiah, S. Atalla, K. F. B. Hashim and M. Daadoo, “Mobile Network Planning Process Case Study - 3G Network,” *Computer and Information Science (CIS)*, vol. 9, no. 3, pp. 115-133, 2016.
- [69] B. M. Zerihun, D. H. Woldegebreal and A. K. Yimer, “Dimensioning and Planning of LTE Radio Network for Future Deployment in Bahir Dar City,” in *Proceedings of the 2nd International Conference on the Advancements of Science and Technology (ICAST 2014)*, Bahir Dar, 2014.

- [70] A. A. M. Khani , A. Soldoozy , F. S. Rudi and E. Zandi , “Improving Signal Isolation in Hybrid RF Duplexer Utilizing a Band-Pass Filter,” *Memories - Materials, Devices, Circuits and Systems (MMDCS)*, vol. 8, no. 1, pp. 1-8, 2024.
- [71] A. Chinig, “Review On Technologies Used To Design RF Diplexers,” *International Journal of Biosensors & Bioelectronics (IJSBE)*, vol. 4, no. 1, pp. 23-25, 2018.
- [72] W. Jiang, “Cellular Traffic Prediction with Machine Learning: A survey,” *Expert Systems with Applications (ESA)*, vol. 201, no. 3, p. 1, 2022.
- [73] F. Bacharuddin, S. Budiyanto and L. E. Siagian, “Analisis Link Budget Dalam Penentuan Titik Antena Pada Sistem DCS1800 Dan UMTS2100 Di Gedung IKEA Tangerang,” *Tesla*, vol. 17, no. 2, pp. 141-153, 2015.
- [74] D. K. Wahyudi and M. Siregar, “Optimization of Scada Systems in a Remote Area by Using DTM6000 and Trunking Tier Three (Case study in Papua),” *International Journal of Advanced Science and Technology (IJAST)*, vol. 29, no. 7, pp. 3445-3456, 2020.
- [75] S. Ferretti, V. Ghini and F. Panzieri, “A Survey on Handover Management in Mobility Architectures,” *Computer Networks (CN)*, vol. 94, no. 1, pp. 390-413, 2016.
- [76] G. Jaimes-Illanes, “Planning and Simulation for Radio Access Networks on “Small Cells” Technology for Heterogeneous Environments,” *Investigación & Desarrollo (ID)*, vol. 21, no. 1, pp. 17-36, 2021.
- [77] A. Badawy, T. Elfouly , T. Khattab, A. Mohamed and M. Guizani , “Unleashing the Secure Potential of the Wireless Physical Layer: Secret Key Generation Methods,” *Physical Communication (PC)*, vol. 19, no. 1, pp. 1-10, 2016.
- [78] S. I. Popoola , A. A. Atayero and N. Faru, “Received Signal Strength and Local Terrain Profile Data for Radio Network Planning and Optimization at GSM Frequency Bands,” *Data in Brief (DB)*, vol. 16, no. 1, pp. 972-981, 2018.
- [79] R. Z. Khayrullin, “Methods and Models of Calibration of Vector Network Analyzers,” *Journal of Physics Conference Series (JPCS)*, vol. 1921, no. 1, pp. 1-9, 2021.

- [80] A. Hajimiri and K. Dasgupta, “Chapter 1 - Holistic Approaches for Power Generation, Linearization, and Radiation in CMOS,” in *Linearization and Efficiency Enhancement Techniques for Silicon Power Amplifiers*, Amsterdam, Elsevier, 2015, pp. 1-34.
- [81] H. Putri, I. Ahmad, A. Hikmaturokhman and D. H. Putri, “Automatic Cell Planning Method for Radio Network Optimization,” *International Journal of Informatics Virtualization (IJIV)*, vol. 8, no. 1, pp. 449-455, 2024.
- [82] M. E. Mohammed and K. H. Bilal, “LTE Radio Planning Using Atoll Radio Planning and Optimization Software,” *International Journal of Science and Research (IJSR)*, vol. 3, no. 10, pp. 1460-1464, 2014.
- [83] Europa Science Ltd, “Altair Acquires WRAP Software,” Europa Science Ltd, 7 May 2023. [Online]. Available: <https://www.scientific-computing.com/press-releases/altair-acquires-wrap-software>. [Accessed 10 July 2024].
- [84] Altair Engineering Inc, “WRAP - Efficient Radio Network Planning and Spectrum Management,” Altair Engineering Inc, 2024. [Online]. Available: <https://web.altair.com/em-propagation-and-spectrum-management>. [Accessed 10 July 2024].
- [85] W. Lei and Z. Jinyi, “Methodology for Improving High-Power Harmonic Measurement Accuracy and Stability,” *Electronics*, vol. 11, no. 22, pp. 1-9, 2022.
- [86] T. Iida, “Identifying Causes of Errors Between Two Wave-Related Data Using Performance Metrics,” *Applied Ocean Research (AOR)*, vol. 148, no. 1, pp. 1-13, 2024.
- [87] Independent Communications Authority of South Africa, “Draft Radio Frequency Spectrum Assignment Plan for the Frequency Band 440 MHz to 450 MHz,” ICASA , Pretoria, 2021.

ANNEXURE A: PERMISSION TO CONDUCT RESEARCH



26 November 2024
C18 Wilgerpark
Stellenberg
Bellville
Cape Town
7530

Email: Nkosinathi.nyawose@transnet.net

Dear Nkosinathi Nyawose

Re: Request for permission to conduct research at Transnet SOC Limited

Your email of request for permission to conduct research at Transnet on **Design of a Digital Mobile Radio Network for a rail-bound mission-critical wireless network** is acknowledged.

We note the conditions of the study to be for strict academic purposes, that the results of the study will be submitted to Transnet, and the research will be confidential and that anonymity for both respondents and the organisation is guaranteed. Should you or **Central University of Technology** want to publish the study in any other manner than the final assignment, Transnet will be approached for permission to do so.

Based on the above conditions, your request to conduct the research study in Transnet is granted. We are looking forward to the outcome and recommendations of your study and the positive contributions towards Wellness of employees at Transnet.

Yours sincerely,



Ms. Puleng Maseko

Head: Learning Enablement & Compliance ~~Reporting~~

Transnet SOC LTD

Date: 21/02/2025

Transnet SOC Ltd	138 Eloff Street	P.O. Box 72501
Registration Number	Braamfontein	Parkview, Johannesburg
1990/000900/30	JOHANNESBURG	South Africa, 2122
	2000	

Directors: A Sangqu (Chairperson) R Buthelesi M Debel B Jiyi L Letsoalo FS Mufumadi D Patel B Sedupane MP Zambane
M Phillips* (Group Chief Executive) N Maphumulo* (Group Chief Financial Officer)

*Executive

Group Company Secretary: Ms S Bopape

www.transnet.net

*This letterhead contains personal information as defined in the **Protection of Personal Information Act, No. 4 of 2013** (the "Act"). The signatory consents to the processing of his/ her personal information and is obliged to handle other data subject's information in accordance with the requirements of the Act*.

TRANSNET HAS A 'ZERO GIFTS' POLICY. NO EMPLOYEE IS ALLOWED TO ACCEPT GIFTS, FAVOURS OR BENEFITS

ANNEXURE B: PAPER PRESENTED RTCSE-2025 CONFERENCE

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 20s, 2025
<https://theaspd.com/index.php>

Design Of A Digital Mobile Radio Network For A Mission-Critical Communication

Nkosinathi Nhlanhla Nyawose¹, James Swart², Pierre Hertzog³

^{1,2,3}Department of Electrical, Electronic and Computer Engineering, Central University of Technology, Free State, Private Bag X20539, Bloemfontein, 9300, South Africa

¹nkosinathi.nyawose@transnet.net

²aswart@cut.ac.za

³phertzog@cut.ac.za

Abstract

The evolution of mobile communication has shifted from analogue to digital technologies, improving reliability, security, and efficiency. Professional Mobile Radio (PMR) systems have long been essential for Mission-Critical Communications (MCC), particularly in railway operations. However, analogue PMR is becoming obsolete due to spectral inefficiency, poor audio quality, and security concerns. This study explores digital alternatives such as Terrestrial Trunked Radio (TETRA), Long-Term Evolution (LTE), and Digital Mobile Radio (DMR), focusing on DMR as a viable replacement for PMR. A comparative analysis evaluates their suitability, followed by the design and simulation of a DMR pilot site. The findings contribute to knowledge on digital MCC solutions, supporting the adoption of modern communication technologies in railway operations to enhance operational efficiency and safety.

Keywords: Professional Mobile Radio (PMR), Terrestrial Trunked Radio (TETRA), Long-Term Evolution (LTE), Receive Signal Strength Indicator (RSSI).

1. INTRODUCTION

The evolution of mobile communication technology has undergone substantial transformations over the past four decades, advancing from the first generation (1G) to the latest fifth-generation (5G) networks [1]. This progress has led to a significant shift from analogue to digital communication technologies, offering enhanced performance in terms of reliability, security, and efficiency [2]. Professional Mobile Radio (PMR) systems, once central to Mission Critical Communications (MCC), have relied on analogue technology for over 25 years. PMR systems, commonly used for MCC, consist of conventional private radio networks that facilitate communication between a base station and multiple mobile radios [3]. These systems have provided essential communication services for public protection and disaster relief (PPDR) agencies, including emergency services such as police, fire, and ambulance teams [4]. The radio communication used in the railway industry is regarded as a MMC system since it directly impacts public safety. The rapid advancement of digital technologies has highlighted the limitations of analogue PMR systems, which are now considered obsolete and inefficient for modern communication demands.

In response to these limitations, several digital technologies have emerged as viable alternatives to traditional PMR systems. Terrestrial Trunked Radio (TETRA), Digital Mobile Radio (DMR), and Long-Term Evolution (LTE) networks have proven to fulfil initial MCC requirements by enhancing voice services with improved availability, security, and reliability [5]. DMR has emerged as a promising replacement for PMR because, unlike other digital radio systems (e.g., TETRA and LTE), it operates within the same channel bandwidth as Frequency Modulation (FM) systems. This allows spectrum license holders to migrate from FM to DMR using the same channel plan [6]. The emergence of these technologies has sparked significant research interest in comparing digital solutions to meet MMC requirements.

The aim of this study is to design and simulate a DMR site as a replacement for an analogue PMR system due to its obsolescence, to evaluate its feasibility and performance in MCC environments. To support this objective, the research will first compare digital communication technologies, including

TETRA, DMR, LTE, to assess their suitability for mission-critical communications. The study will begin with a literature review of these technologies, analysing their capabilities and performance. Following this, the focus will shift to DMR, leading to its detailed evaluation, design, and simulation as a viable alternative to analogue PMR. The results focus on received signal strength levels, illustrating the system's signal performance.

2. LITERATURE REVIEW

The field of telecommunications has experienced significant technological advancements in recent years, driven by increasing demand from both the population and various industries [7]. This demand has also extended to PMR systems, which have traditionally relied on analogue technologies for MMC. These systems have played a crucial role in mission-critical applications, particularly in Public Protection and Disaster Relief (PPDR) agencies and railway operations, where reliable and secure communication is essential. To address the evolving needs of MMC requirements, the discussion will begin with the analogue PMR system, followed by alternative digital technologies that may be considered as alternatives to analogue PMR.

2.1 Analogue PMR

Since Guglielmo Marconi (1874–1937) established a radio connection over a few kilometers in 1895, radio technology has undergone significant advancements [2]. This led to analogue communication evolving from one-way AM broadcasts in the 1930s to two-way AM for police, FM adoption in the 1940s, and the introduction of hand-carried radios by the 1950s. By the 1960s, MMC enabled shared RF channels for both voice and analogue signaling [8]. For public safety applications, this analogue communication is known as PMR, a legacy narrowband technology primarily used for mission-critical voice communications. Operating in the Very High Frequency (VHF) and Ultra High Frequency (UHF) bands, PMR has limited data capabilities but remains essential for emergency response and critical operations [9].

Despite its long-standing and reliable use over the years, analogue PMR networks have notable disadvantages [10], including low audio quality, particularly at longer distances [11], and vulnerability to interception due to analogue voice encryption [12]. These systems also face frequency band limitations, operating within the crowded 136-174 MHz (VHF) and 450-520 MHz (UHF) bands, leading to inefficiencies. Furthermore, analogue systems offer less spectral efficiency as compared to digital systems, which provide enhanced bandwidth and power efficiency [13]. Power efficiency is another concern, as analogue radios generally consume more power than modern digital radios, crucial for portable emergency devices [11]. Additionally, while some digital systems are backward compatible with analogue radios, integrating both into the same network can be complex, limiting the benefits of digital technology [10].

2.2 Terrestrial Trunked Radio

TETRA is a digital trunked radio system standardized by the European Telecommunications Standards Institute (ETSI) to meet the needs of PMR users, including public safety agencies [14]. Its air interface employs the Time Division Multiple Access (TDMA) technique, using $\pi/4$ -shifted Differential Quaternary Phase Shift Keying ($\pi/4$ -DQPSK) for modulation. Operating on 25 kHz spaced radio frequency carriers, each divided into four time slots, TETRA efficiently provides four communication channels per 25 kHz bandwidth [15]. This optimized spectrum utilization makes TETRA a preferred choice for MMC, ensuring secure and reliable digital voice transmission [12]. Additionally, operating in a low-frequency band enables TETRA to cover longer distances compared to LTE, making it ideal for wide-area public safety and industrial applications [16].

Despite its advantages, TETRA has limitations that impact its widespread adoption. The high costs associated with infrastructure deployment and maintenance present financial challenges. Moreover, its significant power consumption limits battery life in mobile applications, affecting portability and efficiency [12]. Another drawback is TETRA's requirement for a larger channel bandwidth, making spectrum allocation more complex compared to Digital Mobile Radio (DMR) [6]. These factors influence both cost-effectiveness and spectrum efficiency. While TETRA remains a trusted solution

for critical communication, advancements in cost management and energy efficiency are essential to ensure its long-term sustainability in evolving communication networks.

2.3 Long-Term Evolution

LTE is a high-speed wireless communication standard designed to provide enhanced data transmission rates, reduced latency, and improved spectral efficiency [17]. Initially, LTE was developed primarily for commercial broadband applications and did not account for the requirements of MCC. However, to integrate critical communications into broadband networks, the 3rd Generation Partnership Project (3GPP) introduced Mission Critical Services (MCX) over the LTE standard in Release 13. Founded in 1998, the 3GPP plays a pivotal role in regulating policies and setting specifications for technologies like LTE [18].

One of the advantages of LTE is that it has enhanced data rates by employing Orthogonal Frequency-Division Multiplexing (OFDM) for the downlink and Single-Carrier Frequency-Division Multiple Access (SC-FDMA) for the uplink. These schemes use different modulation techniques, including Quadrature Phase Shift Keying (QPSK), 16 Quadrature Amplitude Modulation (16-QAM), and 64-QAM. The modulation scheme selected depends on the channel conditions, with higher-order modulations, such as 64-QAM, delivering higher data rates when conditions are favorable [19].

While LTE offers advantages for commercial applications, its use in MCC remains new, with key disadvantages including limited coverage, high costs, and spectrum competition. LTE networks in the 700 MHz band require more sites to match LMR coverage due to propagation characteristics [20], leading to higher infrastructure costs that may be unaffordable for some public administrations [21]. This results in increased capital and operational expenditures, which can be prohibitive for many public sector agencies. Furthermore, MCC users typically representing smaller user bases must compete for spectrum resources with commercial operators, who naturally prioritize services for larger, revenue-generating markets. A key concern lies in LTE's performance under emergency conditions, where it falls short in delivering the low latency, assured Quality of Service (QoS), and user prioritization essential for public safety operations. Unlike LMR systems that provide reliable direct mode operation without network dependence, LTE's Proximity Services (ProSe) feature remains constrained by limited range and often requires network assistance, undermining its reliability during network outages or infrastructure failures [22] [23].

2.4 Digital Mobile Radio

DMR is a digital radio standard developed by the ETSI for PMR, offering reliable and cost-effective voice and data communications for mission-critical applications [24] [25] [26]. It operates in three tiers: Tier I for license-free, low-power devices with a maximum RF power of 0.5 watts, suitable for small coverage areas and emergency applications; Tier II for licensed systems using two-slot Time Division Multiple Access (TDMA) on a 12.5 kHz channel, providing advanced features and IP data services; and Tier III for trunked operations supporting voice, messaging, and packet services, including IPv4 and IPv6 [27].

At the physical layer, DMR employs 4-ary Frequency Shift Keying (4-FSK) modulation and TDMA technology, effectively doubling capacity within existing 12.5 kHz channels while maintaining backward compatibility with analogue systems [28]. It ensures power efficiency, extended battery life, superior audio quality, and system flexibility by enabling simultaneous voice and data transmission, making it increasingly prevalent in public safety and transport sectors, including secondary and low-density railway lines [29].

While DMR offers advantages, it also has drawbacks such as signal degradation in overlap areas where multiple signals are received at different power levels, causing reception issues. Compared to other digital PMR technologies, DMR has lower bit rates, which limits its ability to support high-capacity data applications without significant network upgrades [11]. Furthermore, DMR systems are vulnerable to signal degradation when deployed in complex environments. Urban areas characterized by high-rise buildings, industrial zones filled with metallic structures, and natural terrains such as forests and hills significantly hinder signal propagation. One of the primary causes of this degradation

is multipath fading, a phenomenon where transmitted signals reflect off various surfaces, leading to multiple signal paths that arrive at the receiver at different times.

2.5 Comparison of Digital PMR technologies

A comparison of digital PMR technologies reveals that DMR offers an ideal solution for medium-scale applications, such as railway communication systems. With a 12.5 kHz channel spacing, DMR ensures efficient spectrum use and is cost-effective. Despite its relatively low data rate of 9.6 kb/s, it is sufficient for voice communication and basic data services. DMR's compatibility with analogue systems also facilitates a smooth transition from older infrastructure, reducing costs.

In comparison, TETRA and LTE offer higher data rates but come with higher implementation costs and are better suited for large-scale systems. While TETRA operates on 25 kHz channels and provides a data rate of up to 28.8 kb/s, it is more expensive than DMR. LTE, with its high-speed capabilities, is designed for large networks, making it an impractical option for the railway sector. Table 1 illustrates the comparison of digital technologies that are potential replacements for analogue radio technology.

Table 1. DMR, TETRA, and LTE Comparison [4].

Technologies	DMR	TETRA	LTE
Frequency bands	VHF and UHF	UHF	Various
Modulation	TDMA (2-slots)	TDMA (4-slots)	OFDMA
Channel spacing	12.5 kHz	25 kHz	Various (e.g., 1.4, 3, 5, 10, 15, 20 MHz)
Data rates	9.6 kb/s	28.8 kb/s	Up to 100 Mb/s (downlink), 50 Mb/s (uplink)
Encryption	Yes	Yes	Yes
Compatible with analog systems	Yes	No	No
Implementation	Small to large	Large	Large
Supported by different manufacturers	Yes	Yes	Yes
System cost (per km ²)	€€	€€€	€€€€

2.6 DMR Case studies

Various studies have demonstrated the versatility and reliability of DMR across different applications. Research [11] evaluated DMR for mission-critical applications, comparing it to TETRA in Sardinia's health emergency services. Their study found that DMR provided superior coverage (-110 dBm vs -105 dBm for TETRA) and was the most effective choice for cost savings, spectrum efficiency, and ease of network configuration, making it well-suited for large areas with low to medium traffic.

Similarly, [30] explored the integration of Narrowband Internet of Things (NB-IoT) with DMR to enhance communication reliability, particularly in industrial and emergency scenarios. The system integrates a sensing circuit and an NB-IoT network analyzer at key DMR nodes such as base stations and bidirectional amplifiers to monitor operational parameters including AC current, temperature, RF output, and humidity. The NB-IoT analyzer assesses network stability via RSSI measurements, supporting real-time alerts in the event of abnormal conditions. Their findings demonstrated that this integration improves fault detection and system resilience, reinforcing DMR's suitability for MCC and industrial IoT applications.

Further emphasizing DMR's role in critical communications, [31] analyzed the signal quality of a DMR Tier 3 trunking system along the Makassar-Parepare railway line in Indonesia, where network coverage challenges posed safety risks. Through link budget analysis, radio mobile simulations, and field measurements, they found average Receive Signal Strength Indicator (RSSI) values of -62.49 dBm (calculated), -62.61 dBm (simulated), and -76.47 dBm (measured). With all 36 measurement

points meeting ETSI and TAIT standards, their study confirmed the alignment of theoretical and simulated results with field data, offering valuable insights for improving railway communication and safety.

Additionally, a study [29] assessing replacement options for the analogue railway communication system in Russia compared GSM-R, TETRA, and DMR, highlighting DMR as the preferred choice. Owing to its compliance with operational standards and support for cost-effective migration, DMR was found to offer a balanced solution in terms of performance, spectrum efficiency, and deployment simplicity. Building on these insights, the next chapter presents the Research design, which outlines the simulation of a DMR network using WRAP software to evaluate its practical feasibility, signal behavior, and alignment with real-world deployment scenarios.

3. Research Design

The research design aimed to simulate the DMR radio network site using Wireless Radio Access Planner (WRAP) software, ensuring accurate network planning and performance evaluation. The design process followed a structured approach consisting of three key stages as illustrated in Figure 1:

- Definition of requirements – Identifying technical specifications, site location, and necessary equipment to establish the simulation framework.
- Radio network dimensioning – Performing link budget calculations, determining transmission power, Effective Radiated Power (ERP), and antenna gain to assess network performance.
- Radio propagation model tuning – Using WRAP software for radio coverage simulation and optimization.

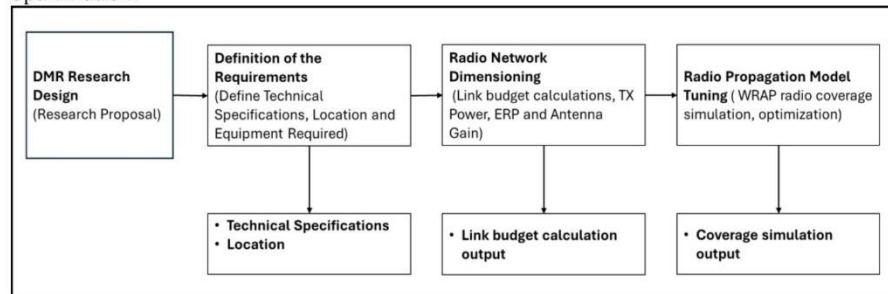


Figure 1. DMR design simulation block diagram.

3.1 Definition of Requirements

The initial stage involves identifying and defining the technical and practical requirements for the simulation stage, beginning with the selection of essential equipment and system parameters. The Webb Corner Reflector (CR400) antenna with a gain of 9 dBi was chosen, along with the Tait TB9300 repeater, which supports a maximum power output of 150 W and a receiver sensitivity limit of -119dbm. The feeder system utilizes an LMR 400 coaxial cable with an attenuation rate of 0.089 dB/m, while the Webb Duplexer, with an insertion loss of less than 1.2 dB, is integrated into the setup. Since the design will be simulated for Transnet, which is a South African state-owned company responsible for freight transport and logistics, it needs to comply with certifications prescribed by the Independent Communications Authority of South Africa (ICASA), and thus a 20 W Effective Radiated Power (ERP) was used.

The Muiskraalkop site in Robertson, Western Cape, was selected for its power availability, terrain suitability, existing infrastructure, and road access. The site is strategically positioned to provide optimal line-of-sight coverage, reducing signal degradation due to obstructions. Additionally, its elevation enhances radio wave propagation, ensuring reliable connectivity across the railway corridor. The location allows for efficient signal distribution, optimizing coverage without requiring excessive infrastructure expansion. These factors collectively support sustained communication reliability and future reduced infrastructure costs if the design was piloted.

3.2 Radio Network Dimensioning

Network dimensioning is essential for deploying a new network, as it determines the minimum capacity required to meet service agreement specifications [32]. A crucial element of this process is the link budget calculation, which evaluates the power gain and losses from the transmitter to the receiver [31]. In this study, the technical parameters were determined using the Effective Radiated Power (ERP) Equation (1), which combines transmit power and antenna gain.

$$\text{ERP} = \text{PTx} - \text{LTx} + \text{GTx} \quad (1)$$

Where:

- ERP: Effective Radiated Power (dBm)
- PTx: Maximum transmitter power (dB)
- LTx: Loss in the cable or connector at the transmitter (dB)
- GTx: Antenna gain at the transmitter (dBd)

Total transmission losses:

- L (cable): 1.78 dB
- L (Duplexer): 1.2 dB
- L (matching harness): 3 dB

$$\text{LTx}(\text{total}) = \text{L (cable)} + \text{L (matching harness)} + \text{L (Duplexer)} \quad (2)$$

$$\text{LTx}(\text{total}) = 1.78 + 3\text{dB} + 1.2\text{dB}$$

$$\text{LTx}(\text{total}) = 5.98 \text{ dB}$$

Transmitter Power Calculation:

Given:

- ERP: 20 W
- LTx (total): 5.98 dB
- GTx: 6.86 dBd

First, convert ERP from 20 W to dBm:

$$\text{ERP} = 10 \log P_{\text{mW}} \quad (3)$$

$$\text{ERP} = 10 \log(20 \times 1000) = 43 \text{ dBm}$$

Using the ERP equation, the maximum transmitter power was calculated by rearranging Equation (1) to solve for PTx:

$$\text{PTx} = \text{ERP} + \text{LTx} - \text{GTx} \quad (4)$$

$$\text{PTx} = 43 + 5.98 - 6.86$$

$$\text{PTx} = 42.12 \text{ dBm}$$

To convert dBm to Watts, the following calculation was performed:

$$P_W = 10^{\left(\frac{P_{\text{dBm}}}{10}\right)} \times 1000 \quad (5)$$

$$P_W = 10^{\left(\frac{42.12}{10}\right)} \times 1000$$

$$P_W = 16.34 \text{ W}$$

For simulation purposes in WRAP, power is converted to dBW as follows:

$$P_{\text{dBW}} = 10 \times \log_{10}(P_W) \quad (6)$$

$$P_{\text{dBW}} = 10 \times \log_{10}(16.34) = 12.13 \text{ dBW}$$

ERP value in dBW for accurate use in the WRAP simulation:

$$\text{dBW} = \log_{10}(W) \quad (7)$$

$$\text{dBW} = \log_{10}(20) = 13 \text{ dBW}$$

The parameters in Table 2 are derived from the calculation of the DMR network design, including an Effective Radiated Power of 13 dBW (43 dBm) and a maximum transmitter power of 16.34 W (12.13 dBW). The system also accounts for transmission losses, while the antenna gain is 6.86 dBd (9 dB). These calculated values will serve as inputs in the simulation stage to evaluate network performance based on the defined system characteristics.

Table 2. DMR Network radio design dimensioning results.

Parameter	Value
Effective Radiated Power	13 dBW / 43 dBm

Loss in Cable or Connector	1.78 dB
Duplexer Loss	1.2 dB
Matching Harness Loss	3 dB
Antenna Gain	6.86 dBd / 9dBi
Maximum Transmitter Power	16.34 W / 12.13 dBW

3.3 Radio Propagation Model Tuning

The final stage of the research design involves tuning the radio propagation model to bridge the gap between simulation and real-world performance. Using the dimensioning results, the WRAP software is configured with parameters such as transmitter power (in dBW), antenna height, radiation pattern, and terrain data. This allows for an accurate simulation of the DMR network's coverage.

4. RESULTS AND DISCUSSION

4.1 Simulated Results

The WRAP simulation software was utilized to predict the performance of the DMR system, generating a signal coverage map that provides a comprehensive visualization of radio coverage. The propagation model selected for the simulation was the Delta-Bullington model with a 90% outdoor coverage reliability setting, which is well-suited for rural and mountainous railway corridors with mixed line-of-sight conditions. The model accounts for diffraction over terrain obstructions, enhancing its accuracy in regions with variable topography. It has also been validated in similar public safety and mission-critical radio communication networks. Figure 2 presents the simulation result from the Muiskraalkop high site, visually representing the simulated signal coverage and its distribution across the designated area. This analysis illustrates how various input parameters influence the RSSI across the designated coverage area.

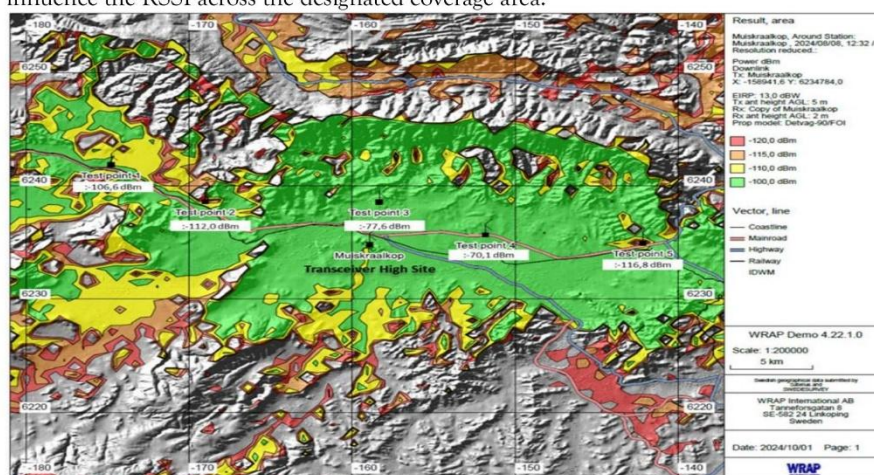


Figure 2. DMR WRAP Coverage Simulated Results.

The simulated results from WRAP showed good coverage across the railway, with RSSI levels varying based on terrain and propagation conditions. Test Points 3 (-77.6 dBm) and 4 (-70.1 dBm) exhibited strong signal levels due to direct line-of-sight with the transceiver. In contrast, Test Points 2 (-112.0 dBm) and 5 (-116.8 dBm) recorded weaker signals due to terrain obstructions. Test Point 1 (-106.6 dBm) displayed intermediate coverage, highlighting the impact of partial obstructions on signal strength. Although some test points recorded moderate RSSI levels, the overall signal strength along the railway remains strong, with areas above -100 dBm appearing in green on the coverage map.

The strongest signals are observed in areas with a direct line-of-sight to the Muiskraalkop transceiver high site, while weaker signals appear in regions with elevated terrain or dense vegetation. This distribution highlights the impact of terrain variations, where obstructions contribute to signal

degradation, whereas open landscapes with minimal interference provide better communication reliability. The results from Test Points 1 to 5, along with observed signal levels along the railway, indicate that the coverage meets the DMR Tait TB9300 repeater specifications. With an acceptable RSSI limit of -119 dBm, all measured test points fall within this range, confirming adequate coverage across the railway.

4.2 Practical Results

To validate the simulation results, a pilot DMR site was deployed at the Muiskraalkop high site, and RSSI measurements were recorded at five test points using a Hytera PD785 handheld radio. Strong signal levels were observed at Test Points 3 (-81 dBm) and 4 (-72 dBm), where direct line-of-sight prevailed. In contrast, weaker signals at Points 2 (-114 dBm) and 5 (-119 dBm) were due to elevated terrain and vegetation. All measurements fell within the receiver sensitivity threshold of -119 dBm, confirming adequate coverage. The practical results, shown in Figure 3, align closely with the simulated predictions and support the validity of the WRAP-based coverage model.

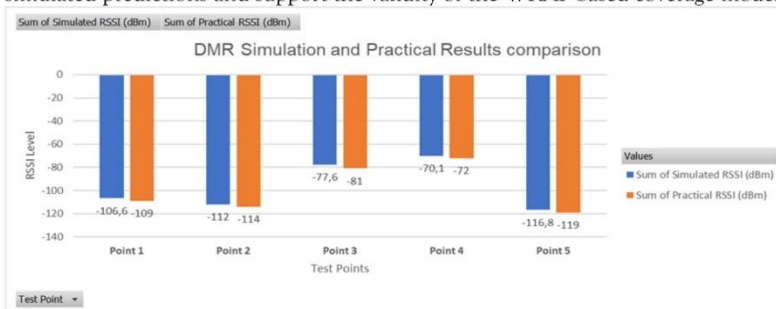


Figure 3. Comparison of Simulated and Practical RSSI Results at Test Points.

5. CONCLUSIONS

This study demonstrates the feasibility of transitioning from analogue PMR to DMR for MMC. Literature findings indicate that DMR provides improved spectral efficiency, enhanced security, and better audio quality compared to analogue PMR, making it a suitable choice for MCC applications and compared to alternatives such as TETRA and LTE, DMR offers a cost-effective and practical solution for railway operations.

The WRAP simulation confirms that the Muiskraalkop high site provides acceptable DMR coverage along the railway. Strongest signals were observed at Test Points 3 (-77.6 dBm) and 4 (-70.1 dBm) due to direct line-of-sight, while weaker signals at Test Points 2 (-112.0 dBm) and 5 (-116.8 dBm) resulted from terrain obstructions. Test Point 1 (-106.6 dBm) showed intermediate coverage. All points (1-5) fall within the Tait TB9300 repeater's acceptable RSSI limit of -119 dBm, demonstrating sufficient coverage for reliable communication.

Future research may explore the integration of DMR with complementary technologies such as LTE, 5G, and the Internet of Things (IoT). Hybrid DMR-LTE systems could support higher data rates, while 5G and IoT convergence may enable intelligent monitoring, redundancy, and real-time diagnostics. Such advancements would modernize mission-critical communications and ensure resilience and scalability for evolving railway network demands.

BIBLIOGRAPHY

- [1] S. Yrjölä, M. Matinmikko-Blue and P. Ahokangas, "The Evolution of Mobile Communications," in *The Changing World of Mobile Communications: 5G, 6G and the Future of Digital Services*, Cham, Springer International Publishing, 2023, pp. 13 - 43.
- [2] A. Kouwen, M. Scanlon, K.-K. R. Choo and N.-A. Le-Khac, "Digital forensic investigation of two-way radio communication," *Digital Investigation*, vol. 26, no. 1, pp. 77-86, 2018.

- [3] K. O. Olasupo, I. Kostanic and O. E. Olasupo, "Investigation of the Impact of Heterogeneous Traffic on Performance of LTE-based Mission Critical Communication Networks," in *Proceedings of the 8th IEEE Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON 2017)*, Vancouver, 2017.
- [4] T. D. Katsilieris and T. E. Karafasoulis, "Capacity and Coverage Planning of DMR Trunking Radio Network for PPDR Services," in *Proceedings of the 24th International Conference on Circuits, Systems, Communications and Computers (CSCC 2020)*, Chania, 2020.
- [5] F. Neto, J. Granjal and V. Pereira, "A Survey on Security Approaches on PPDR Systems Toward 5G and Beyond," *IEEE Access*, vol. 10, no. 1, pp. 117119-117140, 2022.
- [6] A. Fongen, "Integration of Digital Mobile Radio in a Sensor Network," in *Proceedings of the Sixteenth International Conference on Sensor Technologies and Applications (SENSORCOMM 2022)*, Lisbon, 2022.
- [7] M. Ayad, R. Alkanhel, K. Saoudi, M. Benziane, S. Medjedoub and S. S. M. Ghoneim, "Evaluation of Radio Communication Links of 4G Systems," *Sensors*, vol. 22, no. 1, pp. 1-17, 2022.
- [8] M. Ulema, *Fundamentals of Public Safety Networks and Critical Communications Systems*, Piscataway: Wiley- IEE Press, 2018.
- [9] A. Kumbhar, F. Koohifar, I. Güven and B. Mueller, "A Survey on Legacy and Emerging Technologies for Public Safety Communications," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 1, pp. 97-124, 2017.
- [10] V. K. Joshi and T. Kavitha, "Efficient methods to improve power bandwidth measurement of ETSI low bandwidth digital mobile radio," *Measurement: Sensors*, vol. 27, no. 1, pp. 1-7, 2023.
- [11] T. Onali, M. Sole and D. D. Giusto, "DMR networks for health emergency management: A case study," in *Proceedings of the 7th International Wireless Communications and Mobile Computing Conference (IWCMC 2011)*, Istanbul, 2011.
- [12] M. Hanchate, R. Patil, T. Marathe, S. Srivastava, P. Dhivare and S. Singh, "Terrestrial Trunked Radio," *Elixir International Journal*, vol. 93, no. 1, pp. 39668-39671, 2016.
- [13] K. Kunavut, "An Overview of Digital Trunked Radio: Technologies and Standards," *The Journal of Industrial Technology*, vol. 10, no. 2, pp. 111-121, 2014.
- [14] S. Heleno, C. A. Fernandes, J. M. Felício, C. Salem, R. Caldeirinha and N. Leonor, "Development of TETRA Radio Backhaul Network Redundancy Plan for Disaster Recovery in Mission Critical Communications," in *Proceedings of the 17th European Conference on Antennas and Propagation (EuCAP 2023)*, Florence, 2023.
- [15] M. G. Chavez, L. Goratti, T. Rashe and D. Boru, "The Evolutionary Role of Communication Technologies in Public Safety Networks," in *Wireless Public Safety Networks Volume 1: Overview and Challenges*, Elsevier, Amsterdam, 2015, pp. 21-48.
- [16] L.-S. Hsiao and I.-L. Lin, "Integrating 5G and Terrestrial Trunked Radio into Railway Communication System for Railway Safety and Information Security," *Sensors and Materials*, vol. 36, no. 3, pp. 1275-1285, 2024.
- [17] M. O. Odida, "The Evolution of Mobile Communication: A Comprehensive Survey on 5G Technology," *Journal of Sensor Networks and Data Communications*, vol. 4, no. 1, pp. 1-11, 2024.
- [18] A. Santiago, A. D. De Cerio, A. Sanch and F. Liberal, "Analysis of Mission Critical Services Radio Access Network Capacity Limitations Over 5G," *IEEE Access*, vol. 12, no. 1, pp. 6191 - 6203, 2024.
- [19] S. Parasher and S. Kumar, "Effects of Various Digital Modulation Methods on LTE System Over Orthogonal Frequency Division Multiplexed AWGN : A Review," in *Proceedings of the 2022 International Conference on Advances in Computing, Communication and Materials (ICACCM 2022)*, Dehradun, 2022.
- [20] A. U. Chaudhry and R. H. Hafez, "LMR and LTE for public safety in 700 MHz spectrum," *Wireless communications and mobile computing*, vol. 2019, no. 1, pp. 1-17, 2019.
- [21] R. Ferrus, O. Sallent, G. Baldini and L. Goratti, "LTE: the technology driver for future public safety communications," *IEEE Communications Magazine*, vol. 51, no. 10, pp. 154-161, 2013.
- [22] F. Jameel, Z. Hamid, F. Jabeen, S. Zeadally and M. A. Javed, "A Survey of Device-to-Device Communications: Research Issues and Challenges," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 3, p. 2520–2543, 2019.

- [23] X. Wang, M. Chen, T. Taleb, A. Jamalipo and V. C. Leung, "Device-to-Device Communication in LTE: ProSe Challenges and Evaluation," *EEE Communications Magazine*, vol. 52, no. 6, p. 86–92, 2014.
- [24] A. Goeritno, N. Andriana, Indriya, I. Setyawibawa and D. Suhartono, "Application-based Simulation on the Digital Trunking Radio Communication System to Predict the Area Coverage," *Jurnal Ilmiah Teknik Elektro Komputer dan Informatika (JITEKI)*, vol. 8, no. 2, pp. 256-268, 2022.
- [25] W. Wang, L. Zhu, T. H. Luan and C. Li, "DoIP: A Parallel Protocol Conversion Gateway for DMR over Internet Protocol," in *Proceedings of the 97th IEEE Vehicular Technology Conference (VTC2023-Spring)*, Florence, 2023.
- [26] M. Ulema, "Overview of Digital Mobile Radio (DMR) Technology," in *Fundamentals of Public Safety Networks and Critical Communications Systems: Technologies, Deployment, and Management*, Hoboken, Wiley-IEEE Press, 2019, pp. 107-120.
- [27] K. Jin-Guk, S. Kwang-Bok, S. Chul-Uk and K. Man-Ho, "Simultaneous wireless power and data transfer based on 4FSK modulation using the four splitting frequencies of series-parallel combined resonant circuit-based system," *Journal of Electrical Engineering*, vol. 105, no. 2, pp. 1307-1315, 2023.
- [28] H. Ghannadrezaii, J.-F. Bousquet and J. Craig, "Outage Probability Analysis to Address Interference Vulnerabilities in Digital Mobile Radio Networks," in *Proceedings of the IEEE International Workshop Technical Committee on Communications Quality and Reliability (CQR 2021)*, Naples, 2021.
- [29] A. B. Nikitin, I. V. Kushpil, J. M. Kokurin and V. A. Sharov, "New method of trains movement for low-density railway lines of JSC Russian Railways," *Transport Automation Research*, vol. 4, no. 4, pp. 561-579, 2018.
- [30] Y. W. Lo, M. H. Tsoi, C.-F. Chow and S. W. Y. Mung, "An NB-IoT Monitoring System for Digital Mobile Radio With Industrial IoT Performance and Reliability Evaluation," *IEEE Sensors Journal*, vol. 25, no. 3, pp. 5337 - 5348, 2025.
- [31] M. A. S. Firmansyah, D. A. Feryando and A. P. E. Wibowo, "Comparative Analysis of DMR (Digital Mobile Radio) Tier 3 Performance Based on RSSI Parameters at the Rammang-Rammang Site," in *Proceedings of the 2nd International Conference on Railway and Transportation 2023 (ICORT 2023)*, Chandipur, 2023.
- [32] W. Jiang, "Cellular traffic prediction with machine learning: A survey," *Expert Systems with Applications*, vol. 201, no. 3, 2022.

Authors

Nkosinathi Nhlanhla Nyawose

MEng electrical engineering student at the Central University of Technology, Free State.

Prof James Swart

Received his DTech in 2011 and is an Associate Professor at the Central University of Technology.

Prof Pierre Hertzog

Received his DTech in 2004 and is an Associate Professor at the Central University of Technology.

ANNEXURE C: CONSOLIDATED TECHNOLOGY COMPARISON

Sources: [1] [3] [4] [9] [11] [14] [16] [18] [20] [21] [23] [24] [27] [29] [31] [32] [40] [44] [48] [51] [60] [61] [62] [64] [65] [66] [67].

Table C-1- Consolidated comparison of analogue PMR, DMR, TETRA, LTE/MCX and FRMCS/5G-R.

Technology	Quantitative technical profile	Coverage and scalability	CAPEX/OPEX and cost model	Transnet migration role
Analogue PMR	VHF/UHF; typically, 12.5/25 kHz FDMA; one voice path per channel; no native broadband data.	Long range in lower bands and simple sites, but expansion is constrained by ageing equipment, interference and scarce spares.	CAPEX: low where assets are retained. OPEX: high because of obsolescence, maintenance, spares scarcity and inefficient spectrum use.	Current baseline to be retained only during controlled migration; not preferred as the long-term end-state.
DMR	VHF/UHF; 12.5 kHz two-slot TDMA; two voice/data paths; 9.6 kb/s gross rate; 6.25 kHz equivalent per path.	Comparable coverage to analogue in the same band; scalable from a single site to IP-linked multi-site networks for low-to-medium traffic.	CAPEX: low-moderate through site and spectrum reuse. OPEX: low-moderate, with lower energy and maintenance burden.	Most suitable near-term option for narrowband railway voice within the study scope and a practical migration baseline.
TETRA	UHF; 25 kHz four-slot TDMA; four traffic channels; 7.2 kb/s per slot and up to 28.8 kb/s using four slots.	Proven for large, high-traffic networks, but requires centralised switching and more complex network management.	CAPEX: high. OPEX: high because of SwMI/core infrastructure, site density, licences and specialist support.	Technically capable, but less cost-effective than DMR for the pilot's low-to-medium traffic and reuse objectives.
LTE/MCX	1.4-20 MHz carriers; OFDMA; study benchmark up to 100 Mb/s downlink and 50 Mb/s uplink; low latency subject to QoS.	Highly scalable, but resilient MCC requires a dedicated core, QoS, backhaul, power redundancy and sufficient site density.	CAPEX: very high for RAN, core, spectrum and resilient backhaul. OPEX: high for licences, support, energy and managed services.	Suitable for broadband and hybrid services, but not the lowest-cost direct replacement for narrowband operational voice.
FRMCS/5G-R	5G-based broadband platform with scalable radio channels; throughput and latency depend on spectrum, architecture and railway service requirements.	Supports corridor and national-scale evolution, but requires a mature 5G core, resilient backhaul and interoperability during transition.	CAPEX: very high initially. OPEX: high during dual operation, integration, cybersecurity and lifecycle support.	Long-term strategic target; DMR can operate as an interim or parallel voice layer through gateways or an IWF.