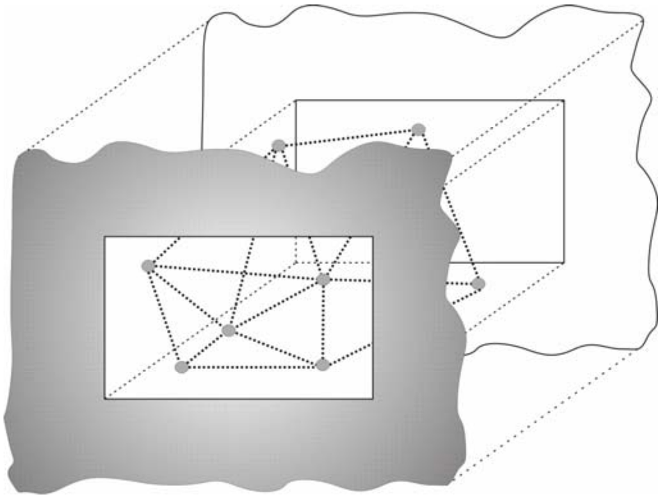

High resilience wireless mesh networking characteristics and safety applications within underground mines

Gareth Allan Kennedy

PhD Thesis

High resilience wireless mesh networking characteristics and safety applications within underground mines

Submitted by

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To the University of Exeter as a thesis for the degree of Doctor of Philosophy

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

……………………… (signature)

Abstract

The work presented in this thesis has investigated the feasibility, characteristics and potential applications of low power wireless networking technology, particularly aimed at improving underground mine safety. Following an initial review, wireless technology was identified as having many desirable attributes as a modern underground data transmission medium. Wireless systems are mobile, flexible, and easily scalable. Installation time can be reduced and there is scope for rapid deployment of wireless sensor networks following an emergency incident such as a mine explosion or roof rock fall. Low power mesh technology, relating to the Zigbee and IEEE 802.15.4 LR-WPAN (low-rate wireless personal area network) standards, has been of particular interest within this research project. The new breed of LR-WPAN technology is specifically designed for low power, low data rate wireless sensor applications. The mesh networking characteristics of the technology significantly increase network robustness and resilience. The self-healing, self-organising, multiple pathway redundancy, and highly scalable attributes of mesh networks are particularly advantageous for underground, or confined space, high-integrity safety and emergency applications. The study and potential use of this type of technology in an underground mine is a novel aspect of this thesis.

The initial feasibility and review examined the current and future trends of modern underground data transmission systems, with particular focus on mine safety. The findings following the review determined the ideal requirements of an underground data transmission in terms of robustness, integrity, interoperability, survivability and flexibility; with wireless mesh networking meeting many of these requirements.

This research has investigated underground wireless propagation characteristics at UHF and microwave frequencies in tunnels. This has involved examining electromagnetic (EM) waveguide theory, in particular the lossy dielectric tunnel waveguide model e.g. (Emslie *et al*., 1975 and Delogne, 1982). Extensive tests have been carried out in three different underground locations (railway tunnel, hard rock mine, coal mine test facility) using continuous wave (CW), or 'pure' transmission at 2.3GHz and 5.8GHz, along with a range of throughput performance tests using various wireless technologies: IEEE 802.11b, 802.11g, SuperG, SuperG (plus BeamFlex antennas), 802.11pre-n. 802.11draft-n, and Bluetooth. The results of these practical tests have been compared with the lossy dielectric tunnel waveguide model showing good agreement that tunnels will in fact enhance the EM propagation through the waveguide effect. Building on previous research during the last 30 years into high frequency underground radio transmission, this work presents a novel investigation into the performance of modern underground wireless technologies operating in underground mines and tunnels.

The feasibility and performance of low power wireless mesh networking technology, relating to Zigbee/IEEE 802.15.4, operating in various underground and confined space environments has been investigated through a series of practical tests in different locations including: a hard rock test mine, a coal mine and a fire training centre (confined space built infrastructure). The results of these tests are presented discussing the significant benefits in employing ‘mesh’ topologies in mines and tunnels. Following this, key applications were identified for potential development. Distributed smart sensor network e.g. environmental monitoring, machine diagnostics or remote telemetry, applications were developed to a proof-of-concept stage. A remote 3D surveying telemetry application was also developed in conjunction with the ‘RSV’ (remote surveying vehicle) project at CSM. Vital signs monitoring of personnel has also been examined, with tests carried out in conjunction with the London Fire Service. ‘Zonal location information’ was another key application identified using underground mesh wireless networks to provide active tracking of personnel and vehicles as a lower cost alternative to RFID. Careful consideration has also been given to potential future work, ranging from ‘mine friendly’ antennas, to a ‘hybrid Zigbee’, such as, optimised routing algorithms, and improved physical RF performance, specifically for high-integrity underground safety and emergency applications. Both the tests carried out and key safety applications investigated have been a novel contribution of this thesis.

In summary, this thesis has contributed to furthering the knowledge within the field of subsurface electromagnetic wave propagation at UHF and microwave frequencies. Key characteristics and requirements of an underground critical safety data transmission system have been identified. Novel aspects of this work involved investigating the application of new wireless mesh technology for underground environments, and investigating the performance of modern wireless technologies in tunnels through practical tests and theoretical analysis. Finally, this thesis has proved that robust and survivable underground data transmission, along with associated mine safety applications, can feasibly be achieved using the low power wireless mesh networking technology. Robust underground wireless networking also has potential benefits for other industrial and public sectors including tunnelling, emergency services and transport.

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Glossary

List of Abbreviations

ACARP	Australian Coal Association Research Program
ADC	Analogue to digital converter
ADSL	Asymmetric digital subscriber line
AFC	Armoured face conveyor
AP	Access point
ASCII	American Standard Code for Information Interchange
ATEX	*Atmospheriques Explosives* – European directive for hazardous environments
bps	bits per second
BPSK	Binary phase shift keying
CAP	Carrierless amplitude/phase modulation
CDMA	Code division multiple access
CDMA	Code division multiple access
CP	Circular polarisation
CSM	Camborne School of Mines
CSMA/CA	Carrier sense multiple access with collision avoidance
CW	Continuous wave
DAC	Digital to analogue converter
dB	Decibels
dBi	Decibels relative to an isotropic radiator
dBm	Decibels relative to mW power (0 dBm = 1 mW)
DMT	Discrete multi tone (see OFDM)
DSP	Digital signal processor
DSSS	Direct sequence spread spectrum
EBG	Electromagnetic bandgap structure – also called PBG (photonic bandgap)
ELF	Extremely low frequency
EM	Electromagnetic
EMC	Electromagnetic compatibility
ERP	Effective radiation power
FFT	Fast Fourier transform
FHSS	Frequency hopping spread spectrum
HF	High frequency
IEEE	Institute of Electrical and Electronic Engineers
ISM	Industrial-Scientific-Medical – license exempt frequency band
IT	Information technology
LED	Light emitting diode
LF	Low frequency
LOS	Line-of-sight

LR-WPAN	Low rate wireless personal area network
MAC	Medium access control
MF	Medium frequency
MIMO	Multiple input multiple output
MINOS	Mine operating system
MRSL	Mines Rescue Service Ltd
MSHA	Mine Safety and Health Administration (US)
MÜZ	Maschinenübungszentrum – Test Facility in Germany, operated by DSK mining company
Node	Data transmission point within a network
OFDM	Orthogonal frequency division multiplexing
O-QPSK	Orthogonal quadrature phase shift keying
PC	Personal computer
PCB	Printed circuit board
PED	Personal emergency device
PHY	Physical layer
PIFA	Planar inverted-F antenna
PLC*	Programmable logic controller
PLT*	Power line telecommunications
QAM	Quadrature amplitude modulation
RF	Radio frequency
RFID	Radio frequency identification
RSV	Robotic surveying vehicle
RX	Receive
SAP	Simple asynchronous protocol
SCADA	Supervisory control and data acquisition
SNR	Signal-to-noise ratio
SPA	Shorted microstrip patch antenna
TCP/IP	Transmission control protocol / Internet protocol
TCR	Tachometer reflectorless (total station with reflectorless laser scanning)
TDMA	Tine division multiple access
TE	Transverse electric
TEM	Transverse electromagnetic
TM	Transverse magnetic
TPS	Terrestrial positioning system (also called total station)
TTE	Through-the-earth propagation
TX	Transmit
UHF	Ultra high frequency
ULF	Ultra low frequency
VHF	Very high frequency

* PLC also refers to power line communication. For clarity, this will be referred to as PLT in the text.

UTP	Unshielded twisted pair
WLAN	Wireless local area network
WPAN	Wireless local area network
WSN	Wireless sensor network
xDSL	Family of digital subscriber line technologies
Zigbee	LR-WPAN Standard

List of Symbols

α	Specific attenuation
β	Phase constant
γ	Propagation constant
δ	Skin depth
ε	Electric permittivity or dielectric constant
ε_0	Electric permittivity of free space 8.854 x 10^{-12} F m^{-1}
ε_r	Relative permittivity
η	Intrinsic impedance
λ	Wavelength
μ	Magnetic permeability
μ_0	Magnetic permeability of free space 4π x 10^{-7} H m^{-1}
π	Constant, π = 3.14159… (ratio of circle's circumference to its diameter)
σ	Electrical Conductivity
χ_{mn}	Represents the *n*th zero of the *m*th order of the Bessel function of the first kind
ω	Angular Frequency ($\omega = 2\pi f$)
a, b	Horizontal and vertical dimensions of rectangular waveguide structure
A_e	Effective area of antenna
C	Speed of light ≈ 3 x 10^8 ms^{-1}
E, $\mathbf{E}$	Electric field (scalar, vector)
$E_{m,n}^{(h)}$	Electric components of the lossy waveguide in the horizontal direction
$E_{m,n}^{(v)}$	Electric components of the lossy waveguide in the vertical direction
f	Frequency
f_c	Cut-off frequency
f_t	Transitional, or characteristic, frequency
G	Antenna gain
H, $\mathbf{H}$	Magnetic field (scalar, vector)
k_0	Wave number for free space
m, n	Indices to represent the propagation mode order
P_{mn}	Propagation mode power
P_x	Antenna received power
R_s	Skin resistance of waveguide wall

Chapter 1: Introduction

1.1 Scenario

The deep underground mining operation you work at is currently utilising a novel low power wireless mesh sensor network. These devices inter-operate with the existing SCADA based networking infrastructure, and the information is fed directly back to the surface. Base stations are mounted in 'Zones' throughout the mine, which act as a gateway between the wireless mesh sensors and the existing fibre optic infrastructure. The wireless sensor devices provide machine monitoring and control telemetry of mobile plant, along with environmental sensory data. The wireless sensors themselves also act as distributed repeaters, making the system highly resilient and robust against failure. On your person, you are also carrying a small wireless mesh network device, which is monitoring your health status, such as body temperature, your heart rate, and whether you are in a vertical or horizontal position. This device forwards your vital information through the wireless sensor network (WSN) back to a database on the surface, triggering an alarm if anything unusual is observed. Also, as you travel around the mine your positional information is being tracked and stored in a computer at the surface, providing useful information from a mine operational and logistical viewpoint, for example, you can be located and contacted quickly. However, the main reason you carry this 'tracking' device, is not for logistics, it could actually help save your life in the dangerous environment you work in. Your current location, or at the very least your last known location, could prove vital during an emergency situation in assisting rescue personnel to reach you quickly, whether this is a personal accident or a mine wide emergency incident, such as an explosion. In the event of a mine emergency, any of the mesh network devices which survive would automatically attempt to find a path to route data, and it would be possible to override the network for limited voice communications as an additional back-up facility. The mines rescue personnel also have wireless sensor network, both for monitoring their own rescue team members 'vital signs' during a rescue operation, and making use of the existing infrastructure in an attempt to locate and contact potentially trapped miners.

1.2 Research Objectives and Overview

The scenario using underground wireless sensor network devices described above is a proposed application following this PhD research project, which was carried out in collaboration between the Camborne School of Mines and the Mines Rescue Service Ltd. These low power wireless sensor network (WSN) devices have many potential applications underground including: monitoring and control telemetry, active tracking of personnel and vehicles and voice (as an override feature given the low bandwidth). The self-organising and self-healing 'mesh' characteristics of the WSN devices significantly increase network resilience and survivability. High resilience wireless underground networking could enhance measures in safety and emergency situations, which has potential applications in both mining and other sectors including public underground railway stations.

This thesis describes the work carried out during the PhD research project, from what was initially a relatively broad overall research theme '*enhancing underground data transmission technology, particularly towards improving mine safety systems*', to the final stages of developing underground wireless mesh sensor network applications. Following the initial literature review and feasibility study conducted during the first year of the project, three core research areas were proposed, which provided the main research objectives and overall direction:

- Use of low power wireless mesh networks underground
- Characteristics of subsurface UHF narrowband radio propagation
- Survivable high-integrity data transmission

1.3 Challenges

1.3.1 Underground and Confined Space Environments

Underground mining operations are an extremely hazardous and harsh environment to work within, and the need for highly reliable underground communications is of high interest globally at present. Whilst safety has dramatically improved in modern mining, recent incidents such as the tragic Sago mine disaster (BBC News, 2006a) and others around the world, for example the trapped Australian miners (BBC News, 2006b) and a recent incident at a UK colliery (BBC News, 2006c), are an unquestionable reminder of the dangers involved. This has prompted organisations such as the US Mine Safety and Health Administration to call for further research and development into robust underground communications (MSHA, 2006). The challenges highlighted in underground communication technologies are not only constrained to mining; one of the main findings from a recent report in the UK, following the July 7 London bombings (Greater London Authority, 2006), highlighted that the emergency services radio communication systems were inadequate. Therefore globally, robust data communications are increasingly becoming a fundamental part of modern underground operations; enhancing efficiency and providing precautionary and reactive measures in safety and emergency situations.

Robust underground wireless communication and data transmission systems are a highly desirable medium in underground operations in terms of mobility, rapid deployment and ease of scalability, within a dynamic underground environment. However, subsurface radio propagation is of a highly complex nature and presents a challenging transmission medium within this type of environment.

In addition to this electrical and mechanical equipment operating within an underground environment has to be extremely robust. Electronic equipment has to be rugged, reliable and both water and dust resistant. Often underground environments, such as coal mines, have potentially explosive atmospheres due to presence of methane gas. Therefore, equipment operating within this type of environment will have to meet strict ATEX (*Atmospheriques Explosives* - European Directive) M1 or M2 regulations (refer to the BS EN 60079-0:2006 standard).

The work within this research project has been primarily aimed at the coal mining industry. Whilst it has been noted that there are potential applications in many underground environments from this research work, coal mines require some of the strictest regulations e.g. ATEX explosive atmosphere regulations. Therefore products designed for this type of environment should more easily migrate across to applications in other underground environments and sectors e.g. hard rock mining, underground public transport, tunnelling, oil and gas (which is also governed by ATEX regulations).

1.3.2 Coal Mining

In 2004 the world production of coal reached 4646 Mt (million tonnes), with Europe consuming around 8% (World Coal Institute, 2005) and the UK consuming around 56 Mt. Coal production in the UK during 2005/2006 was 20.5 Mt, of which 10.2 was produced from underground mines (Coal Authority, 2006). Whilst coal production is steadily declining in UK, coal mining is still very much part of our modern global society.

In modern underground coal mining operations, there are two main methods of mining for coal: ‘bord and pillar’ (also referred to as room and pillar) and ‘longwall’. Traditionally both methods are used around the globe; for example coal is predominantly won by the longwall technique in Europe, whereas coal mining in the US is predominantly bord and pillar (or room and pillar) technique (British Coal, 1989). The diagram in Figure 1.1 below shows the typical layout for a longwall coal mine, showing a network of tunnels (or Roadways) and the longwall coalface, where the coal is being cut. The mine is connected to the surface by either shafts or drifts. The ‘downcast’ shaft provides airflow into the mine, and the ‘upcast’ shaft provides airflow out of the mine. Ventilation is vital to control the environmental conditions of the mine.

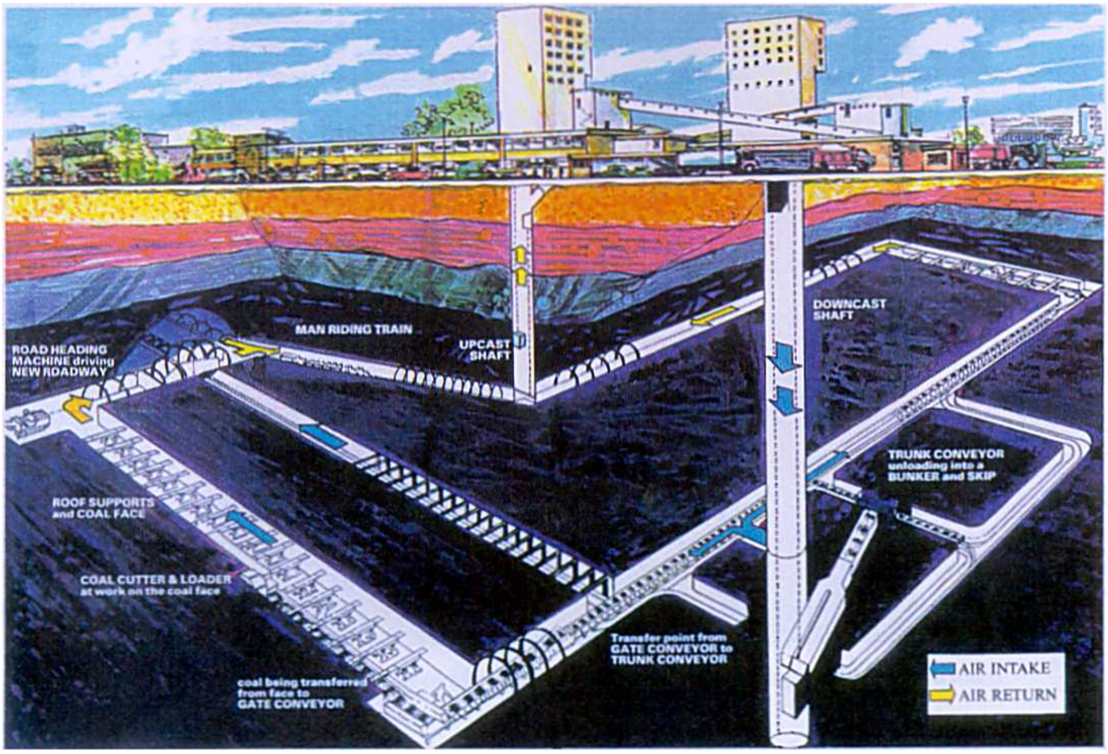

Figure 1.1: Typical Coal Mine Overview

[*Source*: UK Coal (2001)]

Gateroads are driven from the main roadways, each side of a coal face, known as the maingate and tailgate. The ‘Shearer’ cuts coal back and forth horizontally along the ‘longwall’ face. The mechanical roof supports, called ‘chocks’ prevent the roof caving in above the cutting area. The whole coalface ‘retreats’ backwards, both the roof support and the armoured face conveyor (AFC) belt equipment automatically move as the shearer cuts the face. This is known as a ‘retreating longwall’ face. Some mines use an ‘advancing longwall’ face, where the main difference is that gateroad development is done as the coal face ‘advances’ away. Therefore the coal is cut in the opposite direction to the retreating face. A detailed description of coal mining history and methods can be found in British Coal (1989) and UK Coal (2001).

There are ever increasing demands on the global mining industry to increase operational efficiency and improve overall mine safety. This is pushing mining more towards automation and driving the development of new technologies, telecommunication systems are increasingly becoming a vital part of modern underground operations. For example, El Teniente hard rock copper mine in Chile are using automated load-haul-dumpers (LHD) controlled using a WLAN based system, developed by Sandvik Tamrock (Sanvik, 2003). The coal mining industry is also moving over towards ‘single face’ operation, thus further requiring efficient operations and minimised downtime.

1.3.3 Data Transmission

In digital communications, data transmission is the physical exchange of information (binary data) over a channel (transmission medium) from one source to another. This is by means of an electrical or electromagnetic signal representing the digital information of binary 1's and 0's. An example of a data transmission link is sending an email. The email text is first converted into binary data, which is then modulated onto an electrical signal by the MODEM. This is then transmitted along the telephone wire (transmission medium) and then demodulated by another MODEM at the receiving end to convert it back into binary data, from which the computer can decipher the text. In analogue communication systems, it is important for the size and pattern of the signal waveform to remain intact in order to retrieve it at the receiving end, such as in traditional radio communications or telephone signals (user-end of telephony network). Whereas in a digital communication system, with the signal only representing binary digits, the transmission is much more immune to noise and distortion as there is a larger margin for error. Modern digital modulation schemes can also significantly enhance performance and efficiency. For example, OFDM (orthogonal frequency division multiplexing) modulation, also called DMT (discrete multi tone), used in ADSL (Asymmetric Digital Subscriber Line) has enabled 'broadband' Internet access through home telephone cable. Hence in modern data transmission systems, not only 'data' (or information), but 'digitised' audio and video can be transmitted efficiently.

Many factors influence the efficiency of a data transmission link, or how much data it can carry (bandwidth), such as the type of transmission media used and the distance separating the communicating devices. Various transmission/modulation schemes offer large bandwidths, or better immunity to noise and error, depending on the application. Modern wired data transmission systems vary from fixed point-to-point media; from the simplest two-wire or twisted pair to coaxial cable and optical fibre. Wireless data transmission through free-space, is achieved using electromagnetic wave propagation, as in radio communication, infrared, terrestrial microwave (cellular network) and satellite communication.

In underground data transmission systems the priority is that they are of high integrity, resilient and robust, particularly in critical applications e.g. monitoring and control. It is these factors, that has pushed, and in some cases limited, the development of underground data transmission systems. Whereas the usual 'engineering' problems in conventional data transmission systems, particularly telecommunications and IT, are usually power, speed, and bandwidth; of course these are also very important factors in underground data transmission systems, but not necessarily the priority.

The ‘core-enabling’ technologies behind this research stem from recent developments in data transmission systems. There have been significant developments in wireless technologies including: the WiFi family (IEEE 802.11a, b, g, n etc), and mesh (or ad-hoc) technologies such as Bluetooth and Zigbee. Mining companies are also recognising the benefits of ‘open standards’ and ‘interoperability’, for example UK Coal Mining Ltd have recently installed optical fibre Ethernet (See Appendix A.3). A Canadian paper by Wand and Masuskapoe (2005) gives a useful review on the many advantages of Ethernet in underground mining such as network convergence through a TCP/IP backbone infrastructure.

1.4 Contributions of Thesis

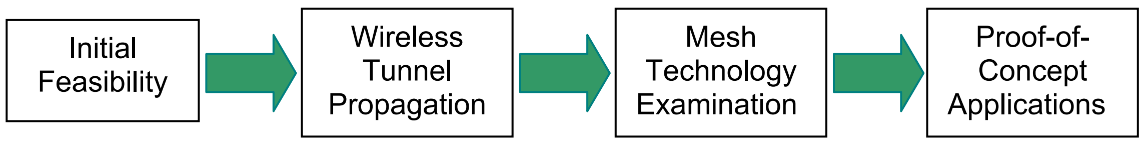

Figure 1.2: PhD Project Stages

The work presented in this thesis has been carried out in four sections (Figure 1.2 above). The initial feasibility and review stage identified the current trends and opportunities in modern underground telecommunications. Wireless networking technology was identified, in particular mesh routing systems, as a major research direction in working towards improving data transmission in regard to underground safety. The research work then involved investigating both the fundamental RF characteristics of wireless tunnel propagation, and the feasibility and potential of mesh networks in underground mines. This thesis examines the wireless propagation, through examining electromagnetic waveguide theory and outlines a series of tests, which certainly support the theory and give some interesting results. The potential use of low power mesh wireless networks is also carefully examined through both desktop review and a series of tests in underground and confined space environments. Novel underground safety related applications and concepts have been identified through this work; where three key applications have been examined further or taken to a proof-of-concept stage. These include (i) distributed smart sensors and remote telemetry, (ii) vital signs monitoring, and (iii) ‘zonal location information’.

1.5 Thesis Overview

Chapter 2: Advanced Underground Data Transmission Technologies – This Chapter presents a review of modern underground telecommunication systems, and then considers emerging data transmission technology. Core enabling technology, underlying this research, is identified during the review and discussed.

Chapter 3: Wireless Tunnel Propagation Characteristics – Underground radio and microwave propagation characteristics is investigated in this Chapter. Electromagnetic theory of waveguides is examined with respect to tunnel propagation. Various practical tests using continuous wave (CW) transmission and various wireless technologies in underground environments are presented, and discussed in comparison to the theoretical predictions.

Chapter 4: Mesh Networks in Underground Environments – The concept of mesh networking is introduced by discussing the feasibility, potential advantages, and potential applications of low power wireless mesh networking technology in underground environments. Practical tests using wireless mesh network technology in actual underground mine environments are presented, along with a discussion on the performance.

Chapter 5: Mesh System for Rescue Personnel in Harsh Environments – The application of low power wireless mesh networks for monitoring the 'vital signs' of rescue personnel is evaluated under harsh operating environments. Details of practical tests that were carried out in conjunction with the London Fire Service evaluating the potential application in a built environment are presented.

Chapter 6: Underground Smart Sensors and Telemetry – The application development of distributed smart sensor networks (e.g. environmental monitoring) and remote telemetry with a 3D surveying instrument is provided. The remote telemetry with the 3D surveying instrument was carried out in conjunction with another research project at Camborne School of Mines (Jobling-Purser, 2006), which is developing a robotic surveying vehicle for unsafe mine environments. The applications were developed to a proof-of-concept stage.

Chapter 7: Zonal Location Information – The novel use of low power wireless mesh networking technology for underground tracking compared with more conventional RFID techniques is examined in this Chapter. A proposed method of tracking mobile nodes within a mesh network to provide 'Zonal Locational Tracking' is given, along with considerations into techniques to achieve more accurate position as potential further work.

Chapter 8: Enhancing Underground Wireless Networks – Consideration towards enhancing underground wireless networking performance is examined. Focusing on the modulation characteristics, antenna design, routing and power budget requirements, discussing potential future work.

Chapter 9: Conclusions – A complete summary of all the main contributions of the thesis, along with conclusions from each aspect of the project is presented in the final Chapter.

Chapter 2: Advanced Underground Data Transmission Technologies

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In this Chapter a review of the state of modern-underground data transmission technologies is presented. This is undertaken by examining how the technology has developed and reviewing the important characteristics and criteria of underground communication systems. A review of emerging data transmission technologies is also presented by reviewing what the technologies have to offer the mining industry. Finally, this Chapter identifies the 'core enabling' technology and requirements of underground critical safety data transmission systems, upon which the research within this thesis is based.

2.1 Underground Telecommunications Review

2.1.1 Overview

Underground communication technology has not progressed as rapidly in mining as other industry sectors have seen in recent years. This is partly because the mining industry, especially in the UK and in other European countries, has seen a large decline in production during recent years. For example, there are currently only seven deep coal mines operating in the UK (BBC News, 2006d). In addition, there are considerable constraints to consider when developing a communication device for a mine, which not all industries have to face, health and safety constraints being imperative. Underground is very harsh environment for an electronic device to operate under, it is essential for underground telecommunication systems to be very reliable and intrinsically safe i.e. they do not pose any risk of igniting a potentially explosive atmosphere.

Whilst the global mining industry is facing the demand to push more and more towards automation in order to increase the efficiency of production, improving underground health and safety is a constant priority. As discussed in Section 1.3.1, recent events around the globe are a constant reminder of the hazardous environment in which the mining industry operates within. This led organisations such as the US Mine Safety and Health Administration to issue an international call-out for improved underground communications to improve the safety for miners and underground workers (MSHA, 2006). The use of robust communication systems underground is becoming of ever increasing importance for improving safety as well as achieving production efficiency.

During the last decade, a small number of organisations internationally have recognised the need in the research and development of improving underground communications. For example, the ‘Leaky Feeder’ has been further developed and is more widely used in mines. High performance ‘wired’ data transmission is being used in mines, such as optical fibre and coaxial cable (CATV). There is also research at present into adapting WLAN (wireless local area network) standards into underground communications e.g. (Einicke *et al.* 2002). WLAN gives the advantage of being a high-speed digital system, whilst providing flexible and mobile communications. Mines Rescue Service Ltd (MRSL), in the UK, has a device called the m-Comm that provides communication in emergency underground rescue operations (Lewis and Brenkey, 1993). There are various systems that have been specifically designed or adapted for mining and underground operations that offer a range of advantages, many of them are summarised in this Chapter. This review of modern underground telecommunications is broadly separated into the following three areas. Although, it is worth mentioning that many systems prove useful in more than one application.

1. *General Underground Communications:*

   Communication systems installed as part of the underground operation, providing a voice, or other communications link between personnel to aid in the coordination of work or the location of individual workers.

2. *Control and Monitoring Data Communications:*

   Data transmission systems such as the MINOS (Mine Operating System), or more recently, SCADA (supervisory data acquisition and control) that employ data transmission to relay mine information for control/automation purposes or for general mine safety, such as gas and temperature level monitoring.

3. *Underground Emergency and Rescue Communications*

   Communication systems for use in emergency or rescue situations; whether it is an alarm to warn of an emergency event (rock fall, fire etc), or to establish a communications link in a rescue operation.

The rest of this section presents a review of modern-day underground telecommunication technology. The technologies discussed either are in use in mines/underground operations today or are currently under development.

2.1.2 General Underground Communications

Nowadays, mines are made up of vast networks of tunnels (or roadways) covering many miles. Essentially, mine communication systems exist to aid in the achievement of coordinated work.

Without effective long-range communication between the miners and other key personnel, a mining operation would be extremely inefficient.

Murphy and Parkinson (1978) and US Bureau of Mines (1984) give comprehensive reviews of underground mine communication technology that was around during the time the reports were written. They are biased towards the US coal mining industry, which predominantly operates using the ‘room and pillar’ method; as opposed to the more popular ‘longwall’ method used in European collieries. However, most of the communication technologies described are generally universal or may only have slight variation between countries. US Bureau of Mines (1984) examines how technologies have been adapted, or specifically developed, for mining communication system solutions, discussing early solutions such as bell signalling, through to the telephony systems, telemetry and radio communications still being used in modern mining operations,

2.1.2.1 Wired Analogue

The long established telephone system was the first method of providing long distance communication by means of an electrical signal. Telephone systems, a major part of modern telecommunications, are still very much in use within mining. The magneto type telephone was one of the first in use underground, consisting of a battery-powered microphone, hand generator (magneto), bells, hook switch, transmitter and a receiver. The hand-cranked generator was used to send an a.c. signal voltage along the telephone line powering the other magneto phones to ring, using a code of long and short rings to identify the calling station. Further developments of the telephone system included: speech powered telephones, pager telephones, and the introduction of telephone exchanges. Technological advances in semiconductors later paved the way for an intrinsically safe loudspeaker system, which is still in use in many collieries today. It is a simple effective communication device that is useful in passing information quickly around production areas, such as near the coalface. Modern mining telephones act as a loudspeaker or private terminal, it allows the user to either dial through the exchange, or quickly page another terminal on the same party line. There is also an emergency feature that allows an additional emergency switchboard to be installed across each phone. Detectors on each phone will override any other communications when there is a response from the emergency network. This could prove very useful in emergency situations, such as being able to contact individual terminals or broadcast information across a number, or all, of telephones through the built-in loudspeakers.

2.1.2.2 Radio Communications

Radio propagation as a transmission medium has been used in broadcasting, voice communication and, the more recent, data transmission applications for many years. Recently, radio communications in general has seen many technological advances, with the move to digital radio transmission. New technology is achieving better noise immunity and very high data rates. Wireless networking technology has seen a particularly significant growth; from very large networks (e.g. the cellular networks) to wireless personal area network (WPAN) systems (e.g. Bluetooth).

Radio, or electromagnetic, wave propagation is perhaps the most desirable transmission medium in an industrial environment when the 'mobility' of an operation is very important. In radio communications, once a link or network is set up there is no need for wires and information can be passed quickly from one point to another from anywhere within range. This proves very useful in communications between personnel or transmitting information remotely.

However, in an underground environment, electromagnetic (EM) wave propagation has severe constraints. Murphy and Parkinson (1978) recognise wireless technology as the most desirable form of communications to reach key personnel on the move within a mine. The paper presents the advantages of radio communications in mining, whilst discussing major drawbacks of EM propagation underground and how some key technologies have overcome such constraints. Although, the review presented in this paper was written for the technology that was around in 1978, it is still remains topical and relevant to this research.

To give a simplified summary of the behaviour of radio in a mine environment, the paper states there are essentially three options available to establish a radio link in a mine:

1. Select frequencies that are high enough in order to utilise the mine entries as a waveguide. Increasing frequency usually becomes restricted to more line-of-sight.
2. Select frequencies that are low enough in order to penetrate the strata, providing 'through-the-earth' propagation.
3. Install a conductor, or 'Leaky Feeder' to aid the propagation of the higher radio frequencies.

Most radio communication technologies that have been developed for mining applications over the years seem to fit into options 2 and 3, given above. Ultra low frequency pager systems are used to achieve mine wide coverage to warn of emergency incidents, e.g. PED (see section 2.4). Various leaky feeder systems have been developed specifically to distribute the higher radio frequencies underground.

The Leaky Feeder

Over the years, the 'Leaky Feeder' technology has become a standard means of establishing radio communications underground, such as in mines or tunnels. The leaky feeder is essentially an open transmission line that is used to distribute radio frequency (RF) signals throughout mines and tunnels. The technology was initiated in Europe by the work of two scientists: Delogne, from the Institute of National Extractive Industries (INIEX) in Belgium (Delogne 1982) and Martin, from the National Coal Board in the UK (Martin 1986).

Early systems used unscreened two-wire ribbon type cable but then later migrated to coaxial cable. There are two main modes of operation: monofilar and bifilar. In monofilar mode, the transmission line carries the forward current and the tunnel wall carries the return. In bifilar mode, the outer conductor carries the return current. The advantage of monofilar is that it is readily exited (or received) by a radio transmission; however, compared with bifilar mode it suffers greatly from attenuation. The key to the operation of a leaky feeder system is in converting from monofilar to bifilar, known as mode conversion.

One method, pioneered by Martin, is to use a deliberately impaired, or partially screened, coaxial cable. This is called a continuously leaky feeder and is the simplest method of achieving mode conversion. A summary of this work can be found in Martin (1986).

An alternative method is the INIEX/Delogne system that incorporates a non-leaky cable with discrete radiating devices (or mode converters) inserted at intervals. The advantage of this system is that is more efficient and greater operating ranges can be achieved, but the system is more complicated to install. Delogne (1982) gives a comprehensive analysis of leaky feeder technology and radio propagation in tunnels.

El-Equip Inc, MineCom, Mine Radio Systems Inc, Tunnel Radio of America and Varis Mine Technology Ltd are examples of companies that have developed leaky feeder systems for use in the mining industry today.

The behaviour of subsurface EM propagation, whether guided by a leaky feeder or not, is very complex. A detailed analysis of this topic is given in Chapter 3.

2.1.3 Control and Monitoring Data Communications

2.1.3.1 MINOS and SCADA

MINOS (Mine Operating System), or more recently, SCADA (Supervisory Control and Data Acquisition) systems are used to relay information (or data) around a UK Colliery. Used for both control/automation purposes: remotely controlling certain machinery, monitoring its operation etc, and environmental/safety monitoring: gas, temperature, dust level monitoring.

Hind (1999) gives a concise review of control and monitoring systems in the mining industry and discusses how the technology has changed over the decades, and presents the general trends for the future. Mines have become increasingly larger and more mechanised as technology has progressed and control and monitoring systems have become more widely used. The paper states that there are generally four elements to a control and monitoring system:

- Sensors to detect information
- Outstations to condition the sensor signals
- A data transmission link to transfer information
- A central station to provide supervisory control and monitoring

MINOS (or Mine Operating System) was one of the earliest control and monitoring systems to be introduced into mines. It was developed during the 1970s, following a National Coal Board (NCB) research project in the UK. MINOS provides a complete control and monitoring system for a mine using computer technology. It is interfaced to equipment, such as ventilation fans, Armoured Face Conveyor (AFC) etc, through sensors and programmable logic controllers.

The 'Simple Asynchronous Protocol', or SAP, technique was later introduced to overcome the problem of incompatibility between various MINOS equipment supplied by different companies. Nowadays, the disadvantage of MINOS is that it was only designed for a specific platform and it is now becoming limited and expensive to support. Hind (1999) also discussed that the existing SAP technique is compatible with modern industrial computer based SCADA systems, which has already been introduced into some mines around the world.

The data transmission link in the control and monitoring systems was essentially established through electrical cable, such as copper twisted pair (as in telephone wire). Optical fibre is being looked into as an alternative, and has already been introduced into some mines. The main advantage is that it enables much higher speed data transmission at intrinsically safe levels.

2.1.3.2 'Open Standards' and 'Interoperability' in Mining

UK Coal Mining Ltd has been installing a SCADA based network, completely replacing MINOS and SAP (Ford 2006). Optical fibre with repeaters at least every 2km provide a 100BaseT Ethernet network. This system provides UK Coal's collieries with a large bandwidth SCADA network, thus providing opportunity for a broad range of applications. A significant aspect of this development is that the SCADA network is an open standard Ethernet system, which follows the ISO (International Standards Organisation) Open Systems Interconnection (OSI) seven-layer model (Figure 2.1 below). In contrast to MINOS this enables interoperability between components from different manufacturers, providing the flexibility needed for future developments. Refer to Appendix A.3 for more information on the UK Coal SCADA system.

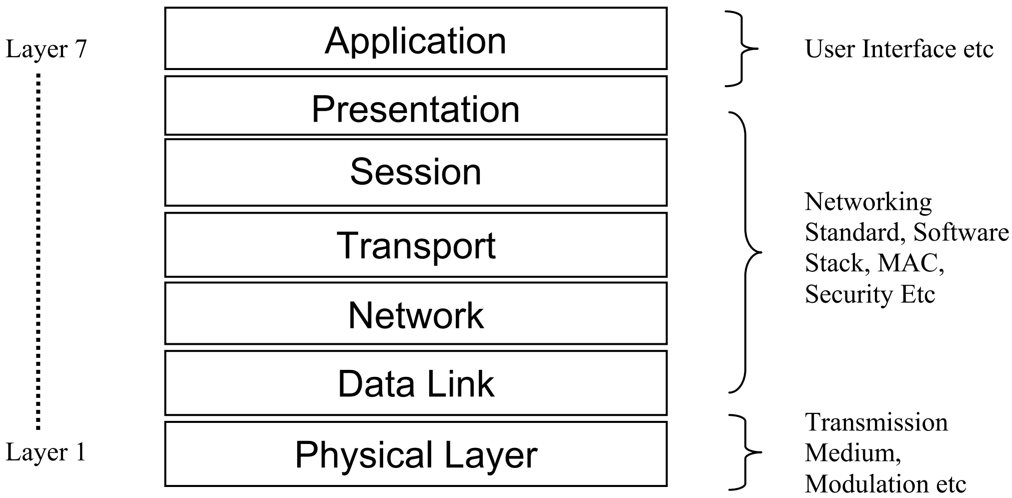


Figure 2.1: ISO Open System Interconnection reference model

2.1.3.3 Underground Wireless Data Communication Technology

Wireless communications is one major area of research currently being conducted by various organisations around the world, for example, an International Workshop on Wireless Communications in Underground and Confined Areas (IWWCUCA) was recently held in Canada during 2005. A number of interesting papers presented at the workshop e.g. (Ward and Masuskapoe 2005, Srinivasan 2005) highlighted the advantages of employing wireless transmission in underground environments. The advantage of wireless data transmission, as in a Wireless LAN, over fixed wired communications is that it allows mobility and the flexibility of being an open system (easily add new devices or nodes in a network). The rest of this section discusses wireless networks that have been developed or tested for underground use.

Hybrid Leaky Feeder Wireless Network

Outalha *et al.* (2000) discussed the advantages of a digital wireless network within the mine. Wireless communication systems that are currently being used, or tested, in the Canadian mining industry are reviewed. Three based on Leaky Feeder systems: ‘Flexcom’ from Mine Radio Systems Inc, ‘Multicom’ from El-Equip Inc and ‘TR-500 UHF / TR-150 VHF’ from Tunnel Radio of America, and one based on CATV coaxial cable with distributed antennas (SIAMnet). The paper discusses the drawbacks of the leaky feeder system such as:

- Low Data rates (9600 bps)
- Data security hard to set up
- No established standard – Therefore high costs per item and same vendor must supply interface.

The CATV technology is a much more flexible and efficient system offering a higher data rate of up to 1.5 Mbps and an increased number of channels. The main disadvantage is that the system does not allow for roaming, a unit operating on one channel cannot cross serving zones as it is fixed to that particular channel. The user would need to switch manually to another channel and identification number.

WLAN (Wireless Local Area Network)

The paper then described an implementation of a WLAN in an underground experimental mine. The WLAN described is based on the IEEE 802.11 standard, which conforms to the Open Systems Interconnection (OSI) model. The standard specifies two medium access types: infrared and radio. Infrared would be very limited due to the range and it is sensitive to obstacles. The radio medium has three specified bands: B1 (902 MHz to 928 MHz *US Only)*), B2 (2.4 MHz to 2.485 MHz) and B3 (5.75 MHz to 5.825 MHz). Radio waves are perceived as the most suitable solution in a mobile underground situation. The main advantages of the IEEE 802.11 WLAN are:

- Operates at high frequencies - Therefore allowing high bandwidth (data rates)
- Allows for roaming - User move from one cell to another without losing connection.
- Prospect of locational information
- Open Standards - Large flexibility in choice of equipment (Lower costs)
- Power Management

This article gives a good case, including some experimental work to highlight the advantages of the functionality of implementing a WLAN in a mine. However, it does not take into consideration the constraints of implementing the system in an underground mine, such as meeting with intrinsically safe regulations, or the limitation of radio (electromagnetic) wave propagation underground.

Einicke *et al.* (2002) describes a mine automation application that makes use of the WiFi standard, IEEE 802.11b, operating in the 2.4 GHz band. The paper discusses the potential weakness of implementing such a system:

- EMC/EMI (Electromagnetic compatibility / electromagnetic interference)
- Managing the coverage window - temporary obstructions, multi-path interference, signal attenuation etc
- Planning, maintenance, redundancy and congestion - prevent data traffic congestion etc
- Fail Safety - put controlled equipment into safe stable state during failure e.g. power communication.
- Matching to technology to application - Integrate with existing infrastructure.

The paper affirms the strengths of implementing a WLAN system in a mine, that it provides a data transmission system that is 'open' and 'flexible'.

UCELNET

Chung (2000) presents a system called UCELNET, which is a 900 MHz radio communications network specifically designed for underground mines. UCELNET, based on a cellular network, is designed to provide voice and data communications in an underground mine. UCELNET is supported by a TDMA-TDD common air interface (CAI) that allows full duplex data transmission. The network is set up by a backbone structure of base stations, allowing a total throughput data rate equal to 1.888 Mbps, which is divided between 59 channels at 32 kbps each. The system is versatile in the sense that some channels can be added together to support a single data transmission rate of up to 192 kbps e.g. to support a 64 kbps digital video signal.

As UCELNET has been specifically designed for an underground environment, the limitations of radio communications have been taken into consideration. Chung states that for the base stations, operating at 900 MHz, maximum line of sight spacing is 600m. The spacing between two base stations around a sharp bend is around 100m. The nominal spacing stated for the UCELNET system is 200m. From a safety aspect, the main drawback in the system is that a backbone network structure would not be a very survivable communications system in an emergency situation i.e. a roof rock fall (the communications link would be broken).

The UCELNET system described in this paper is a method of achieving wireless data communications underground. The main points worth mentioning is that the paper does not state what type of mine it is aimed at, whether it could be meet intrinsically safe standards to operate in a coal mine. Also, it is not stated why the TDMA (time division multiple access) medium access control (MAC) is implemented, as opposed to CSMA/CA or other more common wireless LAN MAC methods, or whether it is the most suitable solution.

2.1.4 Underground Emergency and Rescue Communications

There is a selection of technology available today that has been, or is currently being, developed for underground 'emergency or rescue' communication applications. Many of these technologies rely on radio transmission and each have a novel approach in overcoming some of the constraints of underground radio propagation. A selection of these technologies are summarised in this section.

2.1.4.1 Rescue Operation Communications

Figure 2.2: The m-Comm in Operation

The m-Comm, used by the Mines Rescue Service Ltd (MRSL), is the result of a previous ECSC funded project (Lewis and Brenkley 1993). The m-Comm system is a novel approach to underground communications, designed to provide communications during a mine rescue operation. The system (see Figure 2.2 opposite) employs a guide wire with a base unit and hand units that can be clipped on in any combination onto a copper guide wire. Operating ranges of 5 km can be achieved. The advantage of this system is that it is very portable and can be rapidly deployed in an underground or confined space emergency situation.

Figure 2.3: The Heyphone

The Heyphone (Figure 2.3) communication system was designed by the British Cave Research Council (BCRC) and the Cave Radio and Electronics Group (CREG). It is a device aimed at providing communications in cave rescue operation between the surface and rescue personnel underground. It operates at a frequency of 87 kHz Offering a range of up to a kilometre. It can either be used with a large open loop antenna or, if possible, an earth antenna that achieves a better quality signal. The earth antenna is set up using earth pegs and tape, embedded in the ground and stretched out over a large area to achieve a good earth connection. This type of system seems to be well suited to cave rescue operations but could be very limited and difficult to set up for mine rescue operations.

2.1.4.2 Emergency Warning Communications

An area, which is seeing some technological advances in the mining industry, is in the development of mine wide early warning systems. There are systems employing through-the-earth electromagnetic propagation for mine wide paging (discussed later), the LAMPS project (see below) is a system employing high frequency radio with multiple beacons introducing redundancy pathways to achieving a 'survivable' wireless transmission.

Einicke *et al.* (2000) gives a summary of an ACARP (Australian Coal Association Research Program) project 'Location and Monitoring for Personal Safety (LAMPS)'. The system comprises personal UHF transponders worn by staff and a survivable network of standalone wireless beacons. LAMPS provides bi-directional communication and staff locational information to a control and monitoring facility. The network achieves 'survivable' communications along multiple redundant line of sight paths within underground tunnels. Figure 2.4 below shows an overview of a LAMPS network using eight wireless beacons (Einicke *et al.* 2000).

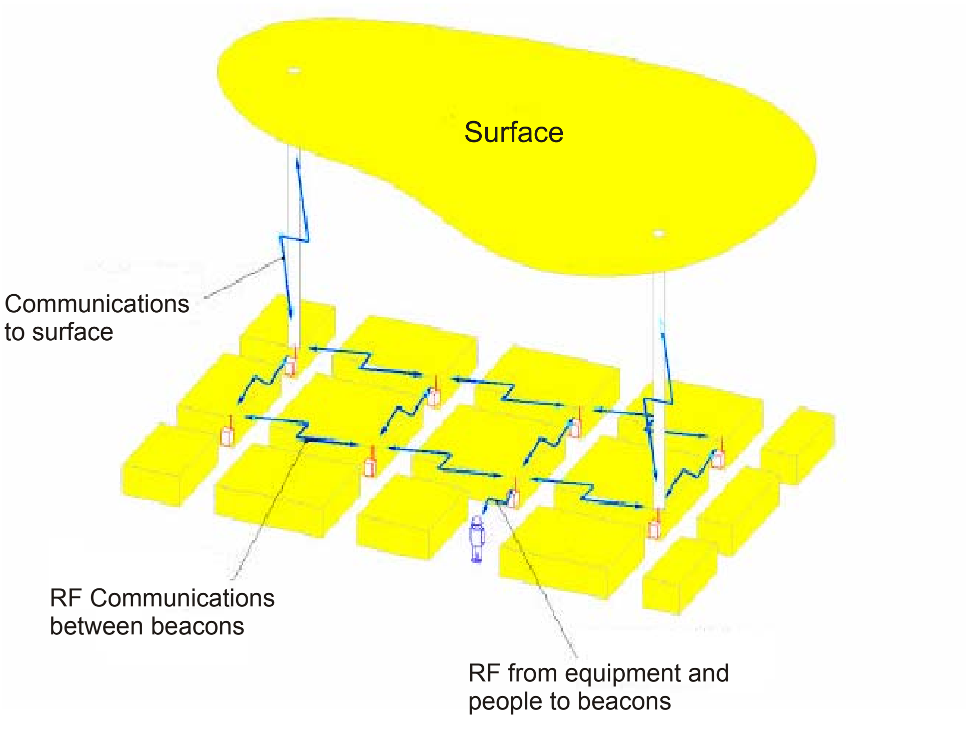


Figure 2.4: LAMPS Network Overview

[*Source*: Einicke *et al.* (2000)]

The LAMPS system has shown an effective method of achieving a survivable active tag transponder wireless network, not reliant upon a main backbone infrastructure, which was one of the main drawbacks in terms if survivability with the UCELNET system described earlier.

Einicke (2003) gives a review of various active and passive tag systems and presents a comparison of each system, including LAMPS. The paper is written from a mining automation perspective for applications of automatic proximity identification and tracking. It points out the advantages of active tag systems including: power, range, and storage capacity. The LAMPS system has particular advantages as it has been specifically developed for underground use offering robustness, survivability and is bi-directional. Passive tag systems are very well suited to certain applications and offer the advantage of not requiring an external power source, however, passive tag reader stations can be very expensive. This is discussed in Chapter 7.

Through-The-Earth Propagation

Through-the-earth (TTE) electromagnetic propagation is a method of achieving mine-wide communications. Mine wide coverage by propagating through the earth strata makes it very suitable for emergency warning communications. The RF characteristics are very much influenced by the electrical properties of the strata material. TTE communication is achieved at low radio frequencies: ELF, VLF and LF. The disadvantage being that bandwidth is very limited; thus severely limiting the transmitted data rate.

PED (Personal Emergency Device) is a commercially available paging device from Mine Site Technologies, see Figure 2.5 below. It is one-way (simplex) transmission device that utilises high-power ultra-low frequency (ULF) radio. It can penetrate hundreds of metres of rock strata, providing a fast and reliable method to inform underground miners of emergency situations. A receiving device is built into the cap lamp causing it to flash when a signal is received. Further developments of the TTE PED system have lead to applications including remote blasting and personnel tracking.

Figure 2.5: The PED System

[*Source*: www.minesite.com.au]

Wayne and Yewen (2002) describe an evacuation alert system that utilises a unique low frequency, narrow-band FM ‘tele-magnetic’ field. The proposed system is to have a receiver and an RFID (Radio Frequency Identification) transmitter integrated into the miners cap lamp. The RFID transmitter is proposed to provide locational, ID and date/time information of the miner.

A report by Bunton *et al.* (1999) described a project that also relied on bi-directional TTE transmission for emergency mine communication. The aim of the project was to demonstrate the feasibility of the emergency mine communication system rather than produce a prototype.

The system makes use of DSP (digital signal processing) technology. The project successfully demonstrated a mine-to-surface link, although the communications within the mine deviated from the theoretical predictions. However, there is plenty of scope for further development.

2.2 Emerging Data Transmission Technologies

2.2.1 High-Speed Fixed Wire Data Transmission

There are various fixed point-to-point data transmission technologies that are on the market, or being developed, at present, particularly in the field of what is now known as 'Broadband' communications. Broadband is a term used to describe high-speed data transmission systems. The growing use of the Internet and requirement for high-speed access is one example of the push in development of broadband technologies. Digital Subscriber Line (DSL) and cable modem are fast growing technologies that are in use in many homes around the world today.

In industrial applications, there is a demand for communications networks to support an increasing number of users and allow the exchange of more information. Especially in transferring information such as video, audio and pictures from point to point. In the mining industry where there are real-time voice and video applications, there is a requirement to transmit large amounts of data. There are key broadband data transmission technologies emerging at the moment, some of which are already being considered or even implementing in mines, others are not. Some of these technologies are summarised below.

2.2.1.1 DSL Technologies

Digital Subscriber Line (DSL) technologies, collectively known as xDSL, are a group of technologies that offer high-speed data transmission of existing copper twisted pair (telephone wire). xDSL technologies include HDSL (high-speed DSL), SDSL (symmetric DSL) and the now much more common, ADSL (asymmetric DSL) and VDSL (very high speed DSL).

When copper telephone wires were first installed, they were not intended to support a high bandwidth. The novel technique that allows xDSL transmission is a multi-carrier technique called DMT (Discrete Multi Tone). Single carrier techniques (CAP or QAM) may be used but they occupy a much wider bandwidth. In DMT the total data stream is divided into 256 sub carriers of approximately 4kHz. This is equivalent to having 256 modems operating in parallel. Each sub-carrier is then modulated at around 40 kbps. A digital signal processing technique called a 'Fast Fourier Transform' (FFT) is used to recover the data.

The main advantages of xDSL is that it uses passband transmission, e.g. ADSL operates at frequencies from 25 kHz to 1.1 MHz; thus allowing an ADSL and a telephone to operate on the same line at the same time. Another advantage is the DMT technique allows what is called ‘frequency selective fading’. This is useful in preventing interference at certain frequencies or utilising the frequencies that suffer the least intrinsic interference.

ADSL typically offers data rates of up to 6 Mbps downstream and 800 kbps upstream, with a range of typically 5km. VDSL typically offers up to 50 Mbps downstream and up to 2 Mbps upstream in asymmetric operation, or up to 26 Mbps upstream and downstream in symmetric operation. Though the maximum range is around 1km. Czajkowski (1999) presents a detailed overview of xDSL technology, outlining the advantages and disadvantages below.

Advantages:

- ADSL utilise existing telephone cable infrastructure
- High bandwidth data transmission

Disadvantages:

- Interference: Both intrinsic from high power electrical sources and potential extrinsic interference caused from the transmission over the UTP (unshielded twisted pair) copper telephone cable.
- Unless utilising existing UTP cable, xDSL is not really suitable as a separate data transmission system/medium, especially compared to Ethernet.

Potential Underground Applications:

- More suitable to specific applications, where high speed broadband data transmission would be required where the UTP cable is already in place.

2.2.1.2 Optical Fibre

Optical fibre cable carries transmitted information in the form of a fluctuating beam of light. Light has a much higher bandwidth than electrical waves enabling optical fibre to achieve transmission rates of hundreds of megabits per second. Unlike electrical and radio transmission, light waves are immune to electromagnetic interference and crosstalk. This makes optical fibre extremely useful in electrically noisy environments which employ high voltage and current switching applications. Also as the signal does not radiate from the transmission line, optical fibre is very useful when security is important, as it is difficult physically to tap or ‘eavesdrop’. In mining, optical fibre is proving very advantageous allowing high bandwidth, immunity from electrical noise and the transmission line itself offers high intrinsic safety.

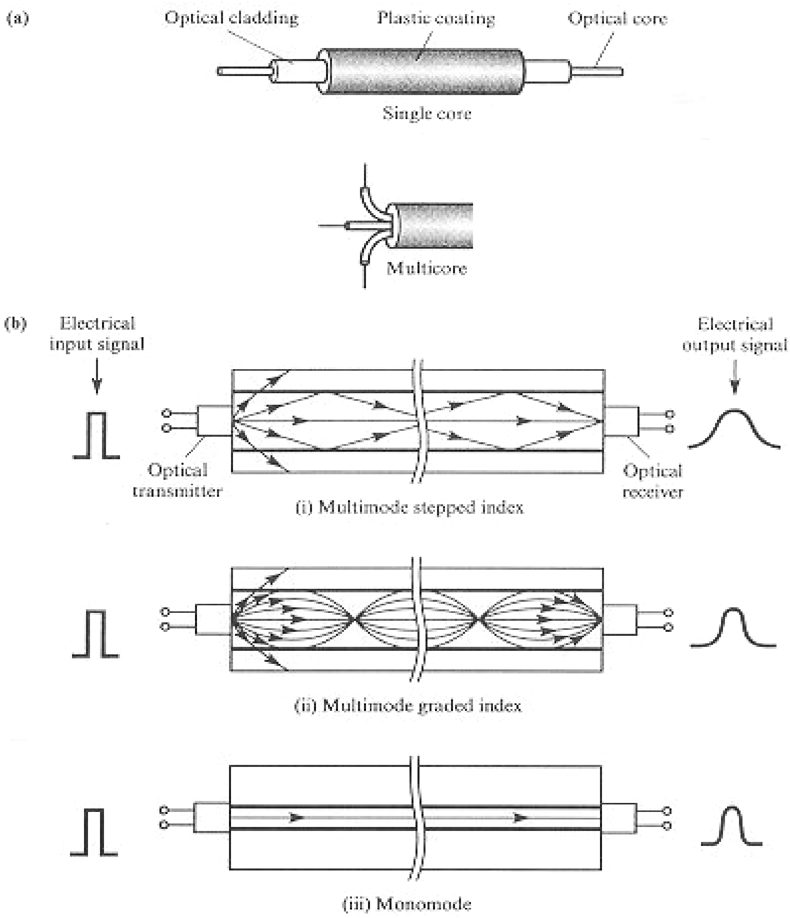


Figure 2.6: Optical Fibre: (a) cable structure, (b) transmission modes
[Source: Halsall (1996)]

The optical glass fibre cable consists of two parts: a glass core and an outer cladding with a lower refractive index. The cable can be single or multicore (Figure 2.6a). Light is transmitted using a light-emitting diode (LED) or laser diode (LD) and then propagates through the optical fibre core by refraction. Light propagates along the core in one of three ways depending on the type and width of core material used: multimode stepped index, multimode graded index and monomode (Figure 2.6b). Optical fibre essentially behaves as a waveguide structure; monomode (or singlemode) is specifically designed to allow a single mode of light propagation, and a larger structure will allow multiple propagation modes. There are two types of multimode fible. Each of the three types of optical fibre are described below:

Multimode stepped index – Core and cladding has different but uniform refractive index. Light emitted from the diode at less than the critical angle is reflected back along the core. The light will however, take a variable amount of time to propagate along the cable causing the receiver to receive a wider pulse than the input signal. This type of cable is primarily used for modest bit rates and relatively inexpensive LEDs rather than LDs. The core of multimode fibre is typically 62.5 µm. Multimode stepped typically operates up to around 50 MHz.

Multimode graded index – Similar to multimode stepped except the core has a variable refractive index. The fibre uses variations in the composition of the glass in the core to compensate for the different path lengths of the modes thus making the light refract by an increasing amount as it moves away from the core. The resulting curve paths reduce multipath dispersion caused between the modes travelling at difference velocities. Minimising the difference in velocity between the propagating modes allows the received pulse to be narrowed further. This typically allows operational frequencies of up to 2 GHz

Monomode – Monomode, also called singlemode, fibre has a core typically around 8-10μm in size. This only allows a single light ray to travel, thus reducing the multipath dispersion. Consequently, this allows a dramatic increasing in operational frequency up to around 100 THz. Monomode is normally used with LDs allowing the extremely high data rates.

The advantages and disadvantages of optical fibre transmission over other types of media are given below.

Advantages:

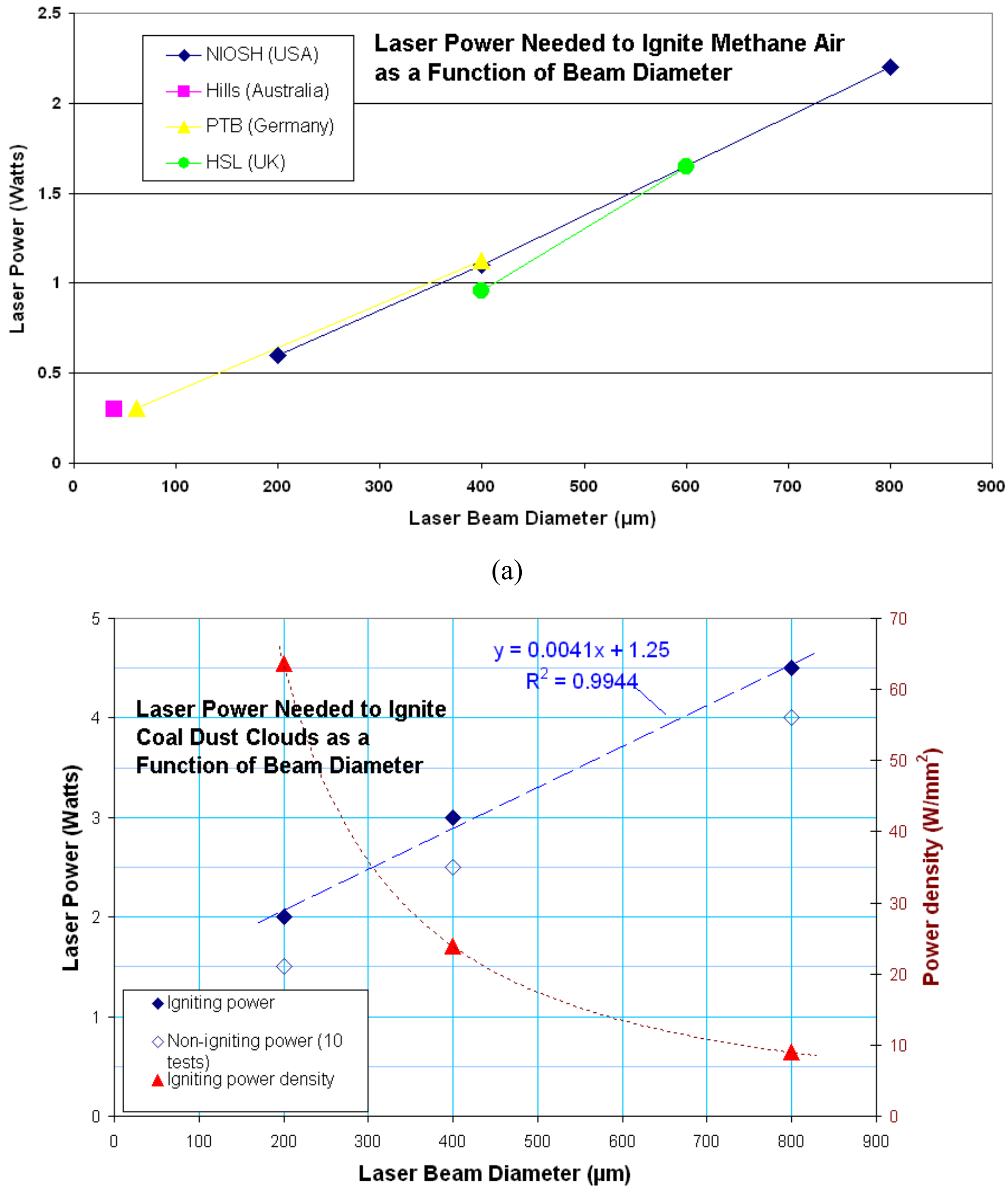
- High speed, high bandwidth.
- Long distances
- Relatively safe provided the energy levels are used (see 'disadvantages' below), compared with electric signal transmission.

Disadvantages:

- Prone to damage, thus requiring very expensive reinforced cables for use in a mine
- Whilst optical fibre is considered relatively safe, there are certain limitations and restrictions to consider in the event of the cable being severed. One is that of damage to the human retina, and secondly, is the risk of igniting a potentially explosive atmosphere.

The European Committee for Electrotechnical Standardization (CENELEC) have defined safe working limits of 150 mW or 20 mW/mm^2 for open beam lasers used in coal mines where methane gas may be present. Figure 2.7a and Figure 2.7b below shows the results from tests carried out by NIOSH (National Institute for Occupational Safety and Health) in the US, looking at laser power vs. beam diameter ignition for both methane gas and coal dust (NIOSH

2004). UK Coal use a 5mW LED as the light source for their Ethernet fibre optic transmission (UK Coal, 2003).



(a)

(b)

Figure 2.7: Laser Safety in Underground Coal Mines (a) Methane ignition – power vs. diameter (b) Coal dust ignition – power vs. diameter

[*Source*: NIOSH (2004)]

Potential Underground Applications:

Optical fibre is already being used in industrial Ethernet, for example UK Coal Mining Ltd are using optical fibre as the main transmission medium in their Ethernet based SCADA (Ford 2006). Optical fibre is particularly suited to applications requiring secure, high bandwidth and long range data transmission.

2.2.1.3 Power Line Telecommunication (PLT)

The concept of utilising existing power line infrastructure as a communications medium has been around since the turn of last century. The initial driving force behind power line telecommunications (PLT) (also called power line communications) was remote electricity supply metering. The last 20 years has seen the most significant development in PLT technology, where in particular digital techniques have unlocked many potential applications e.g. (Abbott 2002, Ferreira *et al.* 1996, Pavidou *et al.* 1996). PLT technology can be broadly separated into two areas: narrowband (kbps) systems in the frequency range 3 to 148.5 kHz, and broadband (Mbps) systems operating in the 1-30 MHz frequency range.

Narrowband power line communication systems have been around for decades. The idea of utility power lines serving as a communication medium is probably as old as the existence of power lines themselves (Abbott 2002). Ripple systems, employing low frequency high-powered signals were imposed on power lines during post World War II to control electrical loads. In recent years, narrowband PLT systems have been developed for AMR and industrial monitoring and control applications. Narrowband applications include control and automation, AMR (automatic meter reading), and remote surveillance etc.

Broadband systems have become far more widely available and established in the telecoms industry in recent years; mainly targeting residential applications e.g. Internet, telephone, home networking and AV (audio/video) distribution. Access PLC, Broadband PLC, and PLT are terms used to describe technology that provides broadband telecommunications over power lines. One of the initial trials of such technology was conducted in the UK by NOR.WEB. NOR.WEB (a joint venture between Norweb and Nortel) performed field trails of a PLT system in Manchester in 1997/1998 using frequencies of up to 6MHz. Operation rates of up to 1Mbps were achieved. Whilst NOR.WEB has since ceased trading, in recent years a number of broadband PLT systems are currently being trialled or piloted. Details of a field deployment of a broadband access system in Europe are given in Liu *et al.* (2003) and details of similar technology in the US are also discussed in Jee *et al.* (2003). In both systems MV and LV network is used to provide broadband telecommunications services e.g. Internet (as shown in Figure 2.8 below).

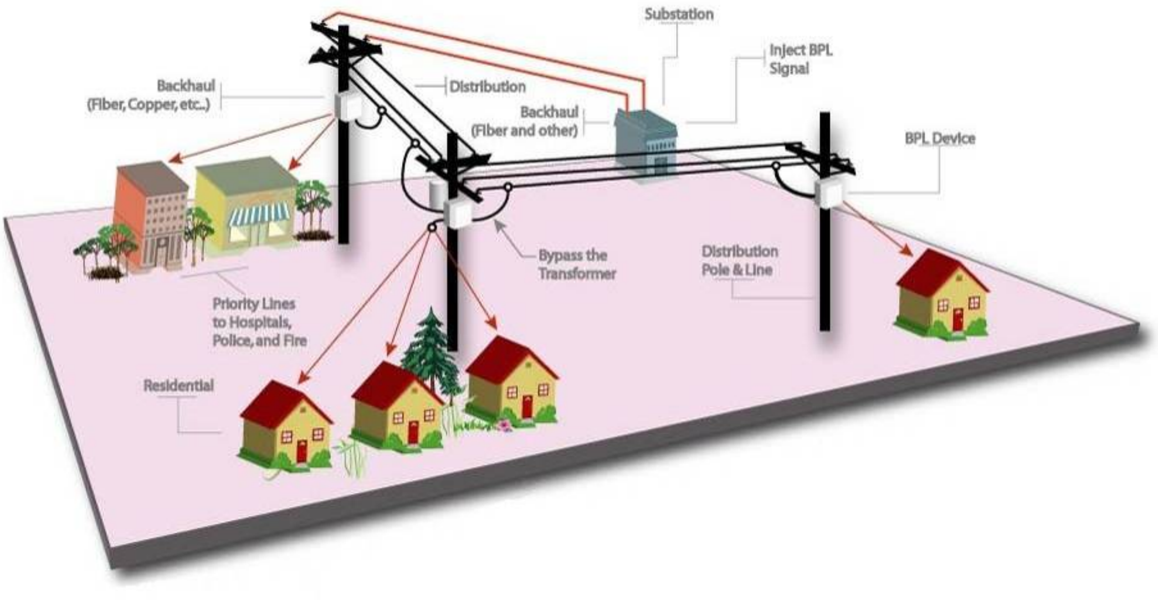


Figure 2.8: Broadband over power line system

[*Source*: www.plexeon.com]

The telecommunications company sets up a link to the MV network via a substation router (or node). An MV/LV coupler is needed to bypass the transformer. Both inductive and magnetic coupling can be applied. Finally, gateway node is then required at the user end to establish the connection. Additional in-home network services e.g. (HomePlug technology) can also be connected to the gateway. OFDM modulation is optimal choice, at a transmission rate of <10MHz outdoor PLT and >10MHz for indoor PLT. HomePlug (www.homeplug.org) is part of a family being termed as in-home PLC (or PLT). These technologies are primarily aimed at home network distribution for PC and audio/video applications, with high data rates over short distances.

EMC is the main issue involved with the success of PLT, mainly due to the potential interference it may cause to radio transmission operating in the same frequency bands. This is possibly far less of an issue for underground mines as there are not many radio systems in use. The main advantage of PLT is that it uses existing infrastructure, making it very cost effective.

Advantages:

- Utilising existing cable infrastructure.
- Power line cables are very robust and likely to survive, or partially survive roof rock falls, making the data transmission robust.

- Potential for non-intrusive coupling using toroidal couplers to enable rapid deployment and extended communication in emergency situations. This would be similar, or an extension, earlier research in Lewis and Brenkley (1993).

Disadvantages:

- Power lines are a very hostile medium for data transmission, with varying impedance, high attenuation and susceptibility to noise.
- Data transmission security, as with wireless communications systems, is significantly lower than that of fixed point-to-point wireless media.

Potential Underground Applications:

- Rapid deployment in an emergency and rescue situation.
- Increased transmission resilience; high probability of surviving incidents such as falls of rock.
- Extending the range of remote monitoring and control systems. Used in conjunction with other 'wired' or 'wireless' systems.
- 'Easy to install' alternative to dedicated digital networks, utilising existing network infrastructure.
- Scope for network nodes to automatically detect and negotiate connections for rapid deployment networks.

2.2.2 Wireless Data Transmission

There are a number of wireless network technologies under development at present that are competing with one another, each system having different advantages. The transmission media used in wireless networks is either radio or optical (infrared). Infrared systems are severely limited to line of sight, but can make use of reflections. This is not very suitable for a mining application where space is restricted and line of sight is likely to be blocked. High frequency radio may be more restricted to line of sight within a tunnel, but will penetrate or propagate around objects.

2.2.2.1 Wireless Local Area Network (WLAN) Standards

There have been developments in the IEEE 802.11 WLAN (wireless local area network) standards and the IEEE 802.15 WPAN (wireless personnel area network standards). WiFi is the name that has been given to the IEEE 802.11 WLAN standards, which operate in the 2.4 GHz or 5 GHz frequency bands. WiFi is now a very established wireless network and is already being considered for use in the mining industry (Einicke *et al.* 2002). The 802.11b standard offers data rates of up to 10 Mbps, 802.11g standard offers data rates of up to 54 Mbps and it is anticipated the new 802.11n will have data rates in excess of 300 Mbps. More information is on the IEEE standards website (http://standards.ieee.org/).

HiperLAN/2 is an alternative wireless LAN standard, which was developed in Europe. It is similar to the IEEE 802.11a standard operating in the 5GHz band using orthogonal frequency division multiplexing (OFDM). The standard is efficient and cost effective compared with WiFi. Although, it is yet to make a significant impact on the market as WiFi has done.

Advantages:

- Mobile, flexible and scalable data transmission.
- Open standard – equipment compatibility and interoperability with other systems.
- Relatively high transmission rates compared with other wireless technologies, suitable for audio and video applications.
- Initial research suggests adequate performance using this type of technology underground.

Disadvantages:

- Heavily reliant on pre-determined network infrastructure. Relies on base station or access point configuration, where it forms a 'star' based network technology. This makes it complicated for setup and roaming devices.
- Use in an emergency and rescue would depend on all network infrastructure, particularly access points (or wireless routers) remaining intact.
- Higher power requirements than other wireless technologies – battery powered for hours of operation.
- Safety – There is a minimal risk of inadvertent ignition to remote detonators. However, the HSE has defined safe working limitation of a transmission power less than 500mW EIRP, which actually allows for increased transmission power.

Potential Underground Applications:

- Suitable for extending data transmission coverage around the mine.
- Enable mobile network access - audio, video, and remote PC (laptop, palmtop) e.g. access importance maintenance information etc *in situ*.
- Possible positional or tracking information.

2.2.2.2 Bluetooth

Bluetooth (www.bluetooth.com) is a short-range radio link technology intended to replace the cable(s) connecting portable and/or fixed electronic devices. Key features are robustness, low complexity, low power, and low cost. Bluetooth establishes ‘ad-hoc’ networks where up to 8 devices directly communication with one another in a ‘piconet’. Essentially the technology operates in the unlicensed industrial, scientific and medical (ISM) band at 2.4 to 2.48 GHz, using a spread spectrum, frequency hopping, full-duplex signal at up to 1600 hops/sec. The signal hops among 79 frequencies at 1 MHz intervals to give a high degree of interference immunity. Maximum RF output is specified as 0 dBm (1 mW) in the 10m-range version and +20 dBm (100 mW) in the longer range version.

Bluetooth radio technology characteristics summary:

- Operates in the 2.4 GHz ISM band.
- 10m to 100m range (depending on Class of device).
- Uses Frequency Hop (FH) spread spectrum techniques, dividing the frequency band into a number of hop channels 23 or 79 (depending on country licence requirements).
- During a connection, radio transceivers hop from one channel to another.
- Supports up to 8 devices in a piconet (two or more Bluetooth units sharing a channel). Supports both synchronous and asynchronous services, easy integration of TCP/IP.
- Piconets are star based topology, with one master and up to 7 slave devices.
- Omni-directional. Non line-of-sight transmission possibility.
- Built-in security.

One of the key advantages observed of the technology is that it can provide transparent and automatic negotiation of connections between devices, providing they remain within a sensible range of one another. A further anticipated benefit is the possibility of using dynamic power control with ERPs of between 1 mW and 100 mW. This ensures devices use the lowest transmission power consistent with satisfactory communication, concurrently reducing interference potential. In principle, the ERP could be increased to 500 mW for underground applications and remain in compliance with the safety limit for electro explosive devices (EEDs). Transmission at this power level would result in significant radio coverage of the local workings.

Advantages:

- Mobile, flexible and scalable data transmission.
- Open standard – equipment compatibility and interoperability with other systems.

- Establishes ad-hoc links with other Bluetooth devices, without the need for pre-determined base stations.
- Automatically establishes and organises the 'piconet' network.
- Relatively low power – battery powered for days of operation.

Disadvantages:

- Not ideally suited to dynamically changing networks; where the time to wake-up from sleep, and the time required for a device to re-establish in a different Bluetooth network, is relatively slow.

Potential Underground Applications:

- Primary aimed at short range, relatively high data rate, cable replacement applications e.g. control, audio and possible video.
- Short range audio communications e.g. local communications between rescue team personnel.
- Zonal location tracking
- UK Coal have installed a Bluetooth controlled shearer at a colliery [see Appendix A.3].

2.2.2.3 Zigbee/IEEE 802.15.4

Zigbee (www.zigbee.org) is a new wireless networking standard aimed at providing a cost effective, reliable, low power wireless network for control and monitoring applications. The standard has been developed by the Zigbee Alliance along side the work of the IEEE 802.15.4 Working Group. The IEEE 802.15.4 standard, which focuses on low data rate wireless personal area networks (WPAN), defines the lower layers ('PHY' – physical layer and 'MAC' – medium access control layer) of a Zigbee system.

The Zigbee protocol stack (Figure 2.9 below) is split between the two standards. Zigbee defines the upper layers i.e. the software controlling the networking to application layer, and the IEEE 802.15.4 standard defines the lower layers, i.e. radio, modulation scheme, MAC (medium access control) etc. More information can be found on the Zigbee Alliance website (www.zigbee.org).

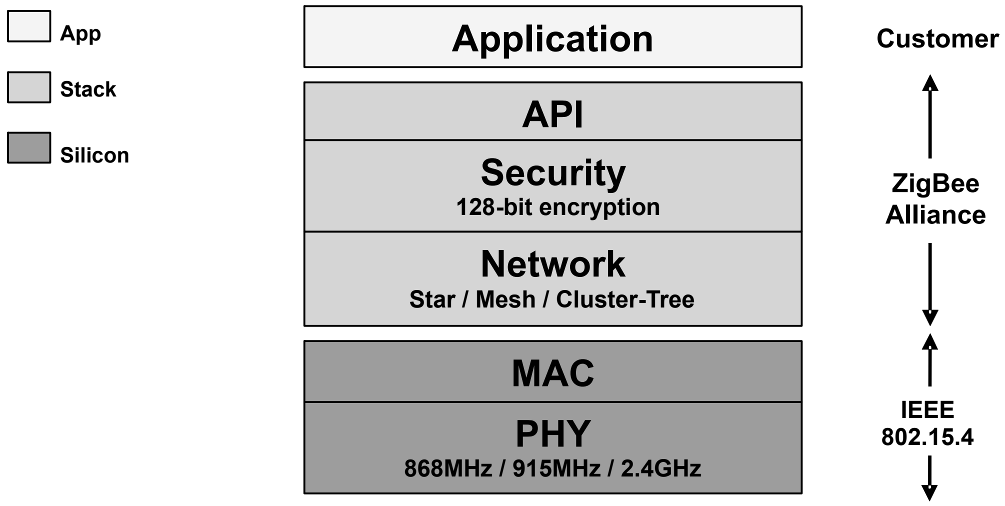


Figure 2.9: Zigbee Protocol Stack
[*Source*: www.zigbee.org]

Transmission Characteristics - IEEE 802.15.4 radio has a number of mechanisms to ensure reliable data transmission. The PHY layer employs Binary Phase Shift Keying (BPSK) in the 868/915 MHz bands and Offset Quadrature Phase Shift Keying (O-QPSK) at 2.4GHz, both robust and simple forms of modulation that work well in low SNR environments. The information is coded onto the carrier with Direct Sequence Spread Spectrum (DSSS), an inherently robust method for improving multipath performance and receiver sensitivity through signal processing gain.

Data Rate - Dates rates of 20 kbps and 250 kbps can be achieved in the 868 MHz and 2.4 GHz European license-exempt bands respectively. The data rates are lower compared with systems such as Bluetooth operating at 1Mbps. The fact that Zigbee is aimed at control and monitoring applications is the driving force for lower data rates.

Data Latency - Zigbee is capable of providing latencies as low as 16 milliseconds. However, there is a trade-off between demanding latency requirements and battery life.

Stack -The Zigbee stack is small (28Kbytes) compared with Bluetooth (250Kbytes) and only requires a moderate amount of system requirements.

Battery Life - Very long battery life is predicted for Zigbee. It is claim that a Zigbee device should last from between 6 months to 2+ years on two AA batteries.

Cost - It is aimed at being a low power, low data rate, rugged and reliable wireless network that is very cost effective.

Table 2.1 below gives a comparison of Zigbee with other wireless network technologies. Each standard has advantages over the other depending on specific applications. Zigbee has a lot of potential in industries like mining, specifically at aimed control and monitoring applications.

Table 2.1: Comparison of Zigbee and other wireless network technologies

Market Name Standard	**GPRS/GSM 1xRTT/CDMA**	**WiFi 802.11b**	**Bluetooth 802.15.1**	**Zigbee 802.15.4**
Application Focus	Wide Area Voice & Data	Web, Email, Video	Cable Replacement	Monitoring & Control
System Resources	16MB+	1MB+	250KB+	4KB - 32KB
Battery Life (days)	1-7	.5 - 5	1 - 7	100 - 1,000+
Network Size	1	32	7	255 / 65K
Bandwidth (KB/s)	64 - 128+	11,000+	720	20 - 250
Transmission Range (metres)	1,000+	1 - 100	1 - 10+	1 - 100+
Success Metrics	Reach, Quality	Speed, Flexibility	Cost, Convenience	Reliability, Power, Cost

Advantages:

- Mobile, flexible and scalable data transmission.
- Open standard – equipment compatibility and interoperability with other systems.
- Mesh networking – self organising, self healing, redundant pathway and adaptable.
- Highly robust network against failure, not as dependant on pre-determined infrastructure.
- Low power – battery power for months, possibly years.

Disadvantages:

- Low data rates of 250kbps.
- Suited to specific 'sensor' type applications.
- Limited knowledge on RF performance underground. Although it operates at same frequencies as Bluetooth and WiFi, which have shown promising results in underground applications

Potential Underground Applications:

- Sensory data acquisition e.g. environmental, machine diagnostics

- Control and remote telemetry
- Zonal location and positioning tracking
- Possible voice communications

2.2.2.4 Discussion on RF Transmission

The various modulations and spread spectrum schemes employed by the various technologies are shown below in Table 2.2. Certainly one aspect to consider with the wide ranging choice of technologies and associated techniques is that of interference. This is not such a problem in underground mines due to the fact that there will be no interference from the outside world. However if various technologies are introduced simultaneously, as wireless transmission seems to be the current trend as observed in this review, interference is certainly an aspect to consider.

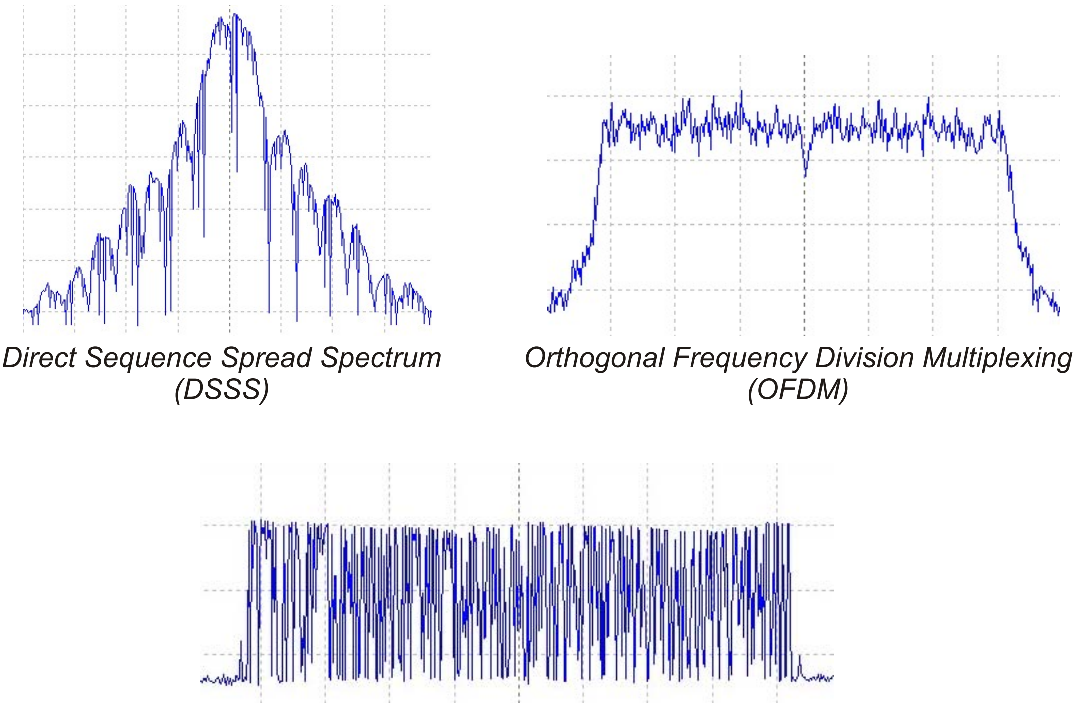
Table 2.2: Overview of Wireless Technologies PHY

Standard	OFDM	FHSS	DSSS	Modulation	Frequency (GHz)	Size	Data rate (Mb/s
IEEE 802.11		✓	✓	Various	2.4	LAN	1, 2
IEEE802.11a	✓			64-QAM	5	LAN	54
HiperLAN/2	✓			64-QAM	5	LAN	54
IEEE 802.11b			✓	CCK	2.4	LAN	5.5, 11
IEEE 802.11g	✓			64-QAM	2.4	LAN	54
IEEE 802.11n	✓			64-QAM, MIMO	2.4 / 5	LAN	540
IEEE 802.16	✓			64-QAM	5	WAN	54
Bluetooth		✓		GFSK	2.4	PAN	0.7
Zigbee			✓	BPSK / O-QPSK	0.868, 2.4	PAN	0.25

OFDM – Orthogonal Frequency Division Multiplex
FHSS – Frequency-Hopping Spread Spectrum
DSSS – Direct Sequence Spread Spectrum
CCK – Complimentary Code Keying
QAM – Quadrature Amplitude Modulation
MIMO – Multiple Input Multiple Output (multiple transmit and receive antennas to increase throughput)
BPSK – Binary Phase Shift Keying
O-QPSK – Orthogonal Quadrature Phase Shift Keying

There are three common spread spectrum techniques used in wireless network technology, in addition to conventional narrow-band techniques. These are frequency-hopping spread spectrum (FHSS), direct-sequence spread spectrum (DSSS), and orthogonal frequency division multiplex (OFDM). OFDM is not, in technically strict terms, a spread-spectrum technique; it simultaneously modulates the signal onto 256 sub-carriers through performing an FFT. The technique is also known as DMT, which was described earlier in Section 2.2.1.1.

Figure 2.10, below, shows the spectral plots for DSSS, FHSS and OFDM spread spectrum techniques. The plots were taken using a Willtek 9102 Spectrum Analyser, with standard technologies: Zigbee (DSSS), Bluetooth (FHSS) and IEEE 802.11.g (OFDM). DSSS produces a more noise-like spectrum, and FHSS produces narrow-band spectral peaks. Direct-sequence spread-spectrum modulation is arguably less likely to interfere because its spectrum is more noise-like, whereas a frequency-hopping signal is a frequency-agile narrowband transmission. OFDM is similar to FHSS in the frequency channel is divided into sub-channels. The signal is then modulated individually onto each of the closely spaced (minimally spaced, orthogonal) carrier frequencies, each of which carries 1/*n* of the total bits in a message, where '*n*' is the number of sub-carriers (or sub-channels). In FHSS, the carrier hops to each frequency sub-channel one at a time, while in OFDM, all carriers are used simultaneously.



Direct Sequence Spread Spectrum (DSSS)

Orthogonal Frequency Division Multiplexing (OFDM)

Frequency Hopping Spread Spectrum (FHSS)

Figure 2.10: Spectral Plot of Spread Spectrum Techniques

The better OFDM systems adapt to the channel by avoiding frequencies that exhibit high bit-error rates. Since this method uses all frequencies (with minimum spacing), it can offer the highest spectral efficiency (bits/s/Hz) of the three methods. This is confirmed in the case of adaptively modulated OFDM formats (as used in ADSL wired links, IEEE 802.11a protocols, and versions which were proposed for the IEEE 802.16 Metropolitan Area Networking standard). Each OFDM carrier can be individually modulated via binary phase-shift keying

(BPSK) or multilevel quadrature amplitude modulation (n-QAM) constellations (usually with n = 4, 16, 64), yielding higher spectral efficiency when the link has a high SNR. Direct sequence has the second best spectral efficiency, and frequency hopping third. OFDM is better suited to a few nodes streaming high data rates, whilst DSSS is better suited for multiple nodes handling relatively limited data per node. In terms of practical systems, Table 2.3, below, shows generalised rankings for the three technologies (Moore *et al.* 2001).

Table 2.3. Comparison of Spread Spectrum Technologies

Typical Ranking	Spectral Efficiency	Non-interference	Power Requirement	Data Reliability	Effective Range
Best	OFDM	DSSS	FHSS	OFDM	OFDM
Median	DSSS	FHSS	DSSS	DSSS	DSSS
Worst	FHSS	OFDM	OFDM	FHSS	FHSS

2.2.3 Hybrid Data Transmission System

An interesting development from Siemens is the SpeedStream (www.speedstream.com) Powerline Wireless DSL/Cable Router (see Figure 2.11 below). The SpeedStream is effectively a universal networking tool kit that brings together three technologies in order to simplify set-up and configuration of networks in the home environment. Whilst this particular router system may not be suitable for a mine application, the idea of using both wired and wireless transmission may be useful for a mining application. A development of this type of system could offer a 'hybrid' network for a mine that is a mixture of a power line communications (or other wired link) and a wireless system, in order to achieve a more rugged data transmission network.

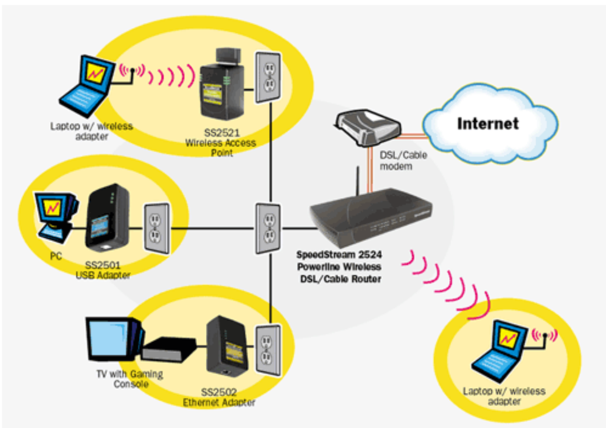


Figure 2.11: Siemens SpeedStream (Powerline/Wireless/DSL/Cable Router)
[*Source:* www.speedstream.com]

2.3 Requirements of Underground Data Transmission

The review has identified that current trends in underground mine data transmission systems are moving towards standards based systems, Ethernet and TCP/IP in particular, e.g. UK Coal's SCADA network (see Appendix A.3). Standards based OSI networking protocols, namely IEEE 802.11.3, enables interoperability and the potential convergence of all data transmission into one system through TCP/IP, for example, VoIP (voice over IP), video and data. Ward and Masuskapoe (2005) discuss the advantages in converging data transmission through Ethernet and TCP/IP along with the associated advantages in utilising wireless networks to extend coverage. Wireless networking can be more flexible and less costly in comparison with optical fibre, and even standard UTP cable, which has a maximum rage of 100m before requiring a switch/router acting as a repeater.

Following this review wireless data transmission has been identified as having significant potential in underground mining applications. Wireless mesh network technology such as the emerging Zigbee and IEEE 802.15.4 standards are of particular interest given the robust nature of mesh networking (discussed in Chapter 4) and range of potential applications. For example, monitoring and control in a modern coal mine typically requires around 15,000 sensors or actuators and a proportion of these are semi-permanent. Given the nature of a coal mining operation, equipment has to be moved at regular intervals e.g. belt conveyor drive. Re-installing cables and sensors for the monitoring and control telemetry requires considerable man-hours. Wireless sensors could potentially reduce the installation time dramatically. Following this initial review, the focus of research in this thesis will concentrate on wireless transmission, and in particular low power wireless mesh networking and associated potential applications.

2.4 Summary

The first part of this Chapter reviewed current and future trends in 'underground' data transmission and communication systems. The second part of this review investigated emerging data transmission technologies of interest and relevance to potential future advanced underground data transmission.

Underground Telecommunications Review:

A review of underground telecommunications technology has been given in this section. Certain types of technology have been discussed, defining three areas: general communications, data transmission for control and monitoring, and underground emergency and rescue communications. Although it is noted that certain technologies can be used for a broad range of applications. The aim of the review has been to present an overview of modern underground systems, highlighting the general trends or growing needs of telecommunications in the mining industry. Following the review, it was found that the main factors driving the development of new underground data transmission technology are:

- *Increased bandwidth*: Automation is increasing in the mining industry placing greater demands on data transmission systems.

- *Open Systems*: Open systems, or standards, allow data communication systems to be scalable and compatible, or interoperable, with other technology.

- *Survivability and high-integrity*: Communication systems operating in a mine, particularly for safety or emergency applications need to be highly survivable and have high integrity.

- *Mobility*: Due to the nature of the work with personnel/vehicles on the move. Radio transmission is very desirable in providing communications links for certain applications to allow users, or nodes, to 'roam' within a network.

Emerging Data Transmission Technologies:

This section has discussed various new data transmission technologies that may be suitable for underground mining. The review has shown that there are a number of both wired and wireless systems that can potentially enhance underground data transmission. The review identified wireless networking technology as key area for further research. Whilst radio is very challenging compared with other underground data transmission technologies, it has many desirable attributes such as mobility, scalability and flexibility. Recent developments in low power wireless network technology with the new Zigbee and IEEE 802.15.4 standard, and the more established Bluetooth standard, have a lot of potential in underground mining. Possible applications include location awareness, control and monitoring of machinery, environment etc. Mesh network characteristics (discussed Chapter 4) are also particularly interesting in that it could provide a means of achieving a 'survivable' network. A hybrid network comprising both wired and wireless transmission media also further improve network resilience in an underground environment. From a functionality perspective, low power wireless networks have significant potential in underground industries. However, the feasibility will be determined by the environmental constraints of operating underground. The physical radio propagation and other issues such as intrinsic safety will be the main factors to consider. The characteristics of subsurface radio propagation at the UHF and microwave frequencies are discussed in Chapter 3.

Chapter 3: Wireless Tunnel Propagation Characteristics

The characteristics of subsurface wireless transmission in underground mines and tunnels are investigated in this Chapter. A theoretical analysis and review of other relevant research on subsurface electromagnetic propagation, in particular UHF and SHF frequencies, is presented. The initial feasibility study, presented in Chapter 2, has shown there are significant potential advantages in employing wireless networking technology operating at these high frequencies in mines and underground environments. Along with the study of propagation characteristics and lossy waveguide model for tunnels, this Chapter presents details of a range of underground tests carried out using pure continuous wave (CW) transmission and various wireless networking technologies. Three different locations have been used to conduct the tests: a disused railway tunnel, hard rock test mine and a replica coal mine test facility. A discussion of the results obtained and the underlying waveguide theory is discussed at the end of the Chapter.

Following the initial feasibility study (Chapter 2), wireless networking has been identified as the main focus within this research project, particularly mesh (or ad-hoc) technology. In support to the research work investigating the feasibility of 2.4GHz ISM band low power wireless mesh networking technology in underground environments (discussed later in this thesis), this Chapter also investigates the fundamental electromagnetic propagation characteristics of such systems in tunnels. This Chapter is separated into three main sections:

- Theoretical Analysis – Reviewing previous work and examining the theory underlying electromagnetic propagation in tunnels.

- Wireless Propagation Tests – Continuous wave (CW) microwave transmission tests were carried out in three different mine/tunnel locations. Throughput versus distance tests were carried out using Bluetooth and WiFi technologies (IEEE 802.11b, -g, -super-g, -pre-n, and -draft-n) within the different tunnel environments, comparing the different modulation schemes and spread spectrum technology.

- Discussion – The observations made during all the CW and wireless technology tests are discussed comparing the results with the underling theory.

3.1 General Subsurface Radio Behaviour

Radio, or electromagnetic (EM), propagation has been studied extensively during the last 100 years yet it still remains a challenging topic in the field in electrical engineering. Underground radio, in comparison to surface radio transmission, is highly complex in terms of being able to characterise, perhaps due to the fact it has only been researched more extensively during the last 30 years. However, owing to a number of key researchers during the last 30 years, e.g. (Chiba *et al*. 1978, Davis 1986, Delogne 1982, Deryck 1978, Emslie *et al.* 1975, Gibson 2003 Goddard 1973, Holloway *et al.* 2000, Legace *et al.* 1975, Martin 1986, Mahmoud 1974, Ndoh and Delisle 2003) and others, we do have a relatively extensive understanding of subsurface EM propagation. In particular, Professor James R. Wait has made an exceptional contribution to the subject e.g. (Wait 1962, Mahmoud and Wait 1974, Wait 1975).

A report by Lewis and Brenkley (1993) contains a summary of some of the characteristic behaviour of electromagnetic propagation at various frequencies underground. A summary of subsurface EM propagation characteristics is given in Figure 3.1 below. Table 3.1 below gives a description of the radio and microwave band classifications.

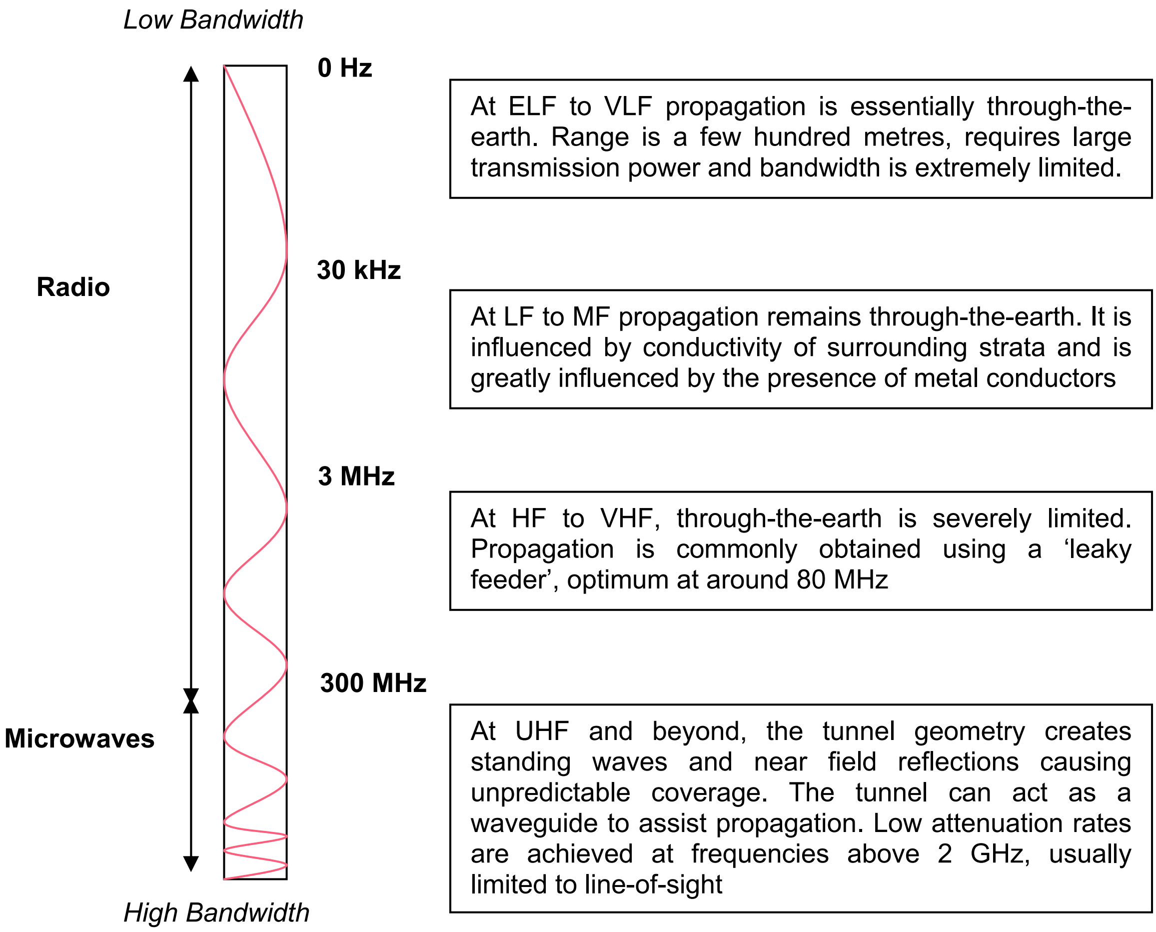


Figure 3.1: Characteristics of Subsurface EM Propagation

Table 3.1: Radio and Microwave Spectrum

Wavelength	Frequency	Classification
10mm – 1mm	30GHz - 300GHz	EHF – extremely high frequency (microwaves)
100mm - 10mm	3GHz - 30GHz	SHF – super high frequency (microwaves)
1m - 100mm	300MHz -3GHz	UHF – ultra high frequency
10m - 1m	30MHz - 300MHz	VHF – very high frequency
100m - 10m	3MHz - 30MHz	HF – high frequency
1km - 100m	300kHz - 3MHz	MF – medium frequency
10km - 1km	30kHz - 300kHz	LF – low frequency
100km - 10km	3kHz - 30kHz	VLF – very low frequency
1Mm - 100km	300Hz - 3kHz	ULF – Ultra low frequency
10Mm - 1Mm	30Hz - 300Hz	SLF – Super low frequency
100Mm - 10Mm	3Hz - 30Hz	ELF – extremely low frequency

There are various technologies exploiting the different characteristic groups of subsurface radio, some of which were discussed in Chapter 2. For example, at ULF to LF through-the-earth TTE radio is used in mine wide paging systems, radio imaging of coal seams and through rock voice communications (Heyphone). At higher frequencies, usually HF to VHF and also UHF, there are various types of leaky feeder systems, which have been widely used throughout the mining industry. In this thesis we are predominantly interested in the ‘natural propagation’ of UHF and SHF frequencies in underground mines and tunnels.

3.2 Underground UHF and Microwave Propagation Characteristics

3.2.1 Electrical properties of rock

At frequencies above the natural cut-off frequency, derived from the tunnel cross-sectional dimensions, a tunnel will behave as a lossy waveguide e.g. (Wait 1975, Delogne 1982, Emslie *et al.* 1975). First of all, to consider whether or not it is possible for through rock transmission or whether propagation at these frequencies tends to take more of a waveguide form, the electrical properties need to be studied. Typically, waveguides are relatively small in size and highly conducting metal structures used in efficient microwave transmission. The electrical properties of rock have typically low conductivity σ, in the region of 10^{-6} to 1 mho m^{-1}. The relative permittivity ε_r, or dielectric constant, of rock material is in the region from 2 to 70, but more typically 4 to 10. The permeability μ of rock material, excluding rocks with high concentration of ferromagnetic metals (e.g. iron, nickel), is very close to μ_0, which is the permeability of a vacuum, μ_0 = 1260 nH m^{-1}. The electrical properties are based on the findings by Cook (1975), see Figure 3.2 below.

A characteristic frequency for a given medium is the transitional frequency f_t which is defined by

$$2\pi f_t \varepsilon = \sigma \tag{3.1}$$

The transition frequency for the different rock materials for each of the four frequencies is also shown in Figure 3.2, below. Below this frequency, conduction currents are more important than displacement currents and the material may be regarded as a conductor. Above this frequency, the opposite occurs in that the material can be regarded more as a dielectric (Delogne 1982).

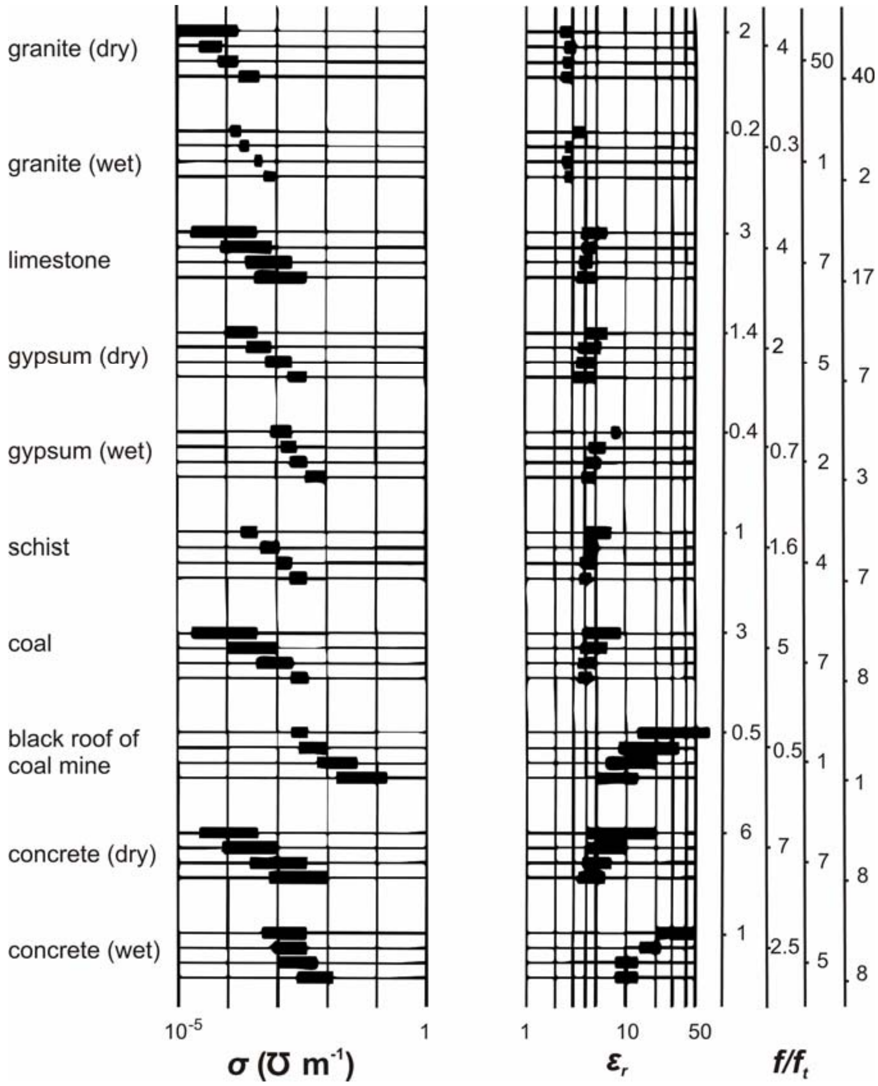


Figure 3.2: Electrical parameters of select materials – The separate bars for each material represent frequencies of 1, 5, 25 and 100MHz from top to bottom respectively.

[*Source*: Modified diagram (Delogne, 1982) based on data from Cook (1975)]

Delogne (1982) states that the propagation constant for a uniform plane wave in a homogenous medium is given by

$$\gamma = \alpha + j\beta = \left(j\varpi\varepsilon_0\varepsilon_r + \sigma\right)j\varpi\mu_0 \quad (3.2)$$

The real and imaginary propagation parameters for a typical rock medium, with relative permeability $\varepsilon_r = 10$, are shown below in Figure 3.3. ε_0 is the permittivity of free space (8.854 x 10^{-12} F/m). The diagram shows the specific attenuation α, phase constant β, wavelength λ, and the skin depth δ versus frequency f, for different conductivity values.

Where skin depth $\delta = 1/\alpha$ (3.3) and $$\lambda = 2\pi / \beta \tag{3.4}$$

The free-space wave number k_0 is also given for comparison, where $k_0 = \varpi\sqrt{\varepsilon_o \mu_0}$.

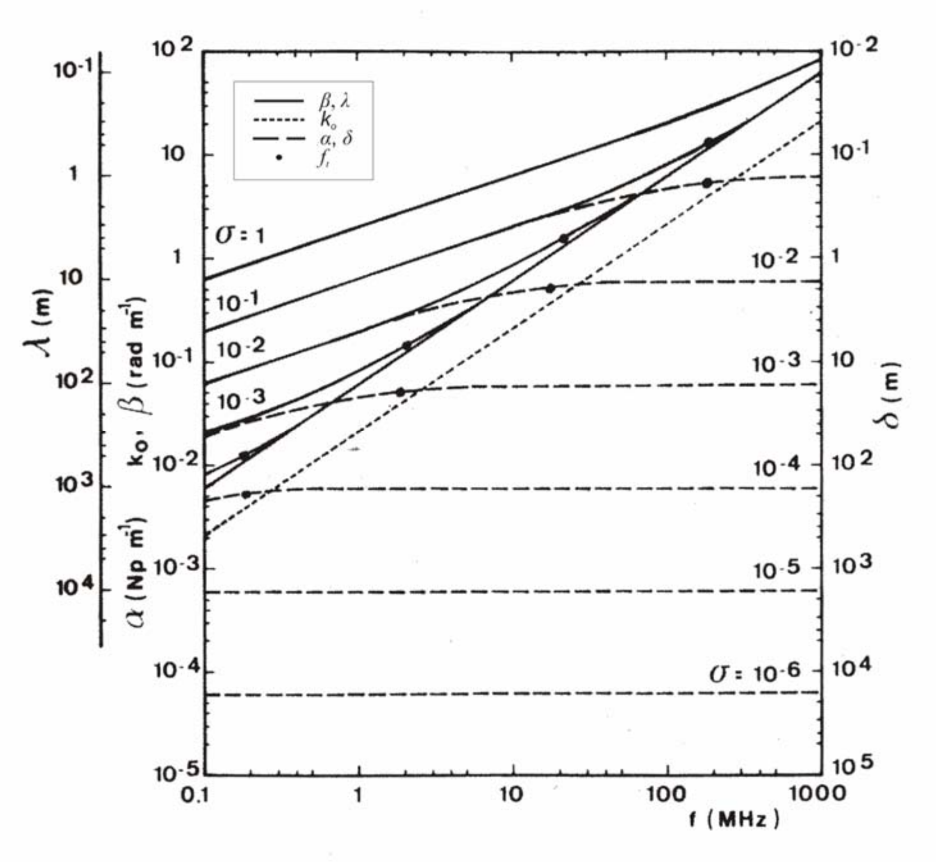


Figure 3.3: Propagation parameters of a medium with relative permittivity (ε_r) = 10
[*Source*: Delogne (1982)]

It has been shown that the specific attenuation increases with frequency and skin depth (or penetration) decreases with frequency. Therefore as you would expect it is possible to achieve a relatively high rock penetration with low frequency radio, however, the skin depth is relatively small at UHF frequencies.

3.2.2 Standard Waveguide Model

In general, electromagnetic waves are commonly of the form transverse electromagnetic (TEM), for example, electromagnetic signals propagating in wire and free-space radio propagation. Transverse meaning that it has it has electric and magnetic fields completely transverse to the direction of propagation. In electric circuits the signal relies upon there being a return carrier, or in free-space (or air) the radio signal is not bound by other medium. A waveguide however, is somewhat different. The waveguide is essentially a transmission medium that has both a boundary and a single transmission path (i.e. no return carrier). Only certain frequencies will propagate within this type of medium. Fibre optical cable, e.g. using multimode stepped transmission, is a good example of a waveguide, which allows electromagnetic wave propagation at extremely high frequencies i.e. light at 10^{16} Hz. The waveguide is dependent on a certain condition, in that only frequencies above the natural cut-off frequency, which is determined by the cross-sectional geometry, will propagate.

Electromagnetic waves will propagate in a number of modes that are either transverse electric TE or transverse magnetic TM. TE modes only have electric (E) fields transverse to the direction of propagation, and have magnetic (H) fields both longitudinal and transverse to the direction of propagation. TM modes are vice versa with H fields transverse only, and E fields transverse and longitudinal. Figure 3.4 below shows an ideal lossless rectangular waveguide, with perfectly conducting side walls and filled with a lossless dielectric material. The EM propagation is defined by Maxwell's vector wave equations (Sadiku, 2001).

$$\nabla^2 \mathbf{E}_s + k^2 \mathbf{E}_s = 0 \tag{3.5}$$

$$\nabla^2 \mathbf{H}_s + k^2 \mathbf{H}_s = 0 \tag{3.6}$$

Where $k = \varpi\sqrt{\mu\varepsilon}$. $\mathbf{E}_s$ and $\mathbf{H}_s$ are the vector components of the electric and magnetic field respectively. Subscript 's' denotes the equations are in phasor form.

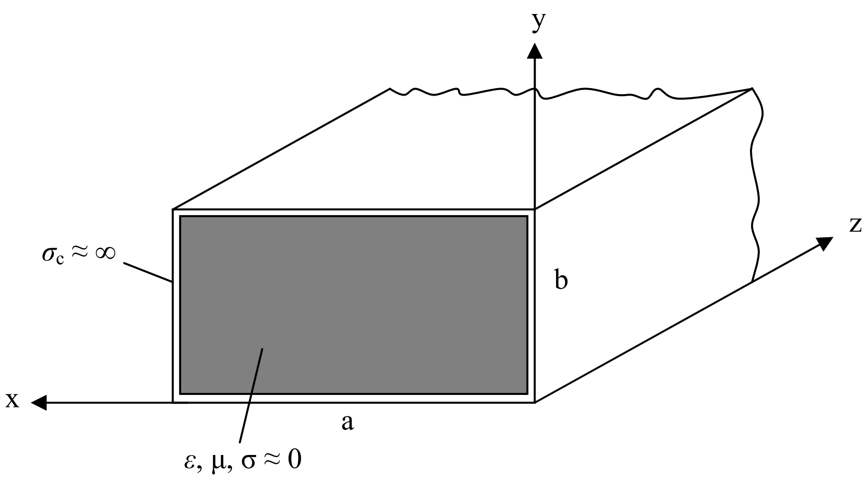


Figure 3.4: Ideal Rectangular Waveguide

Considering three conditions of the propagation constant, we recall from Equation 3.2 for a homogenous medium, which is defined by

$$\gamma = \alpha + j\beta .$$

Where α is the specific attenuation (or attenuation constant), expressed in Np m^{-1}, and β is the phase constant, expressed in rad m^{-1}.

1. *Cut-off Frequency*

The cut-off frequency, where $\gamma = 0$ or $\alpha = 0 = \beta$, is given by

$$f_{c,mn} = \frac{1}{2\sqrt{\mu_0 \varepsilon_0}} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \tag{3.7}$$

or,

$$f_{c,mn} = \frac{c}{2} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \tag{3.8}$$

Where c = 3 x 10^8 m s^{-1} is the speed of light, *a* and *b* are the horizontal and vertical dimensions respectively. The integer '*m*' refers to the number of half-cycle variations in the *x*-direction and the integer '*n*' refers to the number of half cycle variations in the *y*-direction. The lowest order modes in TE for (*m*, *n*) can be (0,1) or (1,0), but never (0,0), and for TM the lowest order mode for (*m*, *n*) is (1,1). The order of the modes increase with *m* and *n* to infinity (or up to the higher order modes cut-off frequency). The dominant mode is always the TE mode, and the lowest order mode.

2. *Evanescent*

Below the cut-off frequency the mode is 'evanescent' and propagation takes a skin depth type of behaviour. Where $\gamma = \alpha$ and $\beta = 0$. The specific attenuation is given by

$$\alpha = \frac{2\pi f_c}{c}\left(\sqrt{1 - \left(f / f_c\right)^2}\right) \tag{3.9}$$

and the skin depth is given by

$$\delta_{ev} = \lambda_c \Big/ \left(2\pi\sqrt{1 - \left(\lambda_c / \lambda\right)^2}\right) \tag{3.10}$$

3. *Propagation*

Above the critical cut-off frequency propagation occurs in the waveguide where the specific attenuation $\alpha = 0$ (assuming it is a perfect conductor) and $\gamma = j\beta$. Where the phase constant is given by:

$$\beta = \frac{2\pi f_c}{c}\left(\sqrt{(f/f_c)^2 - 1}\right) \tag{3.11}$$

The electric and magnetic field lines for the TE_{10} mode is shown below in Figure 3.5.

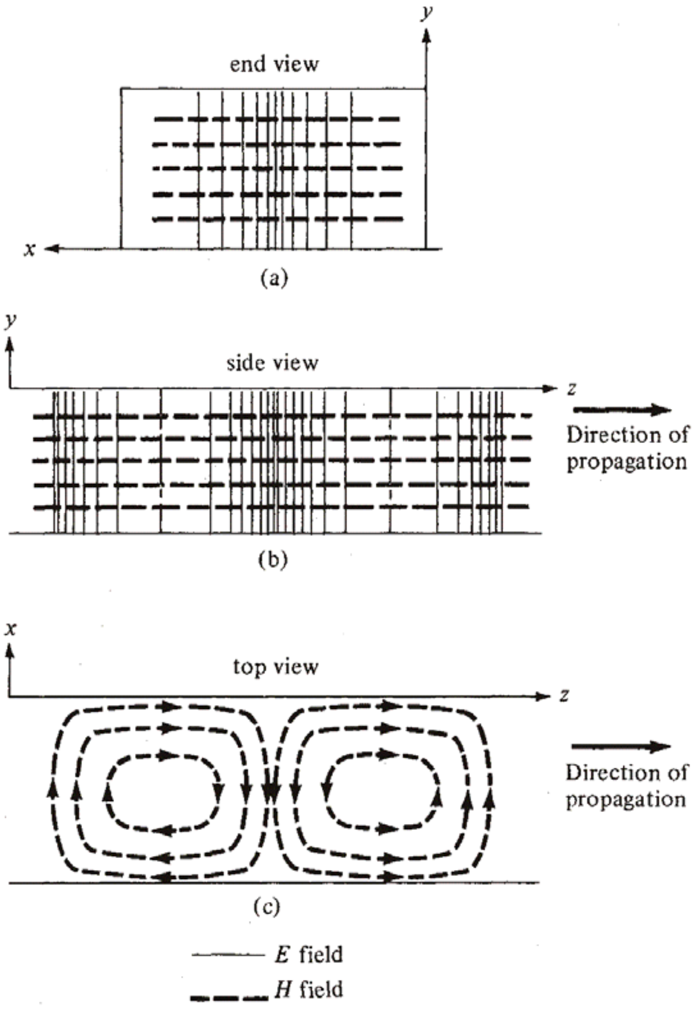


Figure 3.5: TE mode field lines

[*Source*: Sadiku (2001)]

From Maxwell's wave equations (Equations 3.5 and 3.6) each E and H field components can be obtained. The following equations are the field components for the TE mode in a rectangular waveguide (Sadiku, 2001).

$$E_x = \frac{j\varpi\mu}{h^2}\left(\frac{n\pi}{b}\right)H_0 \cos\left(\frac{m\pi x}{a}\right)\sin\left(\frac{n\pi y}{b}\right)e^{-\gamma z} \tag{3.12a}$$

$$E_y = \frac{j\varpi\mu}{h^2}\left(\frac{m\pi}{a}\right)H_0 \sin\left(\frac{m\pi x}{a}\right)\cos\left(\frac{nxy}{b}\right)e^{-\gamma z} \tag{3.12b}$$

$$E_z = 0 \tag{3.12c}$$

$$H_x = \frac{j\beta}{h^2}\left(\frac{m\pi}{a}\right)H_0 \sin\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right)e^{-\gamma z} \tag{3.12d}$$

$$H_y = \frac{j\beta}{h^2}\left(\frac{n\pi}{b}\right)H_0 \cos\left(\frac{m\pi x}{a}\right)\sin\left(\frac{n\pi y}{b}\right)e^{-\gamma z} \tag{3.12e}$$

$$H_z = H_0 \cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right)e^{-\gamma z} \tag{3.12f}$$

Where $h^2 = k_x^2 + k_y^2$, k_x *and* k_y are the wave numbers for the x and y direction components respectfully given by

$$k_x = \frac{m\pi}{a},\ k_y = \frac{n\pi}{b} \tag{3.13}$$

In practice the waveguide is not a perfect conductor, in that the walls are not perfectly conducting. For rectangular waveguides with dimensions a and b, the attenuation (Np m^{-1}) for the TE_{10} mode is given by

$$\alpha = \frac{2R_s}{b\eta'\sqrt{1-\left[\frac{f_c}{f}\right]^2}}\left(\frac{1}{2}+\frac{b}{a}\left[\frac{f_c}{f}\right]^2\right) \tag{3.14}$$

Where $\eta' = \sqrt{\mu/\varepsilon}$, and R_s is the real part of the intrinsic impedance η_c of the conducting wall given by

$$R_s \frac{1}{\sigma_c\delta} \tag{3.15}$$

The attenuation Np m^{-1} for all other TE_{mn} modes ($n \neq 0$) can be expressed as

$$\alpha = \frac{2R_s}{b\eta'\sqrt{1-\left[\frac{f_c}{f}\right]^2}} = \left[\left(1+\frac{b}{a}\right)\left[\frac{f_c}{f}\right]^2 + \frac{\frac{b}{a}\left(\frac{b}{a}m^2+n^2\right)}{\frac{b^2}{a^2}m^2+n^2}\left(1-\left[\frac{f_c}{f}\right]^2\right)\right] \tag{3.16}$$

For all TM modes the attenuation, in Np m^{-1}, is expressed as

$$\alpha = \frac{2R_s}{b\eta'\sqrt{1-\left[\frac{f_c}{f}\right]^2}} \frac{(b/a)^3 m^2 + n^2}{(b/a)^2 m^2 + n^2} \tag{3.17}$$

Thus far, consideration has solely been given to rectangular waveguide; another common shape is that of a circular waveguide structure, which can provide a useful approximation in certain situations. For the purpose of this thesis most of the later tests and results better compare with the rectangular waveguide model, given the approximate geometry of the tunnels. However, for reference the key circular waveguide model equations are stated below.

The cut-off frequency of a circular tunnel is defined by

$$f_{cmn} = \begin{cases} cx_{mn}/2r; & \text{TM modes} \\ cx'_{mn}/2r; & \text{TE modes} \end{cases} \tag{3.18}$$

Where r is the circular cross-section radius, x_{mn} and x'_{mn} are the *n*th zero of the *m*th order of the Bessel function and its derivative respectfully.

The specific attenuation for TE modes is given by

$$\alpha = \frac{R_s}{r\eta'}\left(\frac{m^2}{\chi'^2_{mn} - m^2} + \left[\frac{f_c}{f}\right]^2\right)\frac{1}{\sqrt{1-\left[\frac{f_c}{f}\right]^2}} \tag{3.19}$$

and for the specific attenuation for the TM modes is given by

$$\alpha = \frac{R_s}{r\eta'} \frac{1}{\sqrt{1-\left[\frac{f_c}{f}\right]^2}} \tag{3.20}$$

Deryck (1978) carried out some measurements in both a circular and a rectangular tunnel and compared them with specific attenuation calculations from the standard waveguide model. Figure 3.6 below show the results from Lanaye tunnel in Belgium, which is a circular tunnel of approximately 5 to 6 m in height and 4 to 5 m in width. Compared with a circular waveguide of radius 2.5 m it has a cut-off frequency of 35 MHz. Curve 2 shows the theoretical attenuation of a perfectly conducting waveguide below the cut-off. Line 1 shows the attenuation of through-rock propagation. The solid line curves, above the cut-off, show the theoretical attenuation for different modes in vertical polarisation, and the dashed lines are horizontal polarisation. Deryck's results have shown the theory has relatively good agreement with the measurements, marked 'x'. The TE_{01} is clearly the dominant mode, and attenuation seems to steadily decrease with frequency. This is a unique property of TE_{01} modes in perfectly conducting circular waveguides; however it is this trend is not likely to continue into the higher frequencies when you consider it is not perfectly conducting nor circular (Delogne, 1982).

Similar measurements were also carried out by the same author (Deryck, 1978) in a rectangular tunnel of cross sectional dimensions 4.9 by 17 m. Figure 3.7 below shows the measured results versus the calculated specific attenuation. The circles and solid lines are vertical polarisation for the measure and theoretical results respectfully, and the crosses and dashed lines are for the measured and calculated horizontal polarisation respectively. The results show that the dominant TE_{10} mode, with a cut-off frequency of 8.8MHz, has vertical polarisation, and again, the TE_{01} mode, with a cut-off frequency of 30.6MHz, has horizontal polarisation. However, it can also be seen that both the vertical and horizontal polarisation are not exclusively coupled to the TE_{10} and TE_{01} mode respectfully. In fact the horizontal polarisation has low attenuation below the TE_{01} cut-off frequency (30.6 MHz), and it can also be seen the TE_{10} mode only remains dominant up to around 200MHz. Therefore it can be shown that while the standard model for a perfect, or good conductive, waveguide can provide a degree of accuracy in comparison to tunnel propagation, it clearly has limitations (Delonge 1982). The are many other aspects to consider, such as the fact the tunnel walls are not good conductors, tunnel walls are generally rough, and antennas do not couple efficiently to the waveguide modes. This will be considered in the next section.

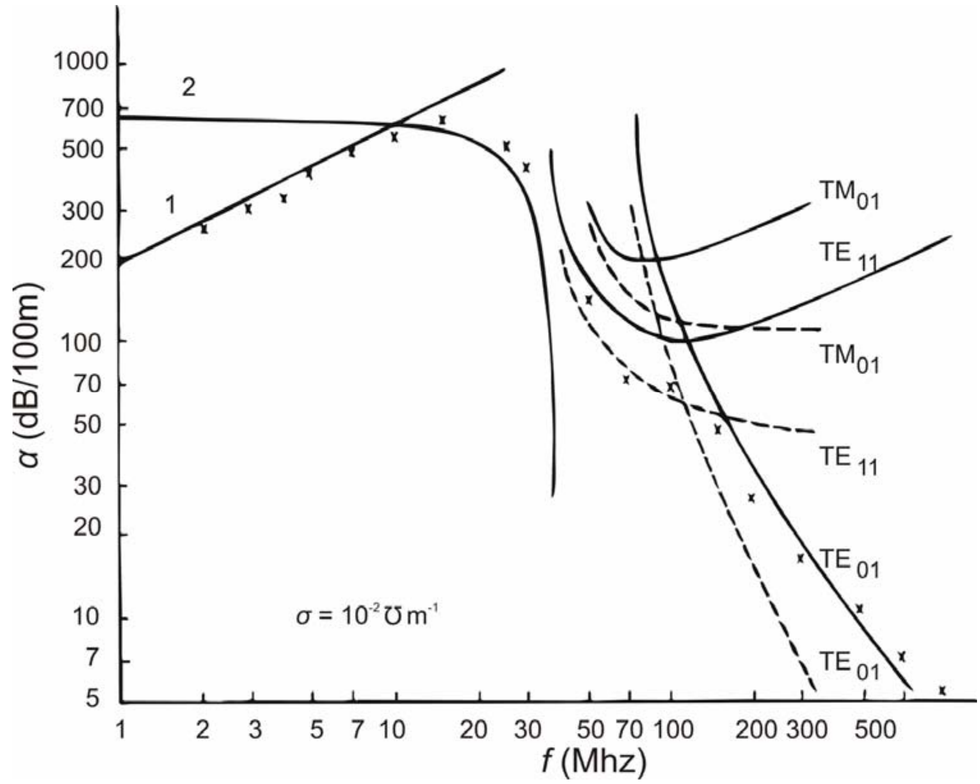


Figure 3.6: Calculated vs. measured specific attenuation in a circular tunnel

[*Source*: Deryck (1978)]

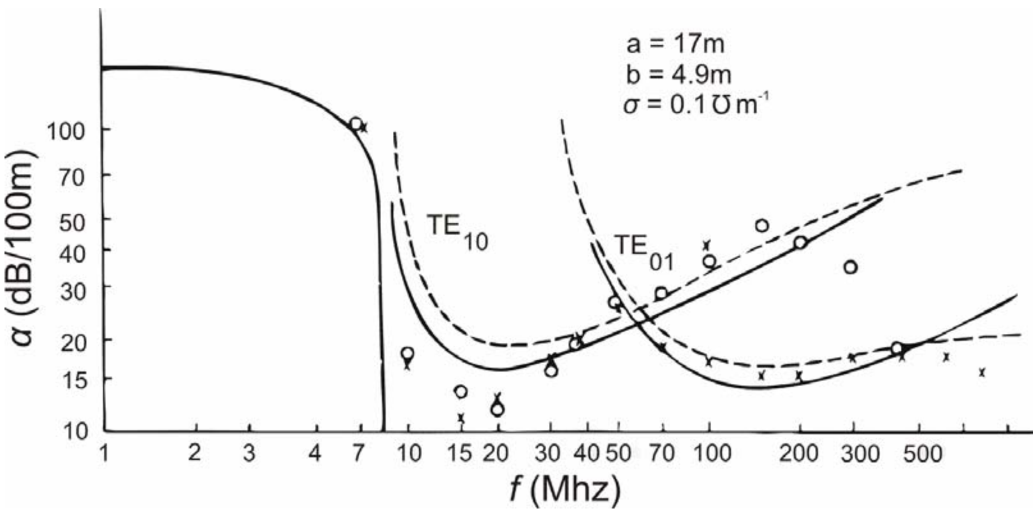


Figure 3.7: Calculated vs. measured specific attenuation in a rectangular tunnel

[*Source*: Deryck (1978)]

3.2.3 Tunnel Propagation Model

3.2.3.1 Lossy Dielectric Waveguide

Tunnels will take the form of a waveguide above a certain cut-off frequency which can be derived from the standard waveguide models and the cross-section dimensions, as shown in the last section. However, standard waveguide models derived for conductive metallic waveguides are somewhat limited. A modified model for a tunnel waveguide is shown below in Figure 3.8. In a tunnel situation, the tunnel wall thickness is very much greater than the skin depth. In fact the tunnel behaves more as a lossy dielectric waveguide, rather than a conductive waveguide (Mahmoud and Wait 1974, Emslie *et al.* 1975). The relative permittivity of the horizontal and vertical walls is denoted by ε_r(h) and ε_r(v) respectfully. In most cases rock has a relative permittivity (dielectric constant) in the range 5 – 10, in some situations the value can vary between the vertical side walls and the horizontal (top and bottom) walls in a tunnel (Emslie, 1975).

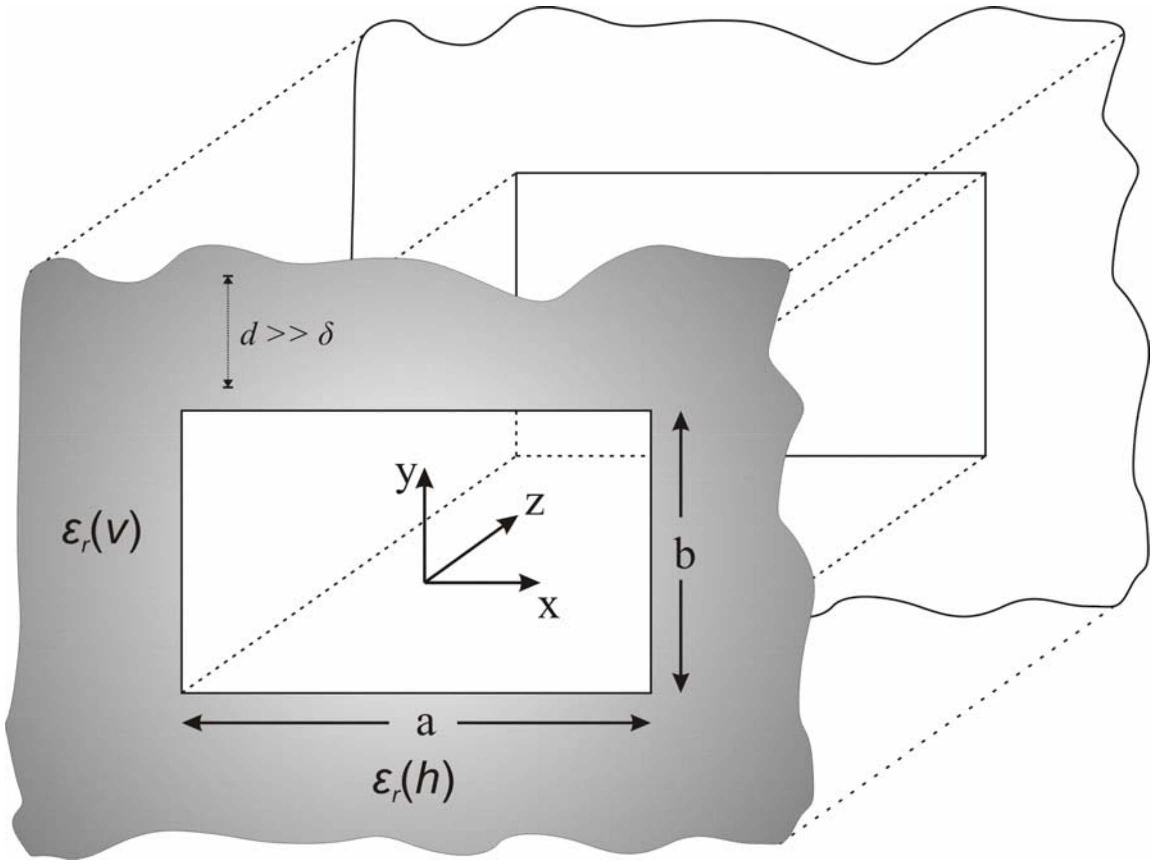


Figure 3.8: Rectangular tunnel waveguide model

Given that the waveguide is not a perfect conductor, and in fact, it has four lossy dielectric walls the field components derived from Maxwell's vector wave equations (Equations 3.5 and 3.6) need to change. As we are now dealing with four imperfectly conducting walls, the standard TE and TM modes no longer apply, we now have to consider $E^{(v)}$ and $E^{(h)}$ modes. These modes are hybrid TE and TM, which have electric components in either the vertical direction, $E^{(v)}$, or the horizontal direction, $E^{(h)}$. Based on Emslie *et al* (1975), Mahmoud and Wait (1974) and Delogne (1982), the field components for a lossy dielectric, first of all the $E^{(h)}$, horizontal components, can be written in the form

$$E_x = E_0 \cos\left[k_x\left(x-\frac{a}{2}\right)\right]\cos\left[k_y\left(y-\frac{b}{2}\right)\right]e^{-\gamma z} \tag{3.21a}$$

$$E_y = 0 \tag{3.21b}$$

$$E_z = \frac{k_x}{\gamma} E_0 \sin\left[k_x\left(x-\frac{a}{2}\right)\right]\cos\left[k_y\left(y-\frac{b}{2}\right)\right]e^{-\gamma z} \tag{3.21c}$$

$$H_x = \frac{jk_x k_y}{\varpi\mu_0\gamma} E_0 \sin\left[k_x\left(x-\frac{a}{2}\right)\right]\sin\left[k_y\left(y-\frac{b}{2}\right)\right]e^{-\gamma z} \tag{3.21d}$$

$$H_y = \frac{j(k_x^2-\gamma^2)}{\varpi\mu_0\gamma} E_0 \cos\left[k_x\left(x-\frac{a}{2}\right)\right]\cos\left[k_y\left(y-\frac{b}{2}\right)\right]e^{-\gamma z} \tag{3.21e}$$

$$H_z = \frac{jk_x}{\varpi\mu_0} E_0 \cos\left[k_x\left(x-\frac{a}{2}\right)\right]\sin\left[k_y\left(y-\frac{b}{2}\right)\right]e^{-\gamma z} \tag{3.21f}$$

Where k_x and k_y are the coordinate wave numbers given by (3.13), and the relation

$$k_x^2 + k_y^2 - \gamma^2 = k_0^2 \tag{3.22}$$

must be satisfied. From these field components, the following important equations can be derived for the $E_{mn}^{(h)}$ mode.

$$\gamma_{mn}^{(h)} = \alpha_{mn}^{(h)} + j\beta_{mn}^{(h)} \tag{3.23}$$

$$\alpha_{mn}^{(h)} \approx \frac{2(m+1)^2\pi^2}{k_0^2a^2}\mathrm{Re}\frac{\varepsilon'^{(v)}_r}{\sqrt{\varepsilon'^{(v)}_r-1}} + \frac{2(n+1)^2\pi^2}{k_0^2b^2}\mathrm{Re}\frac{1}{\sqrt{\varepsilon'^{(h)}_r-1}} \tag{3.24}$$

$$\beta_{mn}^{(h)} \approx \sqrt{k_0^2 - \left[\frac{(m+1)\pi}{a}\right]^2 - \left[\frac{(n+1)\pi}{b}\right]^2} \tag{3.25}$$

From Equation 3.24, we can derive an approximation for attenuation of the $E_{mn}^{(h)}$ modes (in Np m^{-1}) as

$$\alpha_{mn}^{(h)} = \frac{\lambda^2}{2}\left(\frac{\varepsilon_r^{(h)}(m+1))^2}{a^3\sqrt{\varepsilon_r^{(h)}-1}} + \frac{(n+1)^2}{b^3\sqrt{\varepsilon_r^{(v)}-1}}\right) \tag{3.26}$$

Due to the fact the tunnel is symmetrical, we can obtain the $E_{mn}^{(v)}$ modes by interchanging the x and y axis. Therefore, the approximation for the $E_{mn}^{(v)}$ mode attenuation is given by

$$\alpha_{mn}^{(v)} = \frac{\lambda^2}{2}\left(\frac{(m+1))^2}{a^3\sqrt{\varepsilon_r^{(h)}-1}} + \frac{\varepsilon_r^{(v)}(n+1)^2}{b^3\sqrt{\varepsilon_r^{(v)}-1}}\right) \tag{3.27}$$

These equations are based on Emslie *et al* (1975) and Delogne (1982). It was found that the similar expressions in both Emslie and Delogne completely contradicted one another. It had to be assumed there was a misprint in Delogne. Another discrepancy between the authors was that Emslie assumes indices *m* and *n* begin at unity, where in fact Delogne assumes they start at zero. The differences between the authors are purely academic as in both instances the attenuation calculated for the lowest order mode is exactly the same in each paper.

3.2.3.2 Additional Loss Characteristics

In the previous section, the model for a lossy dielectric rectangular wave model was discussed, and the specific attenuation in terms of the propagation modes was identified in Equations 3.26 and 3.27. However, there are other loss factors to take into consideration that will attenuate the electromagnetic propagation in terms of tunnel roughness, tilt, antenna coupling, scattering at junctions, and probably the most severe, tunnel bends.

Wall Imperfections

Given that tunnel walls are not smooth consistent waveguide structures, we have to consider losses introduced by the tunnel walls themselves. Mahmoud and Wait (1974) describes attenuation due to tunnel roughness as an increasing function of frequency. Emslie *et al* (1975) takes a different approach, characterising separate variables wall roughness and wall tilt in terms of scattering of the $E^{(h)}$ mode into other modes generating the 'diffuse' component. Emslie deduces that attenuation due to roughness is a decreasing function with frequency and tilt loss is an increasing function with frequency. As Davis *et al.* (1983) points out, ultimately the two authors reach the same conclusions.

The roughness of each tunnel wall with regard to the relative mine surface level will cause attenuation of the propagating signal. Emslie *et al*. (1975) characterises loss due to roughness as follows

$$L_{roughness} = \frac{\pi^2 h^2 \lambda}{2}\left(\frac{1}{a^4}+\frac{1}{b^4}\right) \text{ Np m}^{-1} \tag{3.28}$$

Where h is the root mean square (RMS) roughness of the walls

The tilt of the tunnel walls will also give rise to signal loss. The loss rate in dB is given by the following equation.

$$L_{tilt} = \frac{\pi^2 \theta^2 z}{2\lambda} \quad \text{Np m}^{-1} \tag{3.29}$$

Where θ is the RMS tilt in radians.

It is recognised that the above expressions for roughness and tilt loss are limited. A recent study by Ndoh and Delisle (2003) presents a much more detailed approach to predicting the diffracting effects of tunnel roughness through numerical modelling, using a method called the cascade impedance method approach (CIM). However, for the purposes of this work we are mainly concerned with rough approximations, given the wide array of parameters and complexity of modelling subsurface underground propagation.

Antenna Coupling Loss

In portable radio devices, antennas such as dipoles or whips tend to be common. However, these types of antennas tend to have inefficient coupling to the waveguide mode. Delogne (1982) derives the coupling loss at a point coordinates (x, y, 0)

$$\frac{Pmn}{P_x} = \frac{2\pi ab}{\lambda_0^2 G}\sin^{-2}\frac{(m+1)\pi x}{a}\sin^{-2}\frac{(n+1)\pi y}{b} \tag{3.30}$$

Which is the ratio between the mode power P_{mn} and the received power P_x. λ_0 is the wavelength in free space. G is the antenna gain given by

$$G = \frac{4\pi}{\lambda_0^2} A_e \tag{3.31}$$

Where A_e is the antenna effective area.

Dispersion

Radio signals are affected by multipath, which is where multiple signals originating from the same source follow different paths by reflecting off various objects, in or around buildings etc. This is known as delay spread or multipath dispersion. The delay between multiple signals following different paths causes the signals from a previous bit/symbol to interfere with the next. This is known as intersymbol interference (ISI). Diversity and equalisation are techniques used to overcome the effect of multipath.

It seems somewhat of a paradox to be considering both multipath and waveguide propagation together, where the whole mechanism for achieving waveguide propagation is through reflecting signals. However, we are not talking about carefully designed perfect waveguide structures, as tunnels are large imperfect and inconsistent waveguides. A study by Nikitin *et al.* (2002), carried out as part of research at Carnegie Mellon investigating HVAC duct waveguide wireless communication, describes attenuation in a non-perfect waveguide due to dispersion. There are three types of dispersion to consider: ‘multipath dispersion’ due to non-uniformities (objects, varying shapes in geometry, bends, junctions etc), ‘intermodal dispersion’ due to the fact that different modes travel at different velocities essentially causing standing waves, and ‘intramodal dispersion’ due to fact that velocities of spectral components of each mode are frequency-dependent. The diagram Figure 3.9 below illustrates these effects. As we are mainly concerned with narrowband applications multipath and intermodal dispersion will have the most significant impact in tunnel propagation. This suggests that there is significant merit in employing diversity techniques as a means of mitigating these effects.

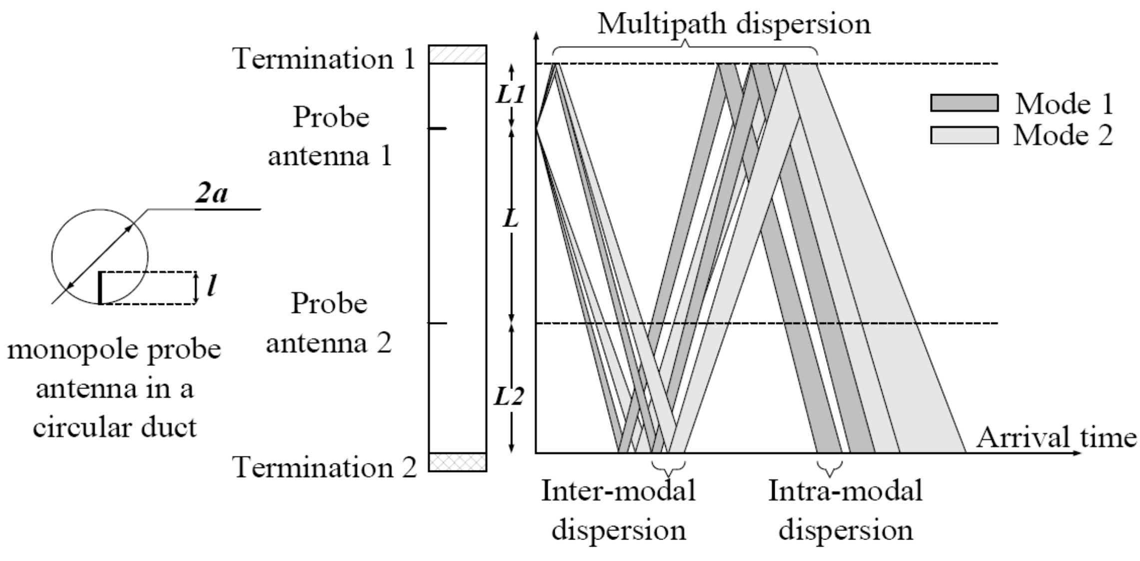


Figure 3.9: Dispersion in a waveguide structure with two modes

[*Source*: Nikitin *et al.* (2002)]

Lienard and Degauque (2000) conducted a number of trials to measure the delay spread (multipath dispersion) effects in a room and pillar mine. The average delay spread ranges from 5 ns (nanoseconds) in a mine gallery, 19 ns for line of sight transmission in room and pillars, to 42 ns for non line of sight in room pillars.

Corners and Junctions

At these frequencies, attenuation in general around corners is relatively severe, and tends to increase with increasing frequencies. Accurately modelling or predicting bend propagation is highly complex and beyond the scope of this research. It is generally widely accepted that radio coverage at these higher frequencies is not attainable around corners and that the use of either a repeater or a leaky feeder system is required. However, it is useful to know whether a degree of non line-of-sight propagation (non LOS) can be achieved. This topic has been given limited coverage compared with straight tunnel propagation. Emslie *et al.* (1975) look at bend attenuation and scattering loss at tunnel intersections in terms of the diffuse component, or scattering loss, from the dominate low order $E^{(h)}$ mode. He predicts that a single bend will add an additional loss of around 70 – 80 dB in the particular tunnel under consideration at frequencies in the range of 1 to 4 GHz. Given the complexity in attempting to theoretically investigate this effect further, it was decided to investigate bend attenuation and scattering loss experimentally. This is covered in the next section.

3.2.4 Previous Experimental Work

The report by Legace *et al.* (1975) is an extensive investigation into radio wave propagation within coal mines from LF to UHF. Experimental work at UHF radio was conducted to look at the applicability of the theoretical approximations derived in Emslie *et al.* (1975). The general findings were that the approximations derived for refraction loss can be practically applied to most cross-sections of tunnel. However for narrow impractical tunnels, e.g. around 4 feet (1.22m) wide or when a train leaves a train-to-wall clearance of 2 feet (0.61m), the attenuation becomes significantly large. The report also includes investigations into the losses caused by haulage vehicles at UHF and radio propagation down longwall faces at UHF.

A report by Davis *et al.* (1983) contains details of experiments conducted to investigate tunnel-guided propagation of frequencies of the range 430 MHz to 24 GHz. The experiments were conducted in a ‘clean’ tunnel and a typical mine roadway. The main findings were that the higher frequencies had a much better transmission range as attenuation decreased with increasing frequency, until around 10 GHz where attenuation increases again. However, this is restricted to more line-of-sight communications. The experimental data collected from transmitting around a sharp bend found that the effects were very severe. At high frequencies there was virtually no propagation and at the lower frequencies there was slight propagation. In all cases the attenuation was found to be in excess of 30 dB/m.

Reuters (1982) contains detailed measurements of radio propagation in tunnels from 0.4 to 10 GHz. The general findings were that at 0.4 Ghz the propagation was not feasible, however longitudinal attenuation decreases with increasing frequency. The presence of water dampens the signals and bends/corners cause significant attenuation. The UHF propagation experimental work of Goddard (1973) again supports that transmission loss decreases at a given distance as frequency increases, and significant attenuation occurs around corners.

More recent studies by Djadel *et al.* (2002), looking at narrowband propagation at 2.45 and 18 GHz underground, and Zhang *et al.* (2001), looking into radio propagation at 900 MHz in coal mines, recognise two distinct areas of propagation. This separated by a critical point, or breakpoint, at certain distance from the transmitter. Propagation losses were observed to be significantly lower after this point than before. However neither author really offers an explanation to why this occurs.

Zhang (2001), which is a follow on of the work by Zhang and Hwang (1998), also gives detailed measurements of additional losses due to bends and equipment, e.g. shearer (5-10dB), trolleys (10-13dB), 90° bend (25dB).

Chufo and Isberg (1978) propose the use of passive reflectors to extend UHF coverage in a mine. Using a combination of distributed and passive reflectors is a possible method of achieving mine wide coverage.

The work of Davis *et al.* (1983) went onto to carry out an extensive examination into the use of a microwave repeater communication system for underground rescue operations. It discusses that passive repeater techniques are not the most practical solution, suggesting that in order to achieve full mine coverage active 'repeaters' would need to be introduced at corners and other obstacles. However, it was found that the repeaters introduce an additional 'coupling loss', and in general coupling loss increases with frequency. The report goes onto suggest that pulse-code or quantized modulation, in conjunction with a repeater that could regenerate the modulated signal would be the optimal solution, allowing virtually any number of repeaters to be introduced.

3.3 Wireless Propagation Tests

3.3.1 Overview

A range of wireless tunnel propagation tests have been carried out at in three different locations. A disused railway, a hard rock test mine, and a coal mine test facility. The following sets of wireless tunnel propagation tests were performed:

- 2.3GHz[1] continuous wave (CW) transmission using different onmi-directional and directional patch antennas
- 5.8GHz CW transmission using an omni directional antenna
- Wireless networking technology throughput vs. distance tests including: WiFi (802.11b, 802.11g, 'SuperG', 'Pre-N' and Draft-N) and Bluetooth

Full details of the test locations, equipment and procedures are given in the following sections.

3.3.2 Equipment

2.3GHz[1] Continuous Wave (CW) Transmission Test Equipment:

- 2.3209GHz[1] CW Transmitter from Kuhne Electronic GmbH

Figure 3.10: 2.3209GHz CW beacon

- 2.4GHz Antennas: (Netgear) 18dBi directional patch, 9dBi omni-directional, 5dBi directional-patch (all antennas used in the vertically polarised position)

[1] 2.3GHz was selected due to equipment availability. The intention of these particular tests is to investigate the performance of ISM band 2.4GHz related wireless networking technology. It was decided that behaviour differences between 2.3GHz and 2.4GHz would be negligible.

Figure 3.11: 2.4GHz Antennas

- Willtek 9102 hand-held spectrum analyser (100kHz – 4GHz Frequency Range)

Figure 3.12: Willtek 9102 Hand-held Spectrum Analyser

5.8GHz Continuous Wave (CW) Transmission Test Equipment:

- 5.802GHz, 150mW (22dBm) CW beacon from Kuhne Electronic GmbH

Figure 3.13: 5.802GHz CW beacon

- Willtek 9102 hand-held spectrum analyser
- 5.8GHz Antennas: (NET-WL-ANT58-11ON) 11dBi omni-directional (used in the vertically polarised position)

Figure 3.14: 5.8GHz Antenna

- Avcom MFC-5060-17/65 5GHz – 6GHz frequency converter to extend frequency coverage of Willtek 9102

Figure 3.15: Avcom MFC-5060-17/65 5GHz – 6GHz Frequency Converter

Wireless Network Throuphput Test Equipment:

- Throughput Test Software

Iperf, a freeware TCP-based data throughput measurement and network tuning utility from the US National Laboratory for Applied Network Research (http://dast.nlanr.net), was used for recording data throughput. Iperf was used as a server on the stationary receiving PC and as a client on the mobile transmitting PC.

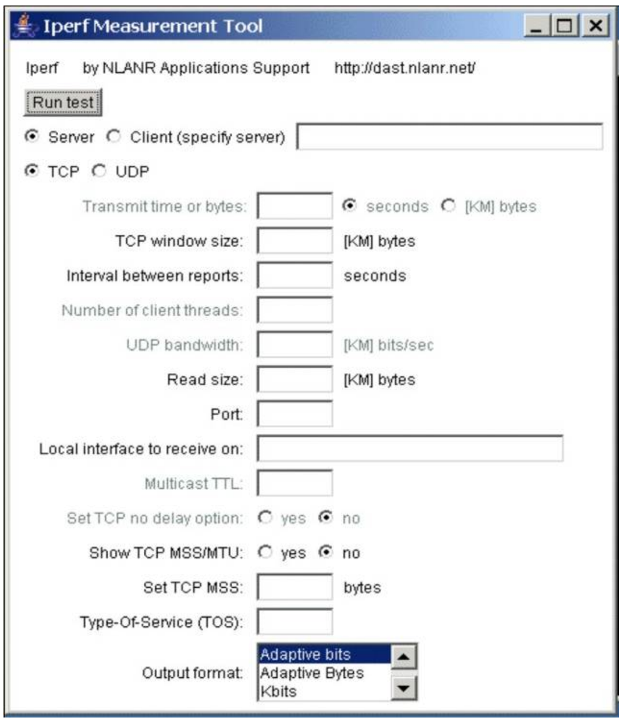


Figure 3.16: Iperf Network Performance Measurement Software

- Wireless network testing transmit equipment
    - A laptop PC operating under Windows XP
    - One of the following PC wireless adapters
        - Linksys WPC11 (IEEE 802.11b)
        - Linksys WPC54G (IEEE 802.11g)
        - Netgear WPN511 (SuperG Rangemax, used with both SuperG APs)
        - Belkin F5D8010 (Pre-N, MIMO)
        - Netgear WN511B (Draft-N, MIMO)
        - Linksys USBBT100 (Bluetooth)

- Wireless network testing receive equipment
    - A laptop PC operating under Windows XP
    - One of the following access points (AP)
        - Linksys WAP11 (IEEE 802.11b)
        - Linksys WAP54G (IEEE 802.11g)
        - Netgear DG834GT (108Mbps SuperG)
        - Netgear WPN824 (108Mbps SuperG with BeamFlex adaptive antennas)
        - Belkin F5D8010 (Pre-N, MIMO)
        - Netgear DG834N (Draft-N, MIMO)
        - Linksys USBBT100 Bluetooth adapter (Bluetooth adapter used as RX also)

3.3.3 Test Locations

3.3.3.1 Railway Tunnel

The first set of tests was carried out in a disused railway tunnel in Ashbourne, Derbyshire (Figure 3.17). The tunnel formerly carried the Ashbourne-Buxton Railway but now carries the Tissington Trail footpath. The tunnel is 350 metres long, approximately 8 metres wide at its widest point, 7 metres wide at its base, and approximately 6 metres tall. It is perfectly straight. The tunnel contains a small amount of electrical cabling for lighting and other purposes.

Figure 3.17: Ashbourne Railway Tunnel

3.3.3.2 Hard Rock Test Mine

The hard rock test mine operated by Camborne School of Mines (Figure 3.18), located in Troon, near Camborne in Cornwall, is used for training and research purposes. It is a hard rock test facility, mined into granite rock. The facility, formerly owned by the Holmans Company for drill equipment testing, has a useful array of tunnels of varying size and shape. The atmosphere is free from dangerous gasses. The Test Mine has been extensively used throughout this research project given the convenience of accessibility and the relatively safe working environment, compared with an operational mine.

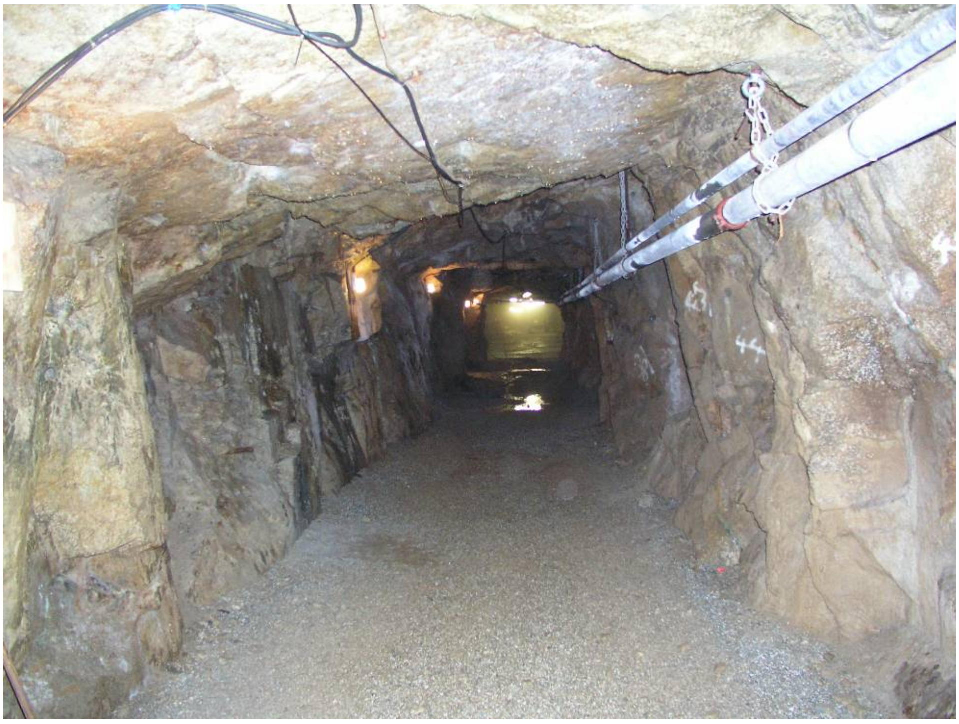


Figure 3.18: CSM Hard Rock Test Mine

3.3.3.3 Coal Mine Test Facility

Maschinenübungszentrum (MÜZ), in Recklinghausen, Germany, is a replica coal mine owned and administered by DSK. The surface facility is built into a coal mine waste heap (tailings) and completely fitted with German colliery equipment. The facility is lined with steel circular roof supports, has various machinery, pipes and cable work and is typical of a European coal mine. It has two replica coal faces; a longwall face and a plough face. MÜZ is used by DSK for training staff in health and safety, maintenance practices training, and research. The main advantage of the MÜZ replica coal mine facility was that it provides a safe working environment where training / research can be conducted without disrupting any 'real' mining operations. The facility provided an easily accessible and non-regulated typical coal mine environment to conduct the wireless equipment trials. Figure 3.19 below shows a typical roadway at the MÜZ facility.

Figure 3.19: Maschinenübungszentrum (MÜZ) Test Mine Facility

3.3.4 Test Procedure

3.3.4.1 Continuous Wave

The basic set-up for the continuous wave transmission tests involved having the 'receive equipment' (spectrum analyser etc) in a fixed location, with 'transmit equipment' moved at regular distances away along the tunnels. Both receive and transmit antennas were kept as close to the centre of the tunnels as possible, unless otherwise stated in the results. The signal strength was then recorded at each pre-survey distance point all the tunnel range tests. Full details of each test are given in the results.

3.3.4.2 Wireless Technologies

The basic procedure for conducting the wireless technology tests involved a stationary laptop (Iperf Server) physically connected through a cable to one of the wireless access points (or adapter in the case of the Bluetooth test). A second laptop with the wireless adapter, matching the associated AP, would be set to run as an Iperf client (transmitting data). Figure 3.20, below, shows the equipment set-up. The mobile laptop was moved at regular intervals in pre-determined distance steps (e.g. 10m) away from the stationary server equipment. The average throughput data over a fixed amount of time was then recorded at each distance point. All equipment was kept as close to the centre of the tunnel as possible, unless otherwise stated.

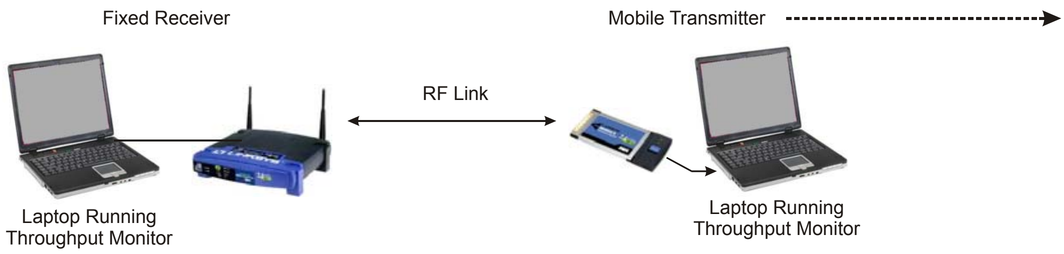


Figure 3.20: Wireless technology test procedure

3.3.5 Railway Tunnel Results

These tests were carried out over a distance of 250m. The receive equipment (spectrum analyser for the CW tests or laptop server and AP for the wireless technology tests) was located at the 0m datum point. The transmission equipment was then moved in steps of 10m up to 250m taking the measurements at each interval. Unless specifically stated, all transmit (TX) and receive (RX) equipment was situated in the centre, or as close as possible, to the tunnel cross section.

3.3.5.1 2.3GHz CW Transmission

Figure 3.21, below, shows the result obtained for 2.3GHz continuous wave transmission using the 18dBi patch directional, 9dBi omni directional and 5dBi patch antenna. Identical antennas were used in for RX and TX. Figure 3.22, below, compares the transmitting 5dBi antenna located along the centre and along each side of the tunnel.

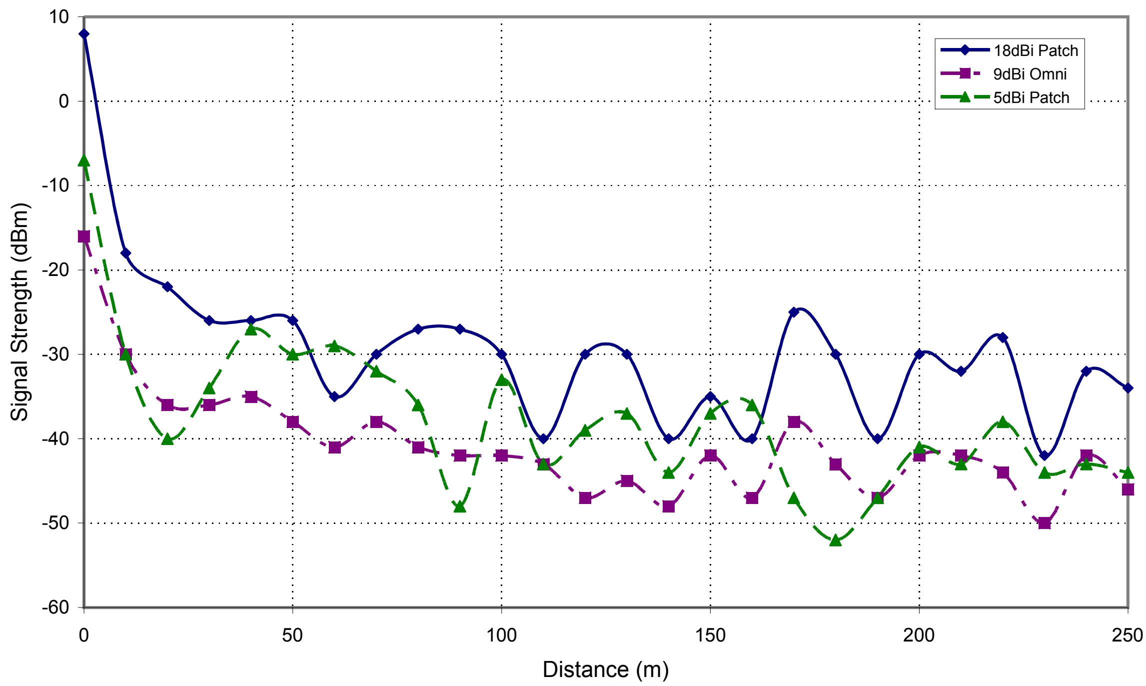


Figure 3.21: Ashbourne 2.3GHz signal strength vs. distance (Centre)

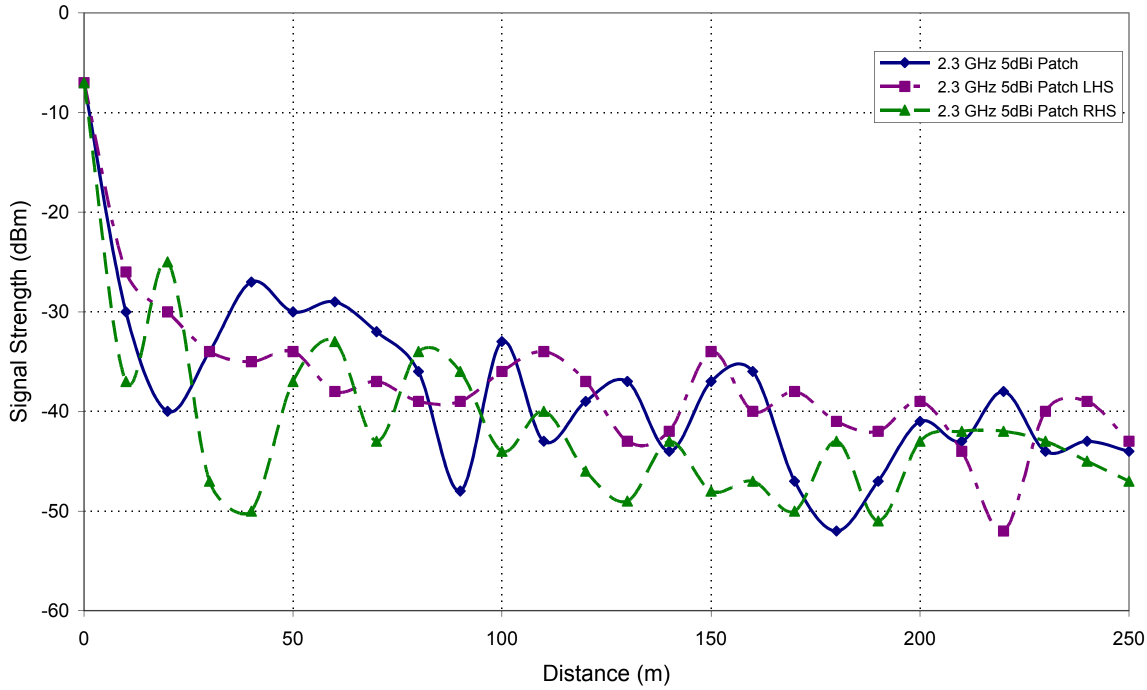


Figure 3.22: Ashbourne 2.3GHz 5dBi Patch - signal strength vs. distance (Centre, Left, Right)

3.3.5.2 5.8GHz CW Transmission

Figure 3.23, below, shows similar results obtained using 5.8GHz CW transmission and an 11dBi omni-directional antenna. Figure 3.24 compares 2.3GHz and 5.8GHz transmission.

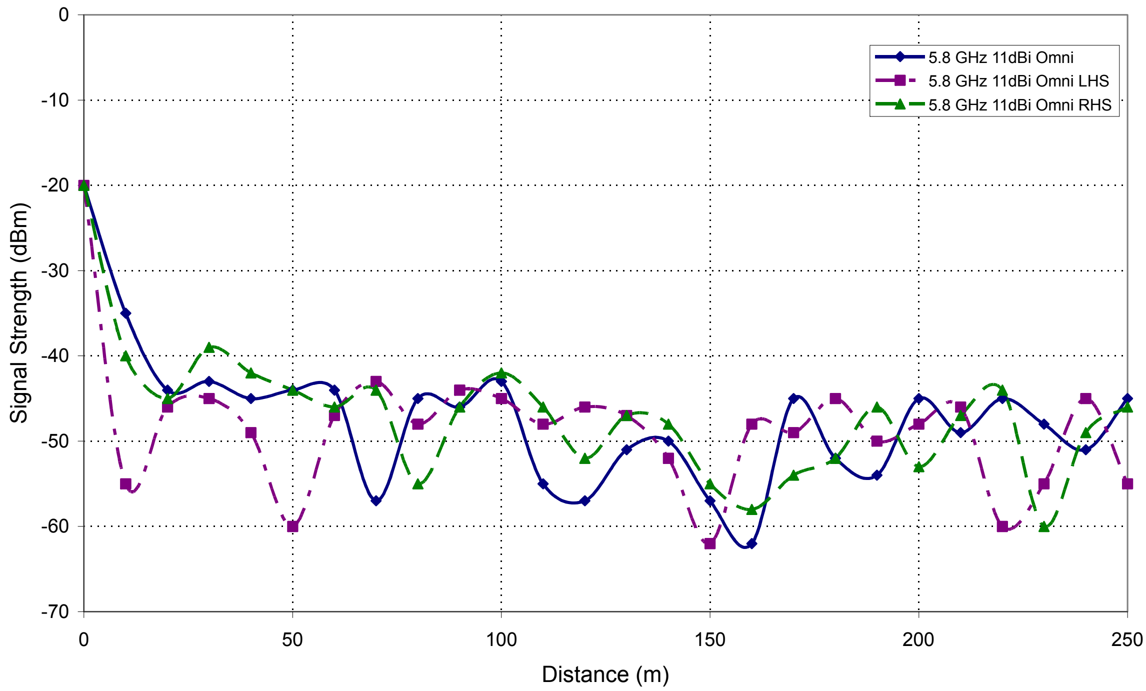


Figure 3.23: Ashbourne 5.8GHz 11dBi omni - signal strength vs. distance (Centre, Left, Right)

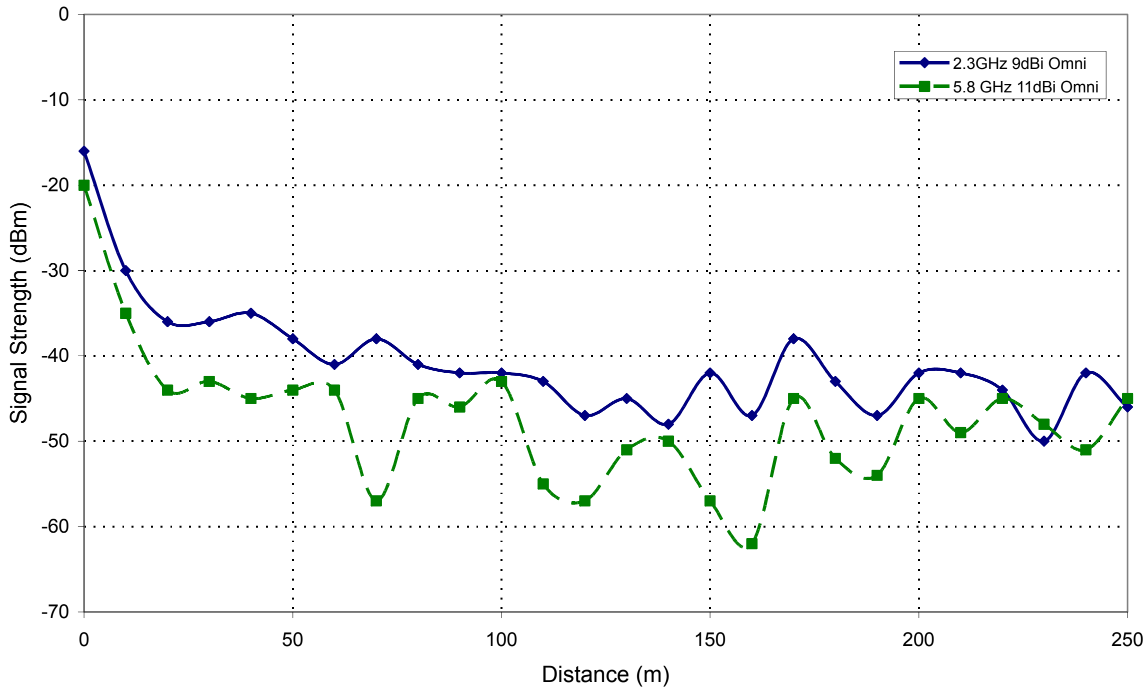


Figure 3.24: Ashbourne 2.3GHz (9dBi omni) and 5.8GHz (11dBi omni) Comparison

3.3.5.3 Wireless Technologies Throughput Tests

Full detailed graphs of the wireless technology tests are given in Appendix A.2. Figure 3.25, below, shows a summary of the throughput versus distance tests for each technology.

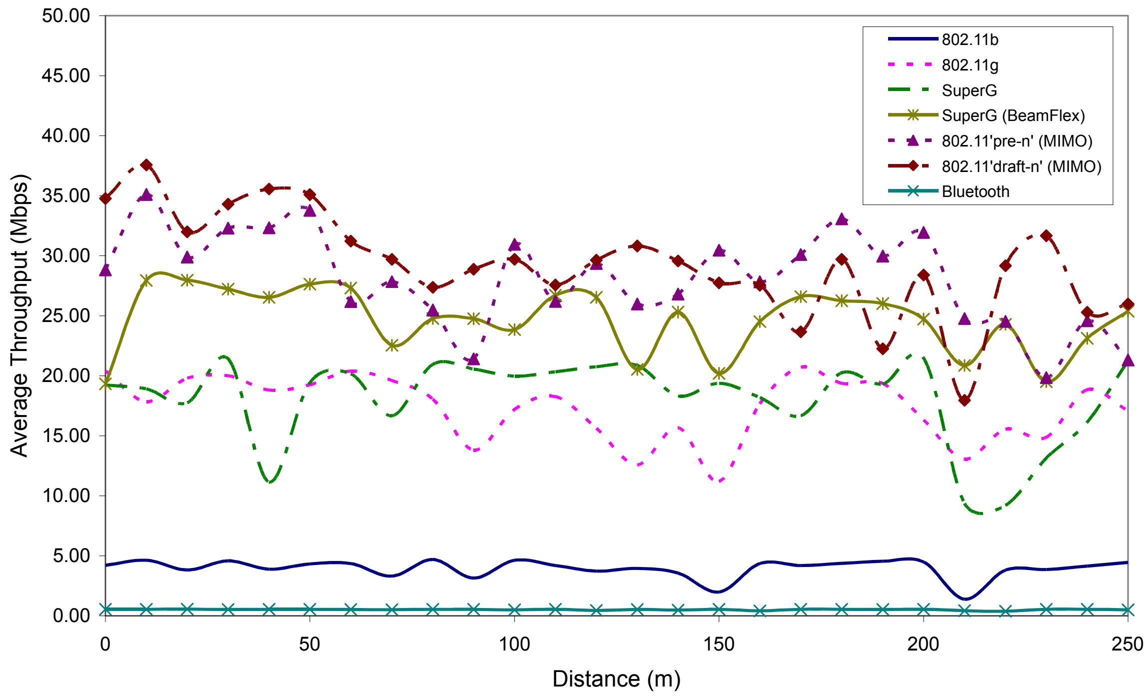


Figure 3.25: Ashbourne WiFi Test Summary

3.3.6 Hard Rock Test Mine Results

A plan of the CSM Test Mine and the various test locations used is shown in Figure 3.26. The tests were carried out using the same format as in the previous test, where the receive (RX) equipment was kept at a particular station point (or datum), as indicated on the plan. The transmit (TX) equipment was moved at regular intervals. Unless otherwise stated, these were 10m steps with the TX antenna kept as close to the centre of the tunnel as possible.

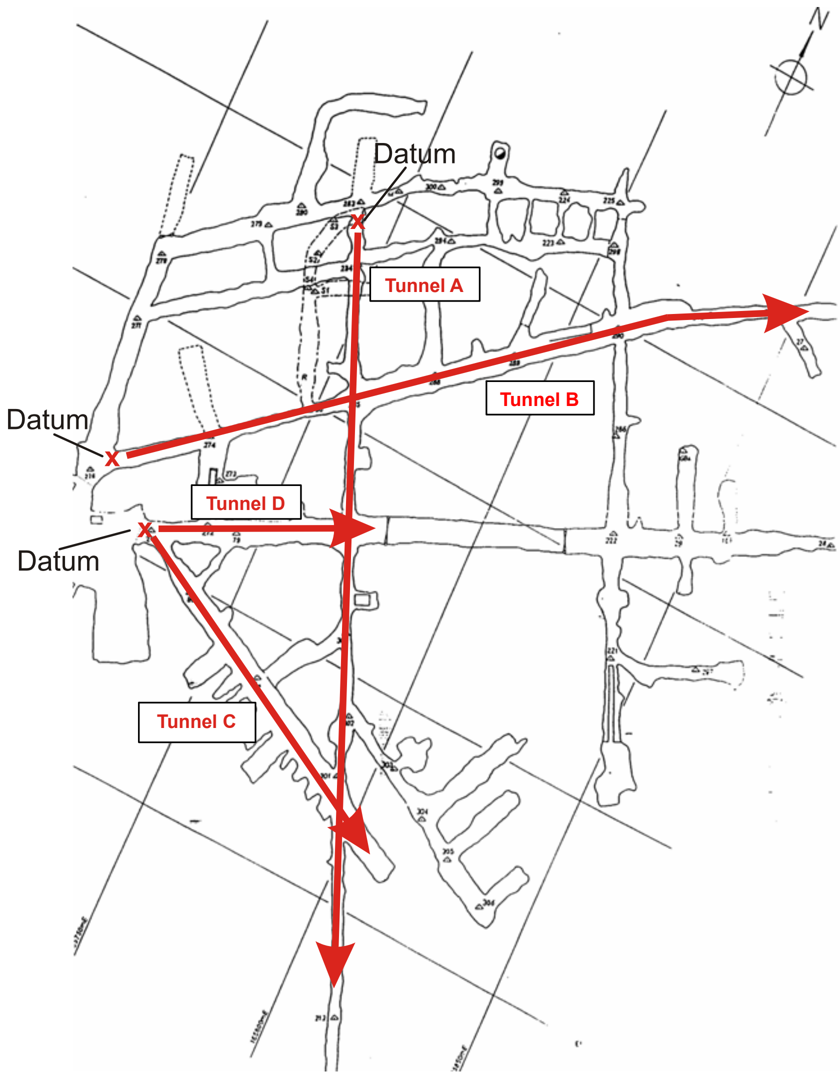


Figure 3.26: Test Locations

List of Tests Carried Out:

- CW 'Straight' Tunnel Propagation (Tunnel A, B, C and D)
- CW Tunnel Bend Attenuation (Tunnel D into Tunnel A)
- CW Tunnel Intersection (Tunnel A/B)
- CW RF screening - Metallic Vehicle Tests (Dump Truck in Tunnel B)
- Wireless Technologies – Straight Tunnel (Tunnel A)
- Wireless Technologies – Bend (Tunnel A into B)

3.3.6.1 2.3GHz CW Transmission

Straight Tunnel Propagation

Signal strength against distance was measured in all four of the identified test locations. Figure 3.27, below, shows the results obtained using a 9dBi omni-directional and 18dBi patch antenna. Tunnel B tests were carried out using 18dBi patch, 9dBi omni-directional and 5dBi patch antennas, using identical antennas for transmit and receive in all cases. Figure 3.28, below, shows the results for Tunnel B with transmitting antenna placed at the centre of the tunnel, and Figure 3.29 shows the received signal with the antenna located to one side of the tunnel. From these results directional patch antennas seem to have better efficiency in tunnels. Figure 3.30 and Figure 3.31 below demonstrate similar results using both the 18dBi patch and 9dBi omni antenna in tunnels C and D.

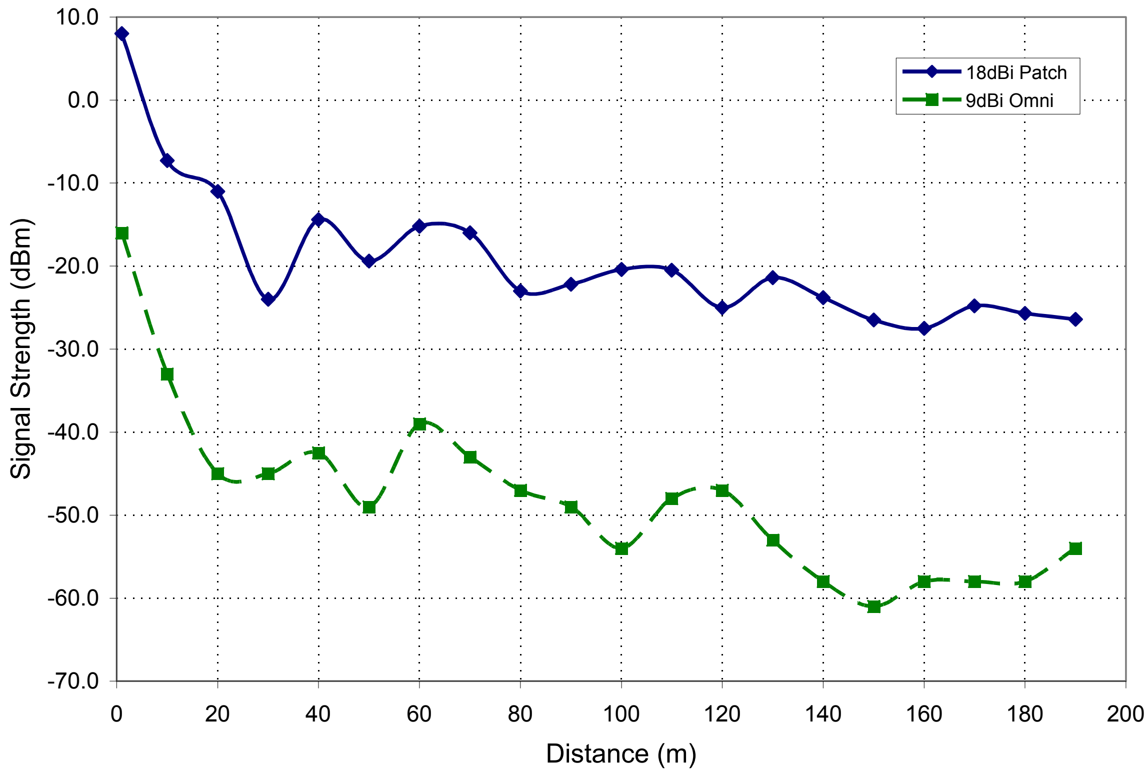


Figure 3.27: Tunnel A – Straight Tunnel Attenuation

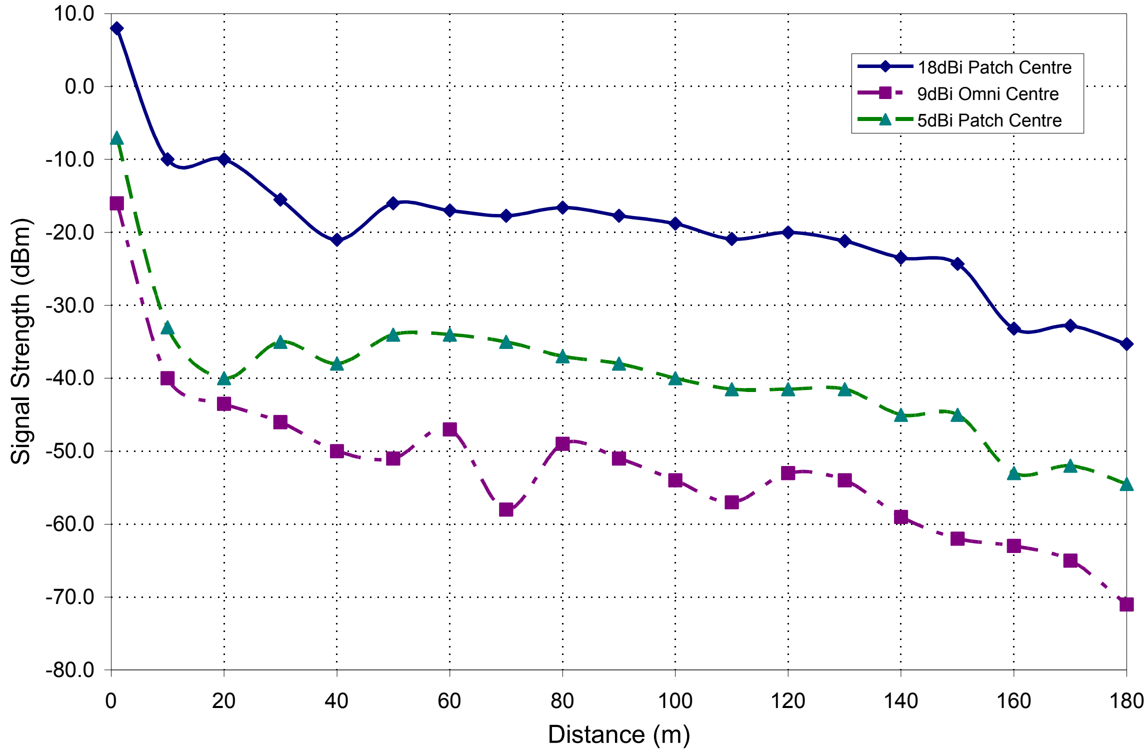


Figure 3.28: Tunnel B – TX Antenna at Centre of Tunnel Cross Section

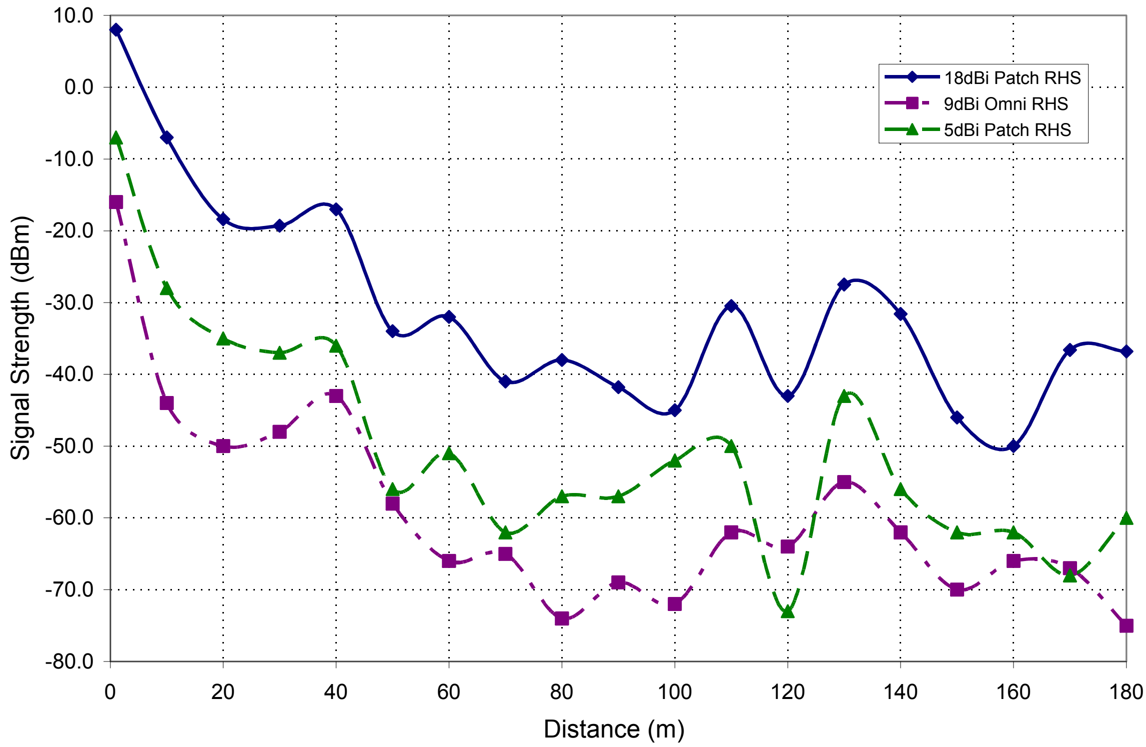


Figure 3.29: Tunnel B – TX Antenna at RHS of Tunnel Cross Section

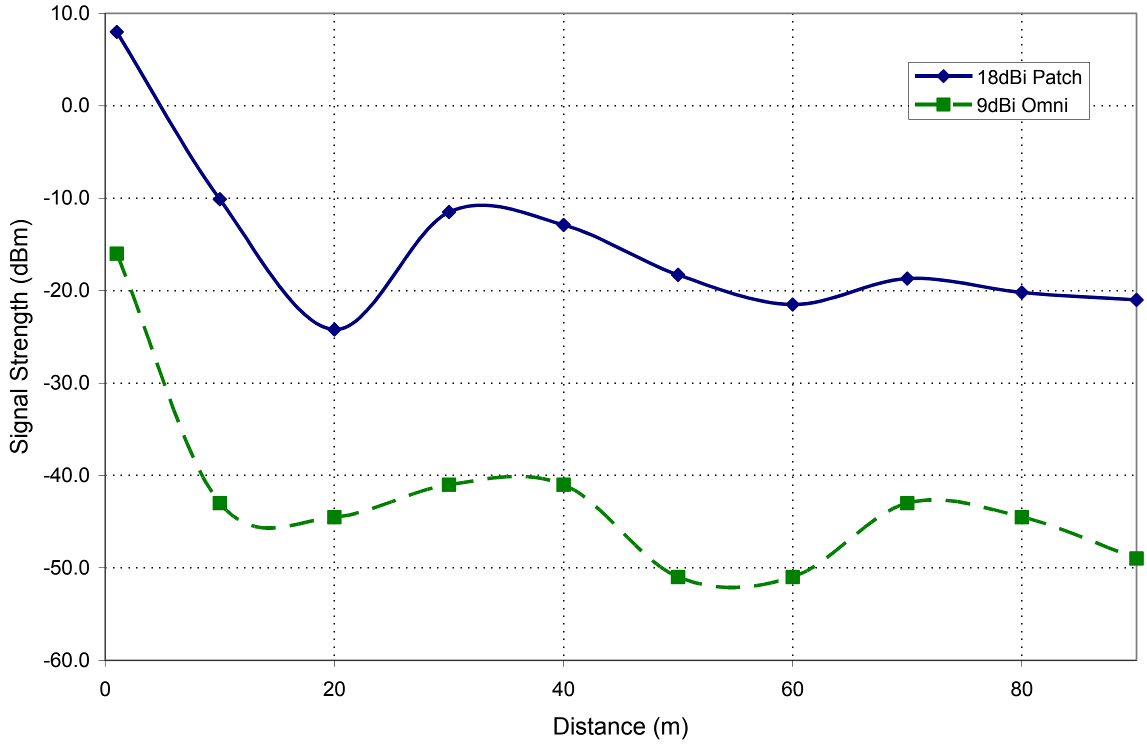


Figure 3.30: Tunnel C – Straight Attenuation

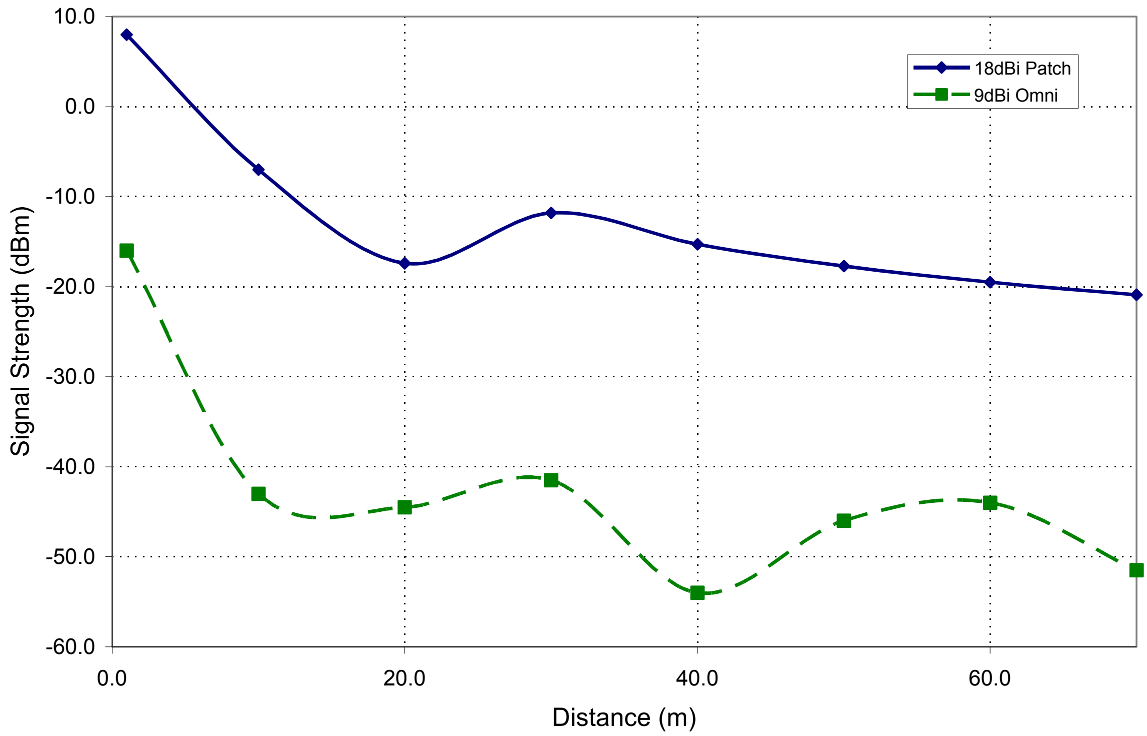


Figure 3.31: Tunnel D – Straight Attenuation

Tunnel Bend Attenuation

The tunnel bend attenuation test was conducted with the datum point located in Tunnel D and the transmitter travelling from the tunnel D/A intersection into tunnel A, as shown below in Figure 3.32. Severe attenuation was observed during the first 10m using an omni antenna. However, when using the directional patch, facing back in the direction of the 'tunnel waveguide' a significantly better attenuation rate was observed. Whilst it cannot be ignored that a degree of propagation may be achieved through rock given the relatively short distances, the below results suggest that tunnel waveguide propagation can be achieved using an efficient antenna.

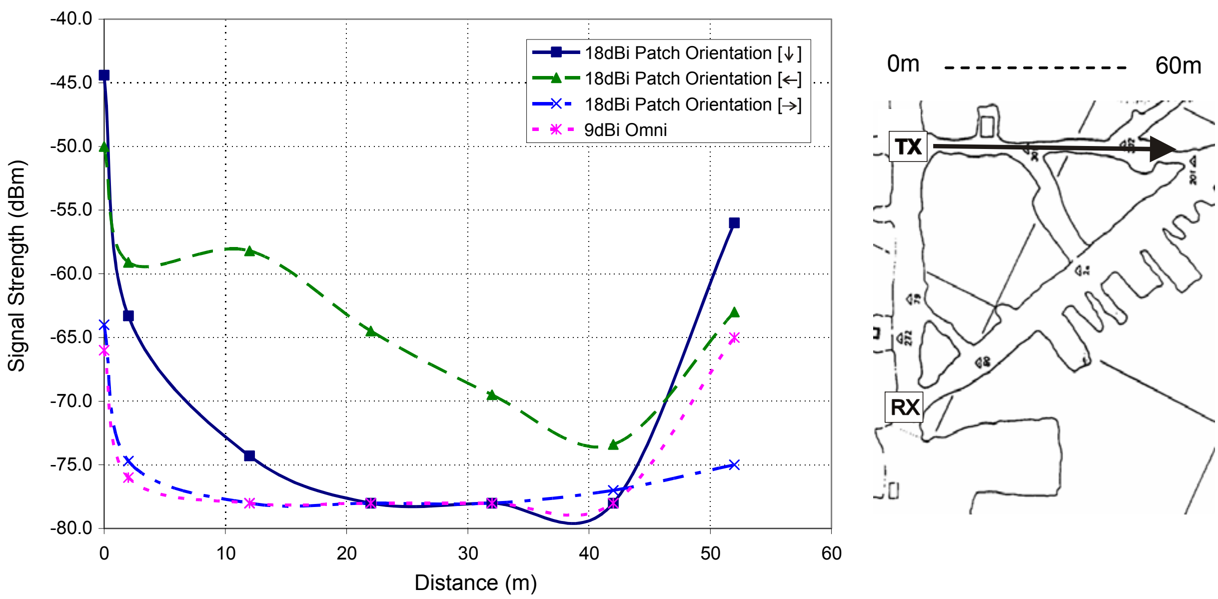


Figure 3.32: Bend Attenuation (Tunnel D into Tunnel A)

Tunnel A/B Intersection

It was observed during the Tunnel A CW test that the transmitter was particularly sensitive at the Tunnel A/B intersection (located between 30m and 40m away from datum). A higher resolution test (1m steps) is shown in Figure 3.33; the original readings are also given for reference. A reverse transmitter and receiver test was also conducted (at lower 10m step resolution) for comparison. The detailed test at the Tunnel A/B intersection demonstrated a higher attenuation rate at the junction. This suggests that tunnels will channel the wave energy in a particular direction and that further attenuation is seen at junctions due to the energy being channelled in different directions. It was also observed that the received signal strength was highly sensitive to slight TX antenna movements. There is a 10dB difference between the original reference data and higher resolution data at the 30m point.

Table 3.2, below, is a horizontal signal mapping of the tunnel cross-section. The TX antenna was kept at a constant mid-height, facing directly towards the receiving equipment.

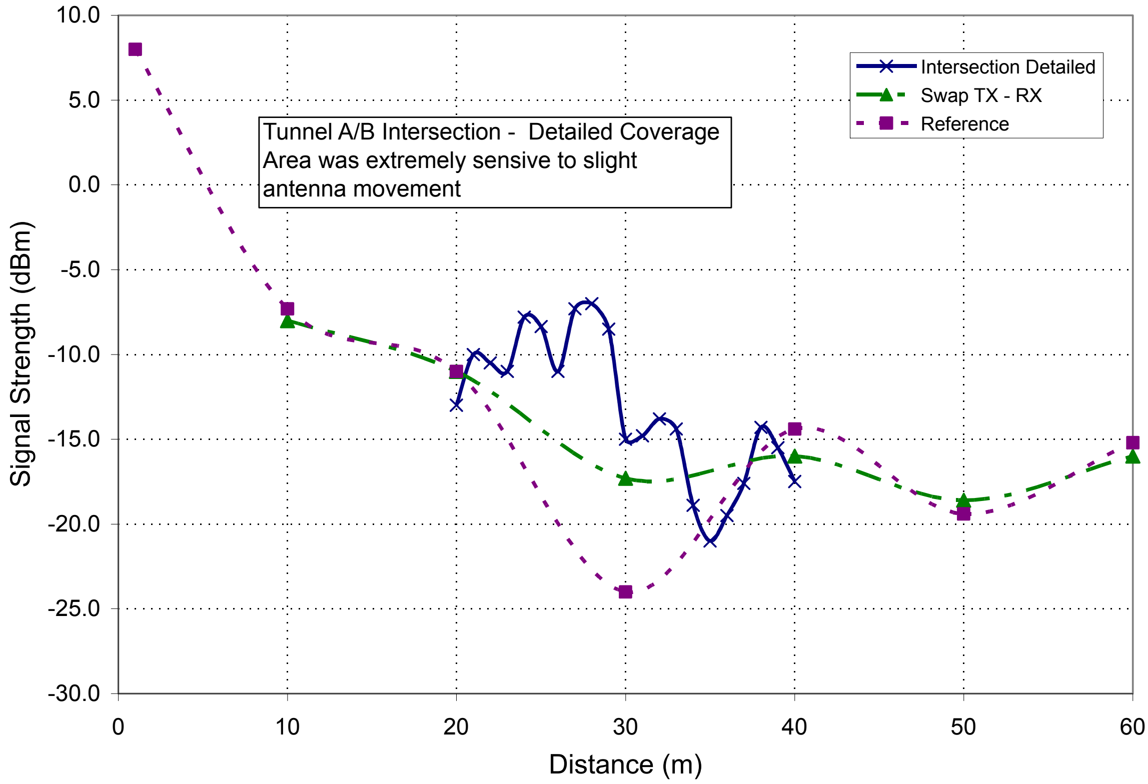


Figure 3.33: Detailed Tunnel A/B Intersection Tests

Table 3.2: Signal strength vs. tunnel horizontal position (at 30m distance)

Distance (m) from RHS	Signal (dBm)
0.0	-15.5
0.5	-20.5
1.0	-11.8
1.5	-18.0
2.0	-16.3
2.5	-14.0
3.0	-23.0
3.5 (Out of line of sight)	-49.0

Vehicle Screening Tests

The objectives of the vehicle screening tests were to examine the screening effects caused by large metallic obstructions (e.g. a mine vehicle). The tests were conducted in Tunnel B with the receiver equipment located at the 'datum' position with the rear vehicle positioned 10m away from the RX equipment, as shown in Figure 3.34 below. The 5dBi patches were used for both the beacon transmitter and receive equipment during the tests.

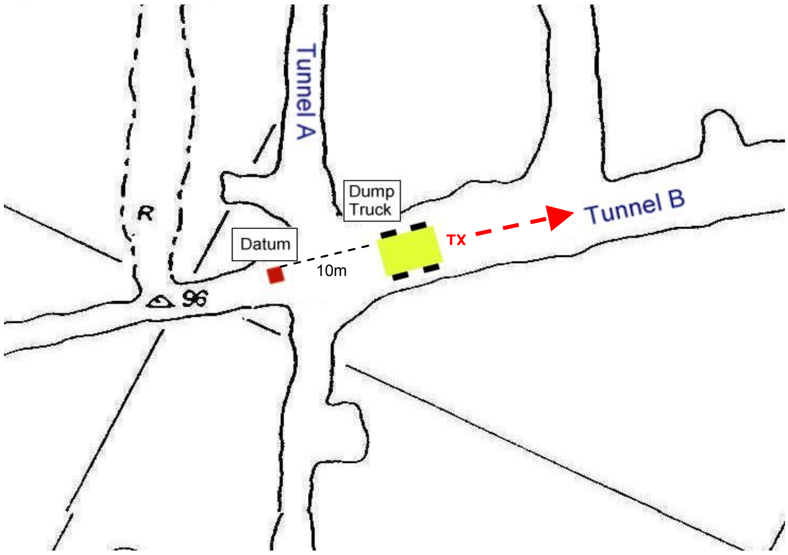


Figure 3.34: Dump Truck Antenna Screening Test Setup

Figure 3.35 show the results obtained with the dump truck obstruction and without the vehicle present for reference.

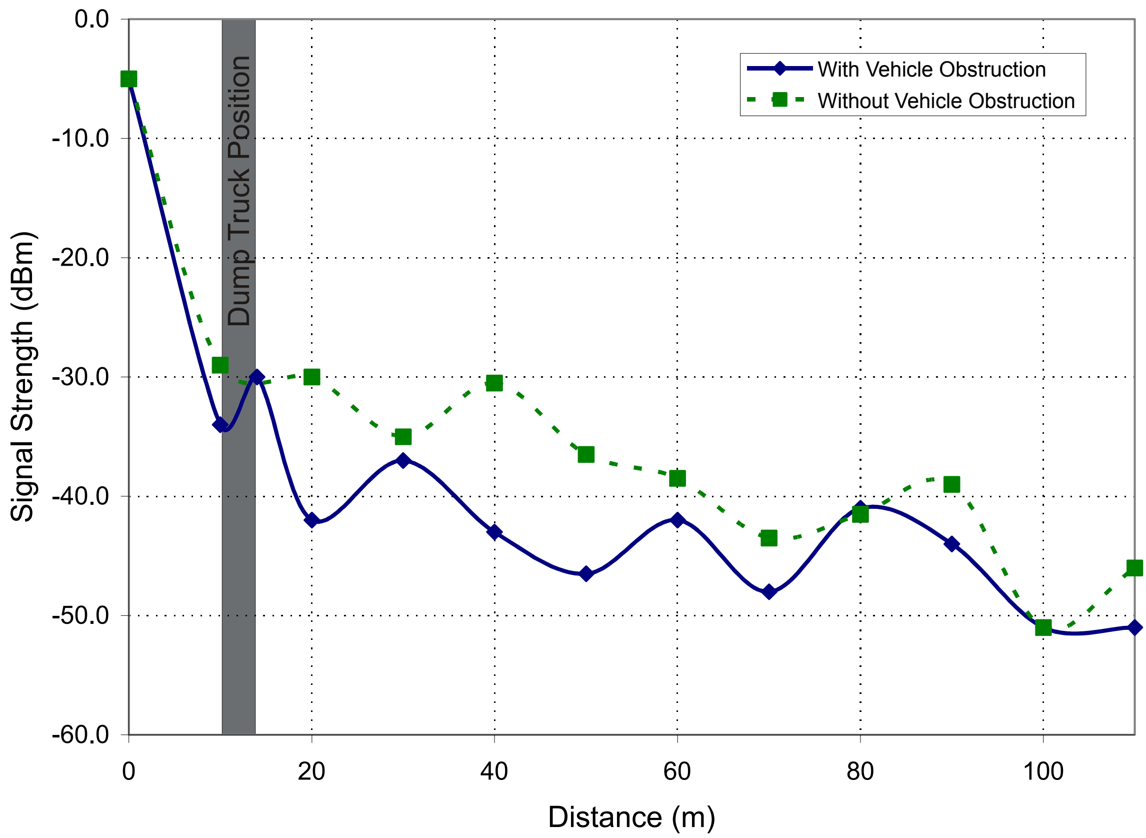


Figure 3.35: Vehicle Screening Test using 5dBi Patch

3.3.6.2 5.8GHz CW Transmission

The 5.8GHz tests were carried out in exactly the same format and locations as the 2.3GHz, but just using an 11dBi omni-directional antenna. Whilst this research is mainly concerned with the 2.4GHz (2.3GHz CW equipment used due to availability) due to the wide range of technologies operating at these frequencies, it is anticipated that more wireless technologies will make use of higher frequencies in the future.

Straight Tunnel Propagation

Figure 3.36, below, shows signal strength versus distance at both 5.8GHz and 2.3GHz. Note the received frequencies at the 0m point where the actual received signal for 5.8GHz is 5dB lower than 2.3GHz, where the actual transmission power for the 5.8GHz was lower than the 2.3GHz. However, the 5.8GHz initially drops further than 2.3GHz in the first 10m compared with 2.3GHz. There is clearly a correlation between overall attenuation rate and pattern. Figure 3.37, Figure 3.38, Figure 3.39 and Figure 3.40 show similar results for Tunnel B, Tunnel B with the TX adjacent to the tunnel wall, Tunnel C and Tunnel D respectively.

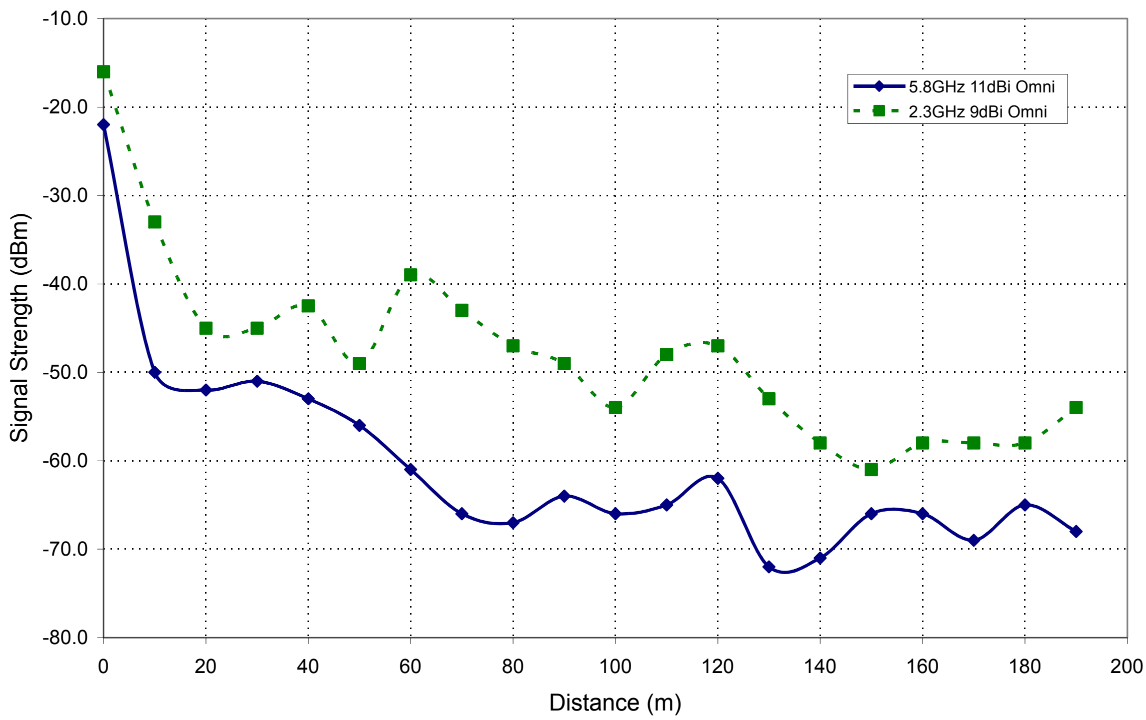


Figure 3.36: Tunnel A - 5.8GHz vs. 2.3GHz (Omni Antennas)

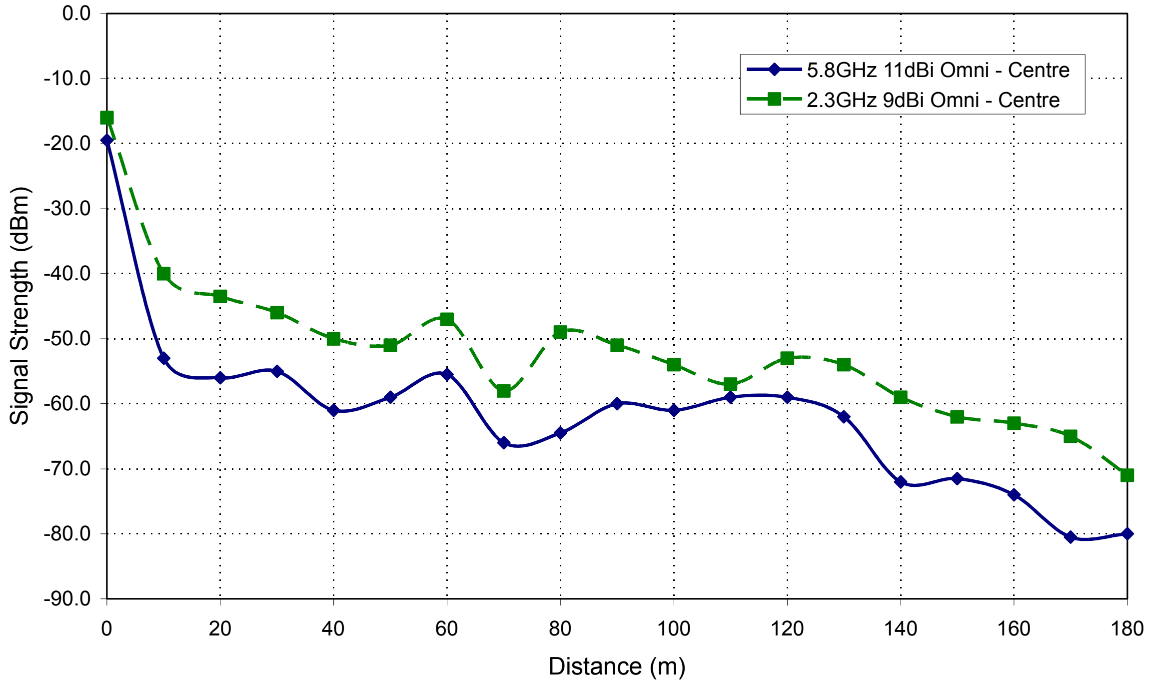


Figure 3.37: Tunnel B - 5.8GHz vs. 2.3GHz (Omni Antennas), TX Antenna at Centre of Tunnel Cross Section

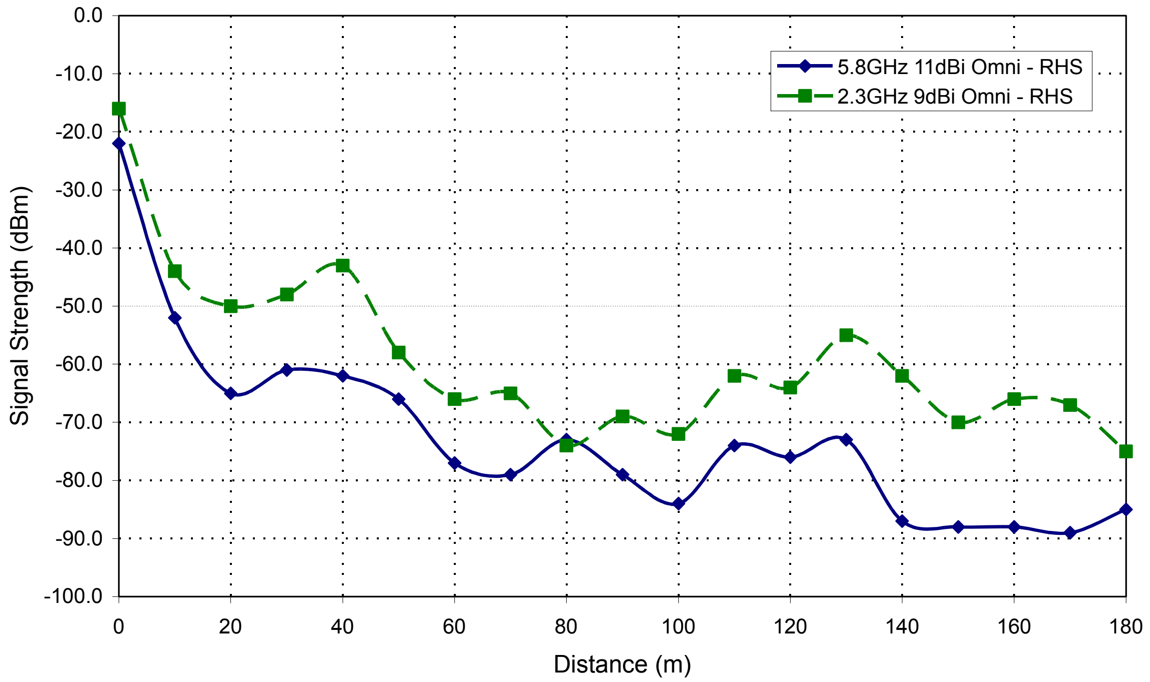


Figure 3.38: Tunnel B - 5.8GHz vs. 2.3GHz (Omni Antennas), TX Antenna at RHS of Tunnel Cross Section

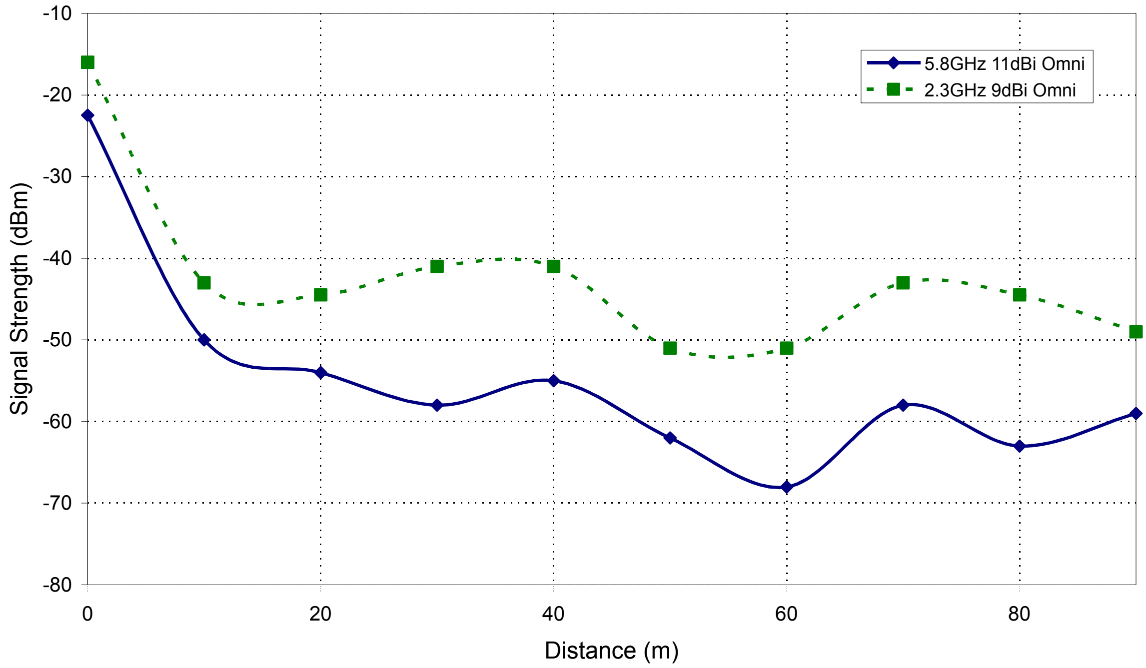


Figure 3.39: Tunnel C - 5.8GHz vs. 2.3GHz (Omni Antennas)

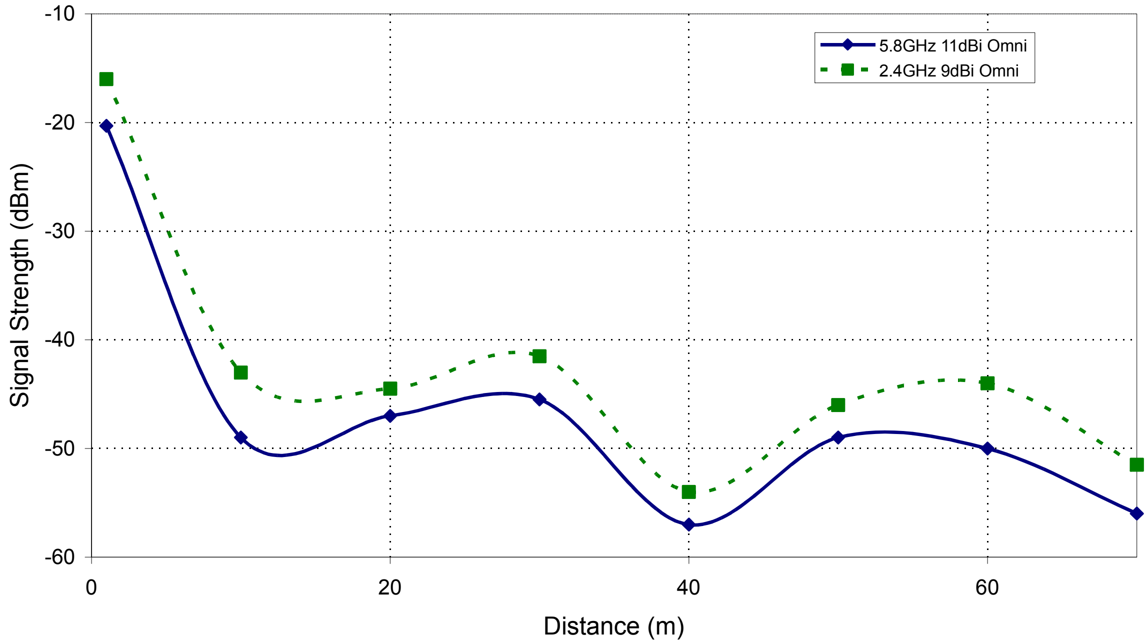


Figure 3.40: Tunnel D - 5.8GHz vs. 2.3GHz (Omni Antennas)

Tunnel Bend Attenuation

Figure 3.41, below, shows 5.8GHz versus 2.3GHz at the tunnel D into A intersection. Note that the receive equipment noise floor was around 80dBm during the 2.3GHz tests and around 90dBm for the 5.8GHz test. Therefore, both sets of data reach the noise floor at the same point, suggesting a similar rate of decay in non line-of-sight situations.

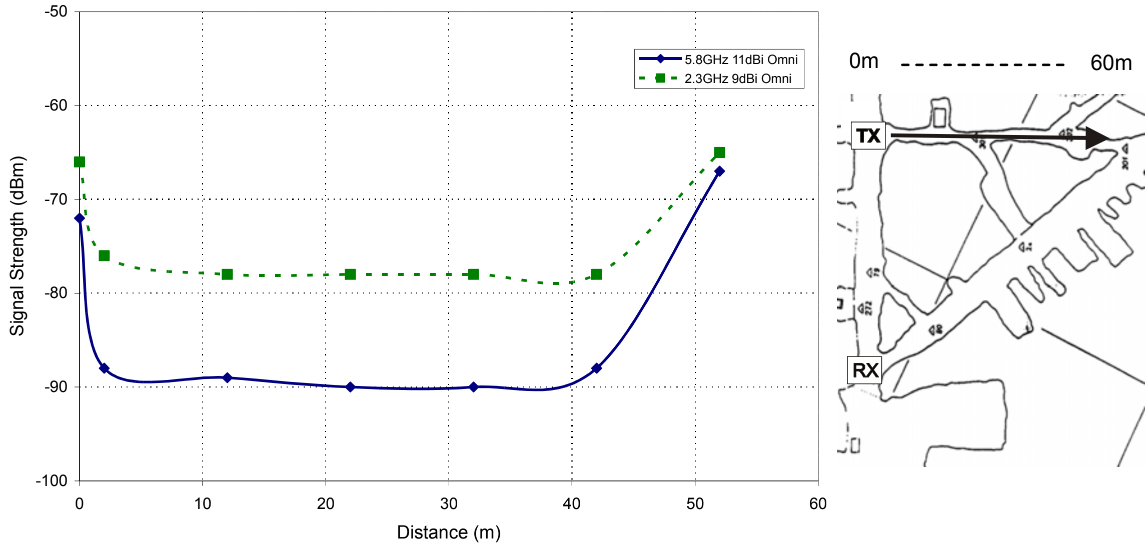


Figure 3.41: 5.8GHz vs. 2.3GHz Bend Attenuation (Tunnel D into Tunnel A)

Tunnel A/B Intersection

A higher resolution tests at the tunnel A/B intersection (as in the 2.3GHz tests) are shown below in Figure 3.42 and

Table 3.3.

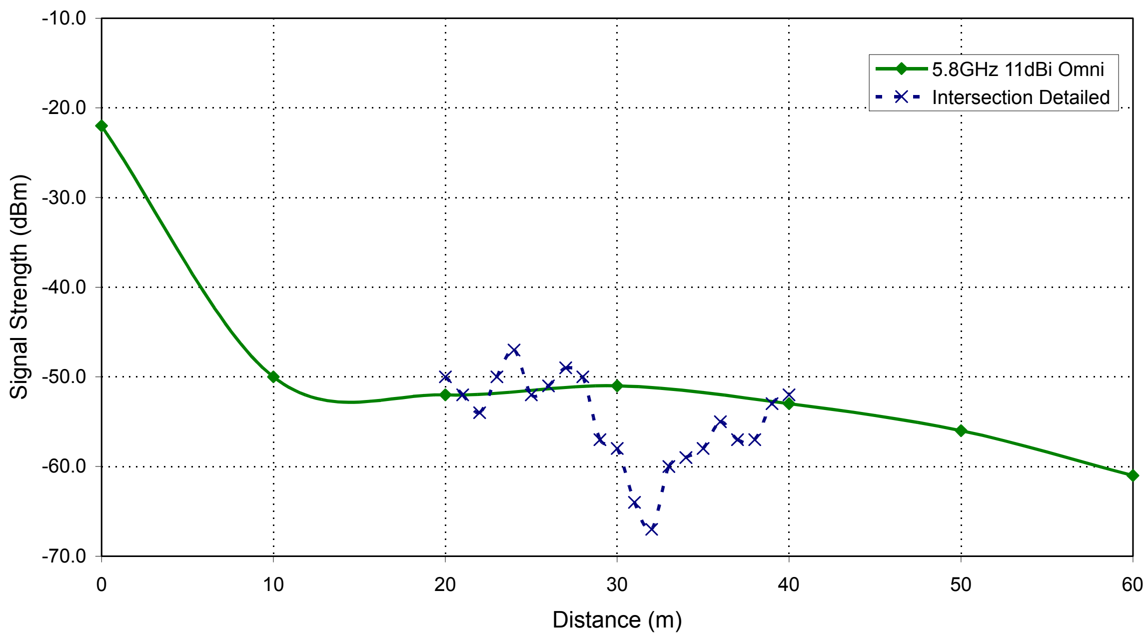


Figure 3.42: Detailed Tunnel A/B Intersection

Table 3.3: Signal strength vs. tunnel horizontal cross section (at 30m distance)

Distance (m) from RHS	Signal (dBm)
0.0	-54.0
0.5	-46.0
1.0	-48.0
1.5	-55.0
2.0	-49.0
2.5	-47.0
3.0	-49.0
3.5	-56.0
4.0 (out of LOS)	-70

Vehicle Screening Tests

Figure 3.43, below, shows the effects of RF screening using a vehicle (dump truck) obstacle. The test was performed in tunnel B with the dump truck situated as shown previously in Figure 3.34.

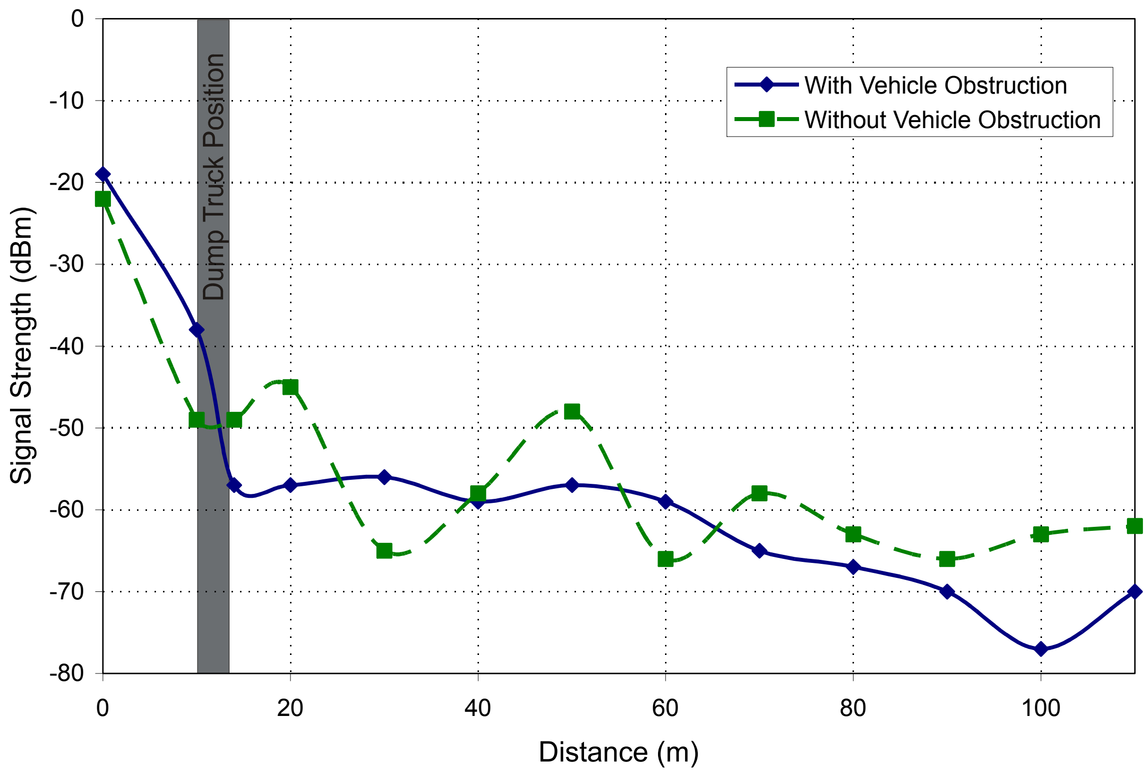


Figure 3.43: Vehicle Screening Test using 11dBi Omni

3.3.6.3 Wireless Technologies Throughput Tests

Figure 3.44 and Figure 3.45, below, show a summary of the throughput versus distance results for the wireless technologies obtained in a straight tunnel (Tunnel A) and around a 90^0 bend (Tunnel A into B). Full detailed graphs of the wireless technology tests are given in Appendix A.2.

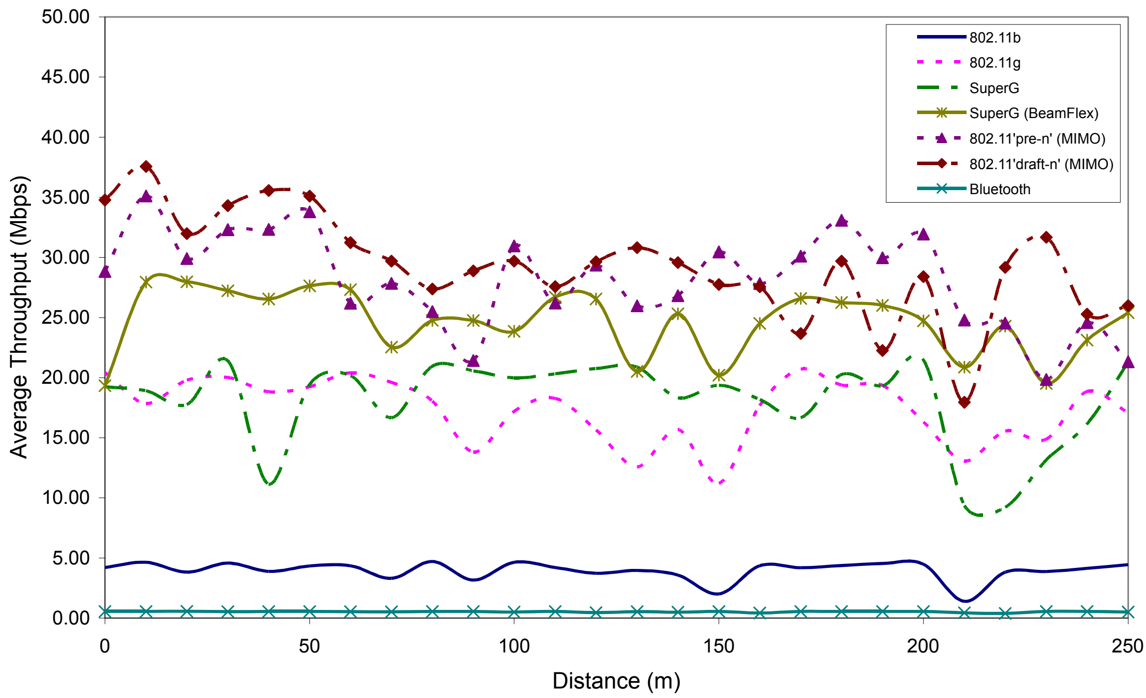


Figure 3.44: CSM WiFi Test Summary (Straight Tunnel)

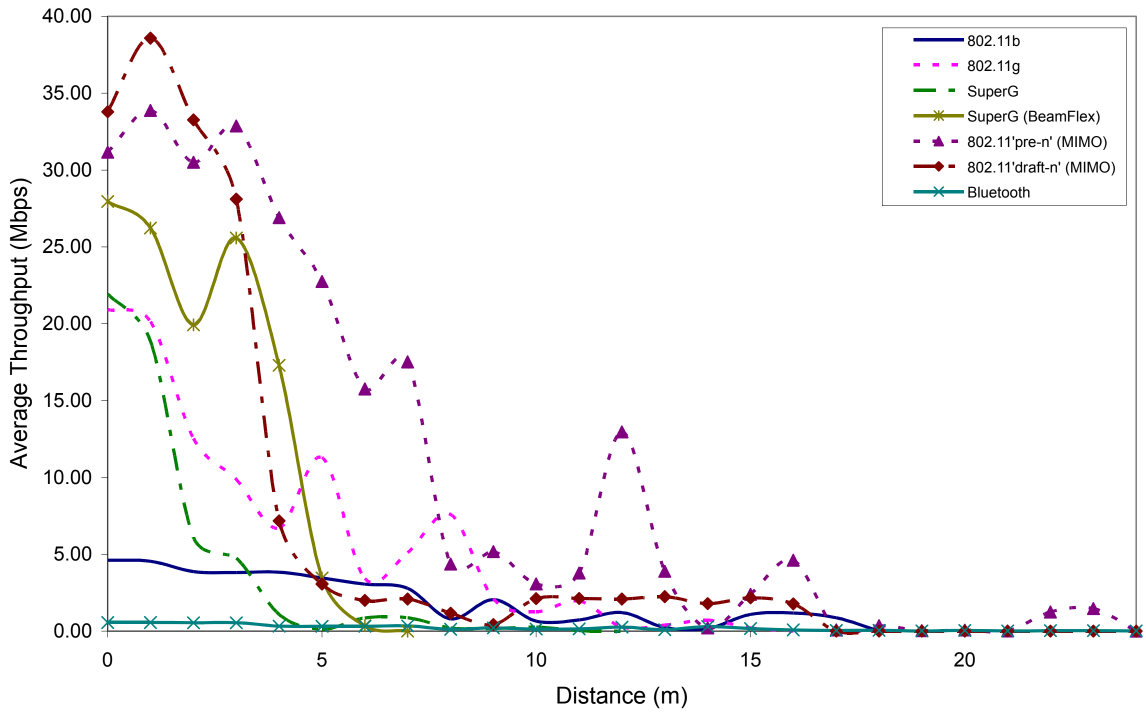


Figure 3.45: CSM WiFi Test Summary (Bend)

3.3.7 Coal Mine Test Facility Results

A plan of MÜZ and the test locations used are shown below in Figure 3.46. The CW tests and wireless technology tests were carried out using the same procedure as in the previous tests. The 5.8GHz equipment was not available at the time these tests were carried, hence only 2.3GHz CW measurements were taken.

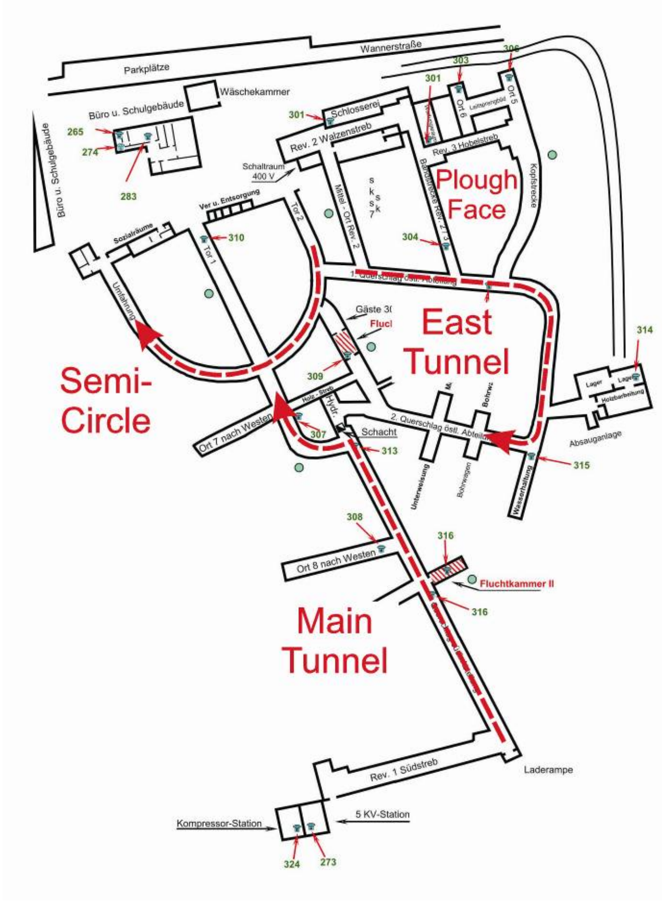


Figure 3.46: MÜZ Plan and Test Locations

3.3.7.1 2.3 GHz CW Transmission

Main Tunnel CW Test

The 'Main Tunnel' results are shown in Figure 3.47 below. The spectrum analyser was fixed in the start position as indicated, and the mobile transmitter TX was moved away in 10m steps. The first 100m of roadway was linear LOS transmission. At 105m, the transmitter travelled into a bend as indicated in the diagram. A relatively consistent attenuation rate was observed during the 100m LOS. At the bend, the signal strength instantly decreased by 10-15dB. However, it was possible to receive a signal for an additional 25m into the bend. The 'noise floor' on the spectrum analyser was at -90dBm; hence further power measurements were considered unreliable beyond this level.

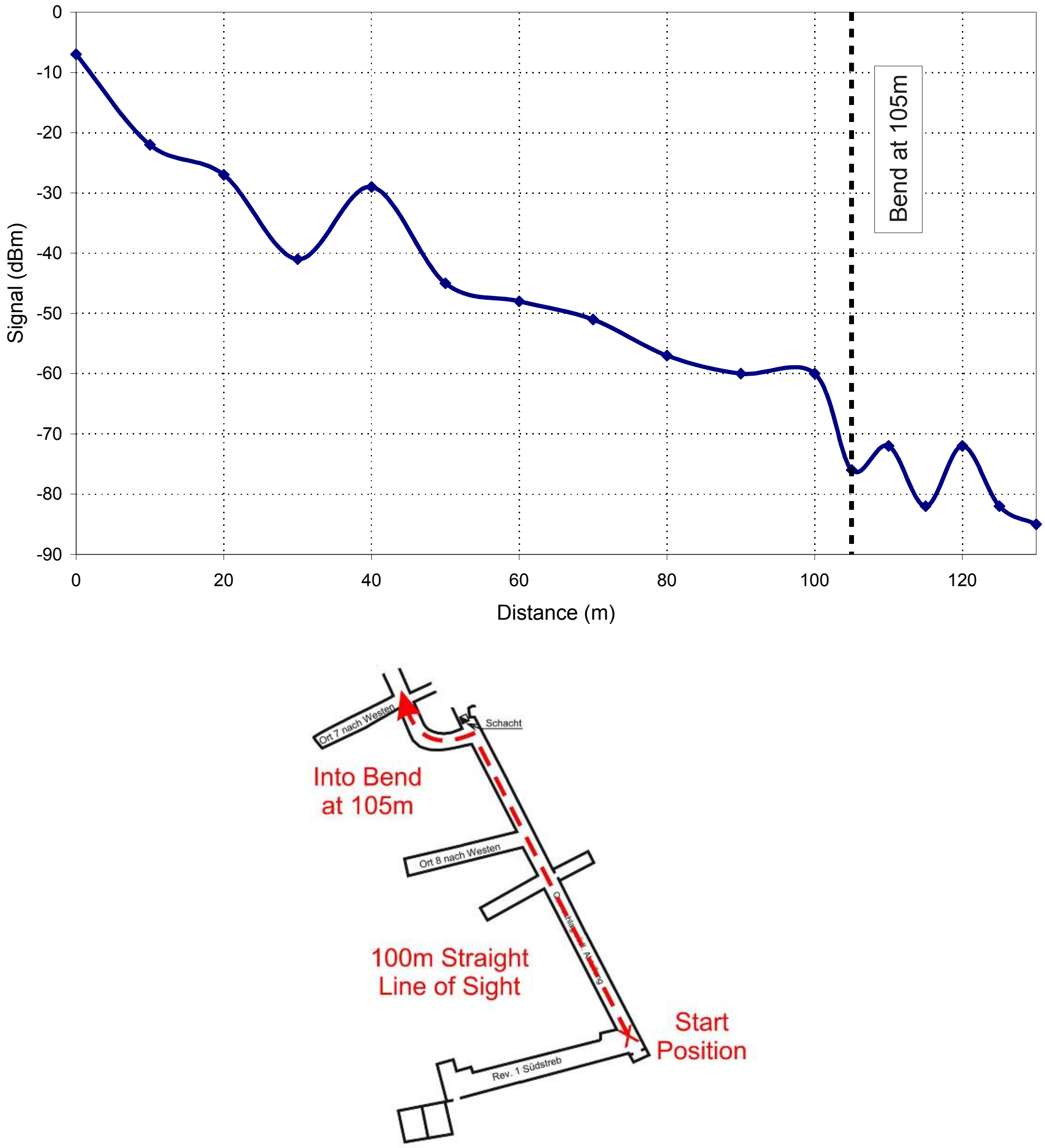
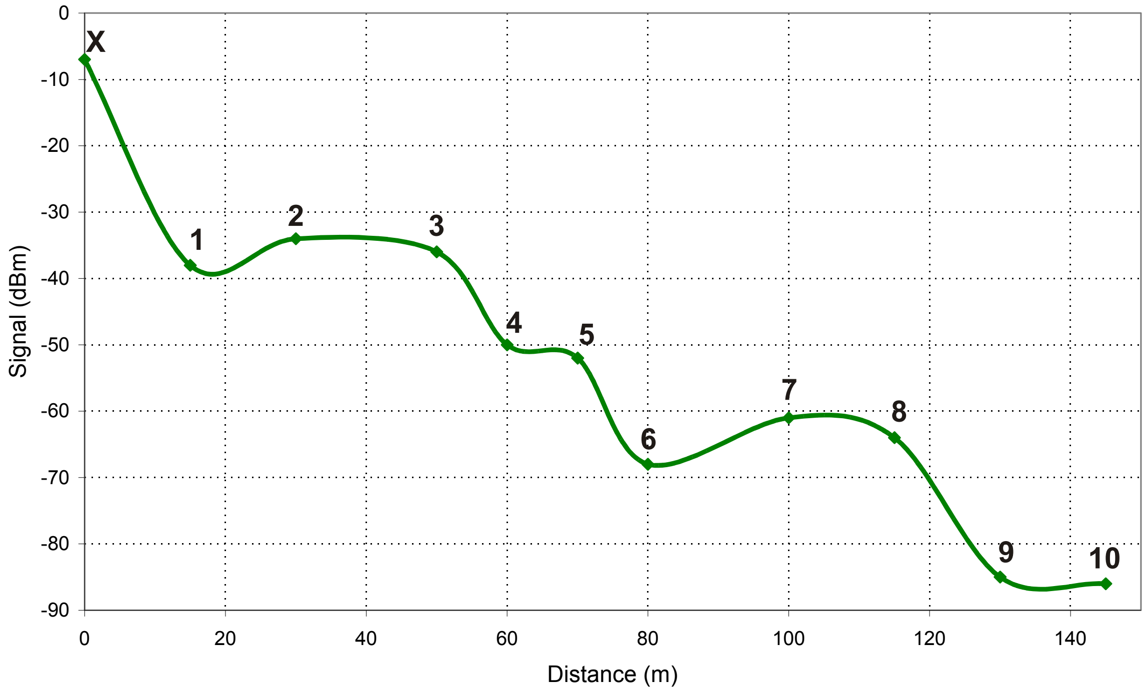


Figure 3.47: Main Tunnel 2.3GHz CW Test

East Tunnel CW Test

The ‘East Tunnel’ results are shown in Figure 3.48 below. The start position where the received equipment was permanently located is marked on the diagram as in the previous test. The mobile transmitter was moved to each reference point (1-10) as indicated. The graph shows approximate distances versus received signal. In previous tests, particularly at the CSM hard rock test mine, attenuation rates out of LOS were very severe. The main differences in this situation are that the actual bend curvature is gradual, and the tunnel is lined with steelwork. It is observed that waveguide-like propagation is being enhanced in this case. The total non-LOS distance achieved was approximately 145m before reaching the equipment noise floor.



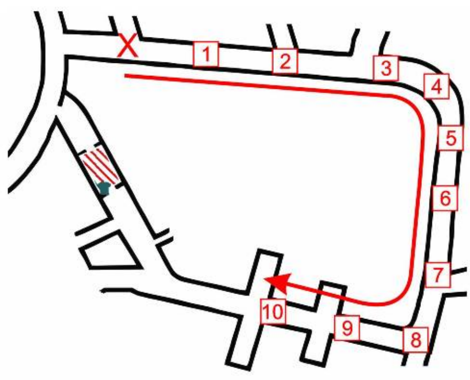
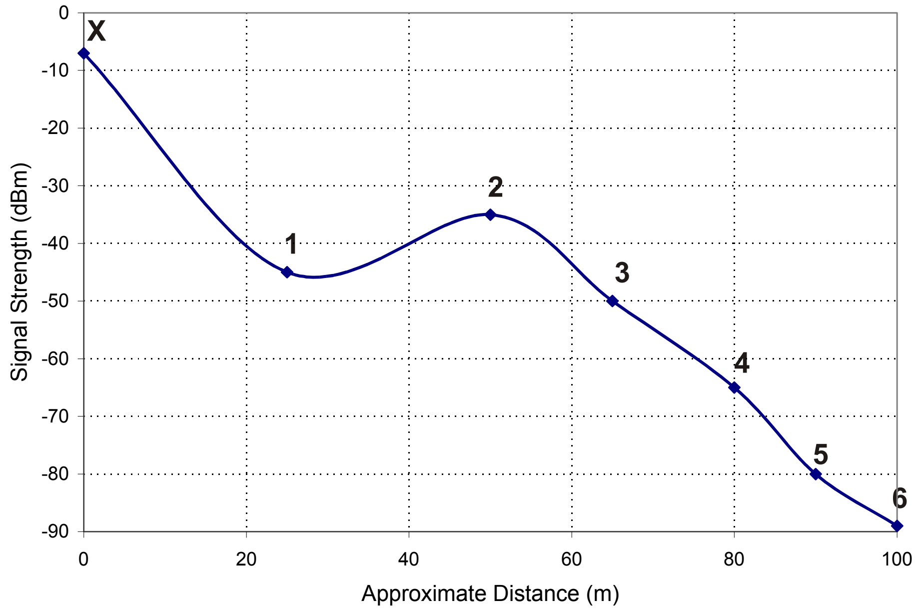


Figure 3.48: East Tunnel 2.3GHz CW Test

Semi-Circle Tunnel CW Test

The ‘Semi-Circle’ test results are shown in Figure 3.49 below. Again, the reception equipment was permanently fixed in the start position. The mobile transmitter was moved to each reference point as indicated. The graph shows approximate distances versus received signal. A relatively steady attenuation rate was observed, showing most, if not all, of the signal is propagating through the tunnel as a waveguide. The signal was completely lost at point ‘6’, which was behind a steel door. The test shows that improved attenuation rates can be achieved in non-LOS situations where the bend has a *gradual* curve gradient i.e. large rounded bends as opposed to conventional sharp 90º bends. Ideally, it would be useful to measure signal attenuation within this type of bend in a ‘bare’ tunnel without the presence of metalwork.



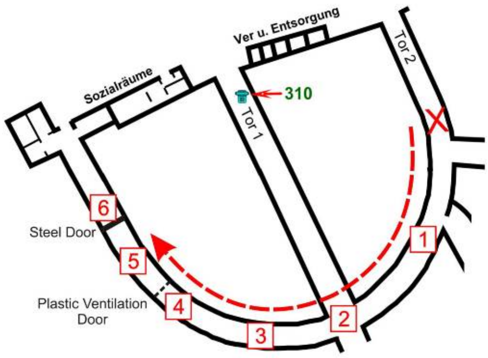


Figure 3.49: Semi-Circle Tunnel 2.3GHz CW Test

3.3.7.2 *Wireless Technologies Throughput Tests*

A summary of results obtained from testing various wireless networking technologies is given below. Figure 3.50 gives the summary of the average throughput performance in the MÜZ 'Main Tunnel' for the wireless technologies: 802.11b, 802.11g, SuperG, SuperG (plus BeamFlex antennas), 802.11pre-n (MIMO), and Bluetooth. These tests were conducted prior to the release of 'draft-n', hence there is no data for this technology. As in the CW tests, the mobile TX travelled into non-LOS at the bend at 105m. Figure 3.51 below shows the results obtained in the 'East Tunnel' using the same technologies. Full detailed graphs of the wireless technology tests are given in Appendix A.2.

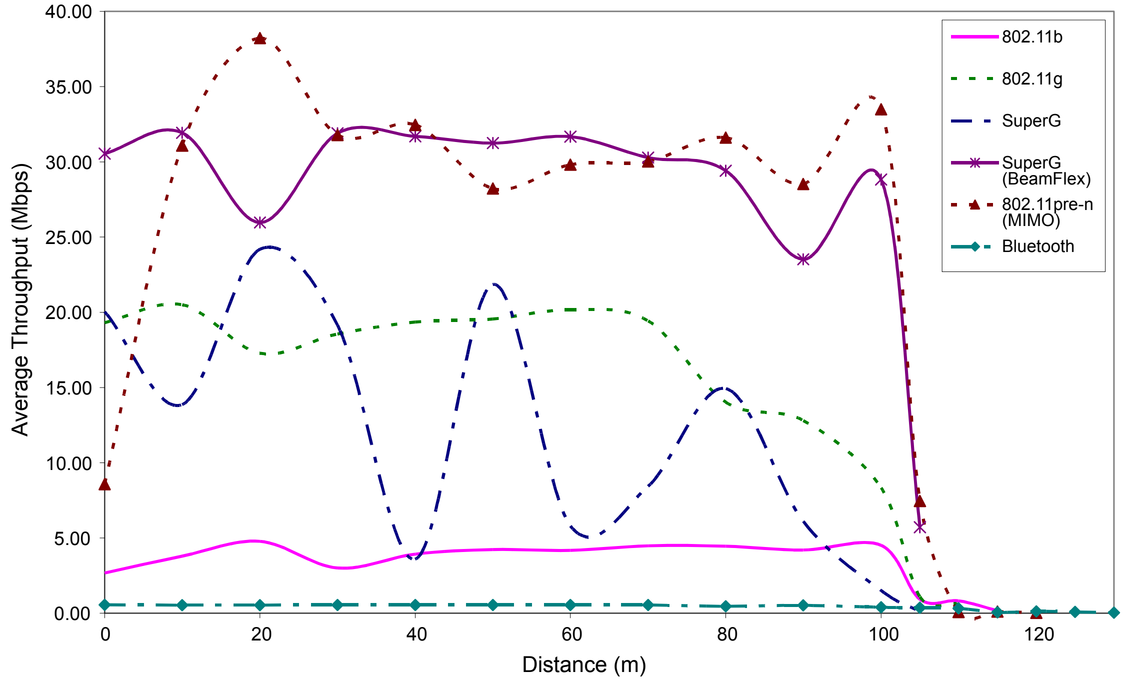


Figure 3.50: MÜZ Main Tunnel WiFi Summary Graph

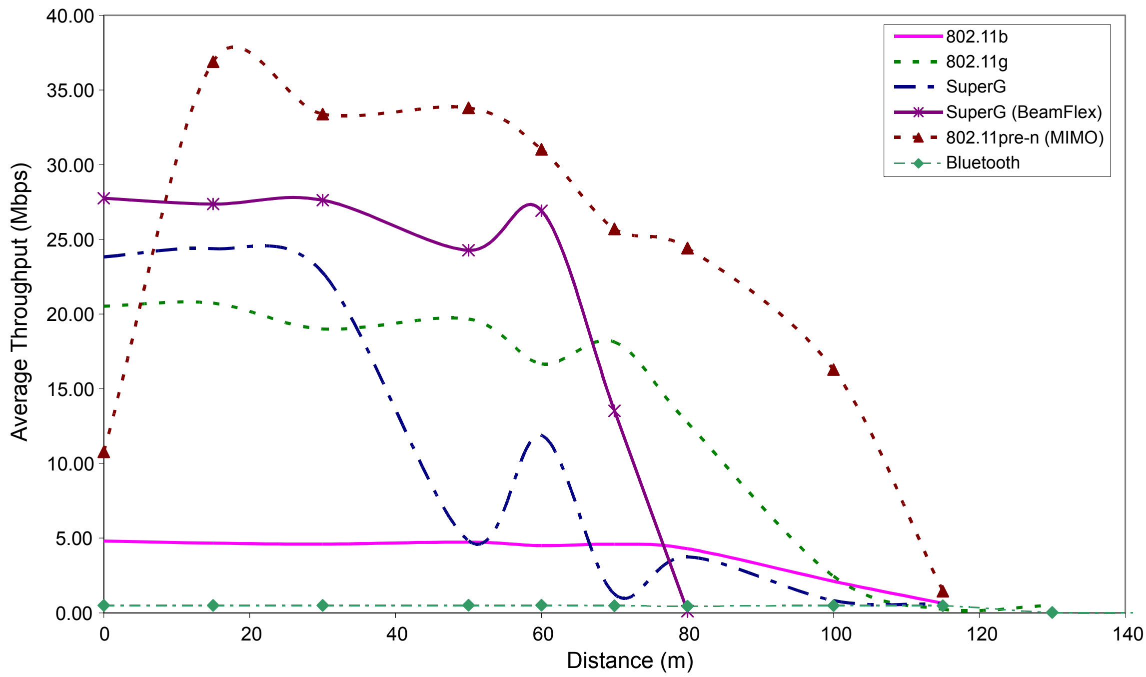


Figure 3.51: MÜZ East Tunnel WiFi Summary Graph

Figure 3.52 below shows a comparison between standard WiFi (802.11b) and Bluetooth operating within the 'Semi-Circle' tunnel. The Bluetooth link was lost at around 100m (behind the steel door), whereas the 802.11b link was lost at around 50m. This suggests that the frequency hopping associated with Bluetooth operation offers high resilience in this type of situation.

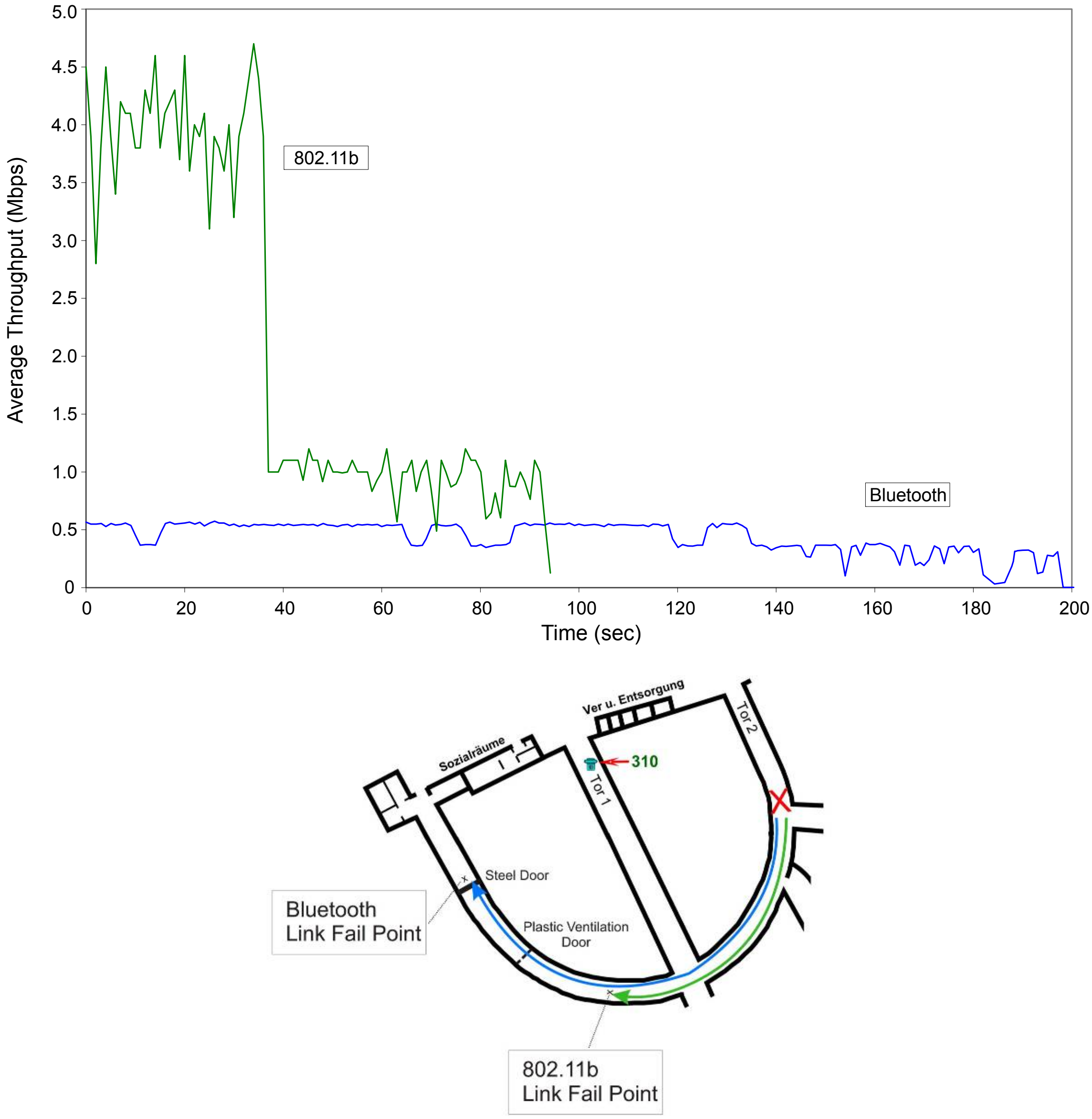


Figure 3.52: MÜZ Semi Circle – Bluethooth vs. WiFi (802.11b)

3.3.8 Discussion

3.3.8.1 CW Transmission Observations

2.3 GHz CW Transmission

Overall Straight Tunnel Attenuation:

The overall signal strength measurements observed in each of the test locations demonstrated that reasonably low attenuation rates versus distance can be achieved in a tunnel environment. This suggests that at higher frequencies relatively low attenuation rates can be achieved over long distances, beyond the initial sharp drop in signal. The exception to the relatively low attenuation rates over long distance generally observed was the 'main tunnel' at MÜZ, where a steadier higher rate in attenuation was observed over the 100m distance (straight section of the tunnel). This particular tunnel contained a significant amount of cabling, pipework, and metallic machinery, as shown in Figure 3.53. The amount of RF obstacles in this tunnel appears to increase the overall attenuation. However, the total attenuation over 100m was in the region of 50dB. This tunnel is representative of a worst case scenario, and the losses are considered more than adequate for the types of wireless applications under consideration in this research.

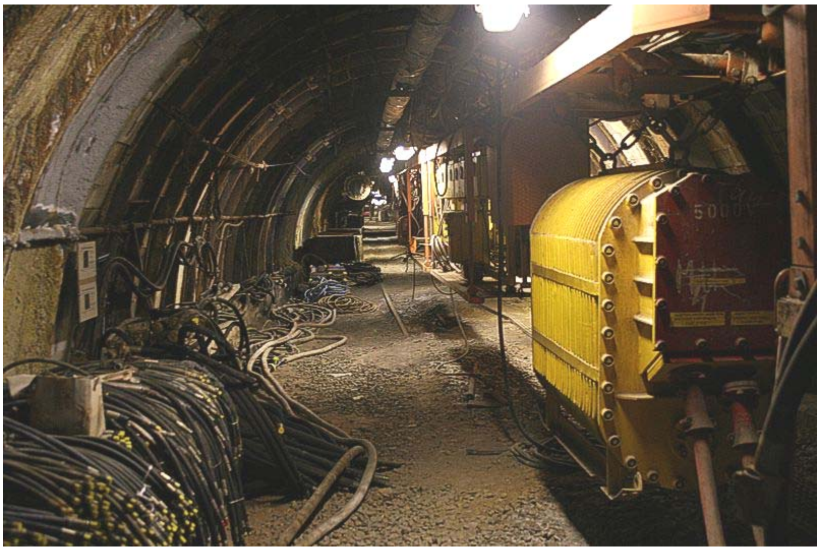


Figure 3.53: MÜZ 'Main Tunnel' – View from RX Equipment

In all tests up to a certain critical point, usually at around 10m, the attenuation rate was relatively high. However beyond this point, relatively low overall attenuation rates can be achieved in straight tunnels within this environment. This type of behaviour was also observed by Zhang *et al.* (2001), Djadel *et al.* (2002), although neither author really offers any explanation as to why this occurs. Figure 3.54, below, shows an example of the two specific attenuation rates, in this case CSM tunnel A using 9dBi omni-directional antennas. The initial rate is 1.9dB/m, then the rate beyond this point becomes 0.11dB/m. Similar behaviour was observed in all the other locations. A hypothesis for this occurrence is due to effect of multi-modes causing interference, and this is discussed in Section 3.3.8.3.

Another key characteristic was that in all test locations fluctuations, or peaks and troughs in the received signal were observed. This was also observed even in a relatively smooth and perfectly straight tunnel (Ashbourne), suggesting that constructive and destructive interference is occurring due to standing waves.

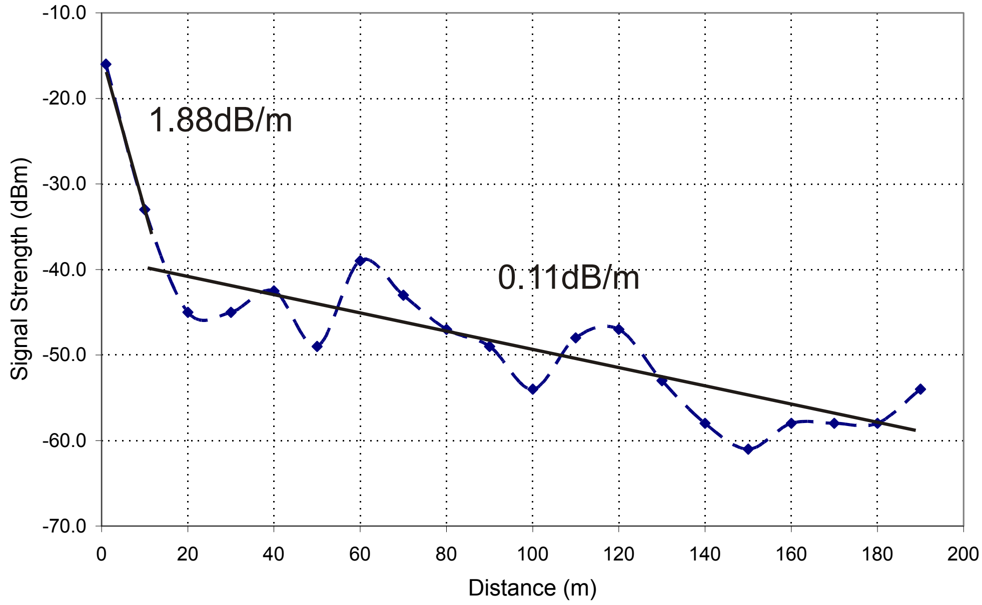


Figure 3.54: Example showing two distinct attenuation rates (CSM Tunnel A – 9dBi Omni Antenna)

Antennas:

A range of antennas were used during the tests, and it was clearly shown that directional antennas were more efficient than omni-directional antennas. It seems that directional antennas couple more efficiently to the waveguide modes compared with the omni-directional antennas. In fact, a 5dBi patch antenna had better performance than a 9dBi omni using exactly the same RF beacon transmitter.

Waveguide Tunnel Irregularities:

Signal loss was observed at junctions where the energy is being channelled in other directions. The signal would often increase again beyond the junction, again suggesting the tunnel 'guides' the signal energy in a particular direction.

A particular sensitive area was identified at the Tunnel A/B Intersection. The irregular shape seemed to cause a high degree of sensitivity to antenna position. Again, this suggests the presence of standing waves, and irregular shapes in the tunnel increases this type of behaviour.

Tests were carried out with the transmitter adjacent to the tunnel wall. The results demonstrated a degraded performance. This was irrespective of whether the TX antenna or RX antenna was placed near the wall, and was cumulative if both RX and TX are adjacent to the tunnel wall.

Non Line-of-Sight:

The non line-of-sight tests carried out at CSM Test Mine showed that a sharp bend in the tunnel will cause a rapid increase in attenuation. The directional patch tests further demonstrated that propagation is travelling along the tunnel in a waveguide form, where the optimal position for the TX antenna was facing back in the direction of the tunnel. Given that limited propagation will occur through rock, albeit with small skin depths at these high frequencies, it is clear that this has no influence for any reasonable range, and that all propagation is reflected along the path of the tunnel. Directional patch antennas would offer a partial increase in non LOS situations to increase the robustness of wireless transmission at these frequencies.

An interesting observation in non LOS situations was in the MÜZ gradual curvature where the attenuation was far less severe. The circular, or gradual, curves seem to attenuate the signal less than a conventional sharp right angle bend, which is similar to the behaviour of underground mine ventilation losses. It was also speculated that the metallic infrastructure lining the tunnels (steel rings, mesh etc) also increase the waveguide effect and assist propagation.

RF Screening Effects:

The MÜZ 'Main Tunnel' results demonstrated an increase in signal attenuation due to the presence of significant RF obstacles, as discussed earlier. The effects of RF screening were investigated using a dump truck vehicle as a deliberate obstacle in the CSM Test Mine. It was found that the signal was attenuated by around 10dB with the TX antenna close to the obstacle. Beyond the vehicle obstruction, the additional loss would decrease as the transmitter moved away.

2.3GHz versus 5.8GHz Transmission

A range of additional 5.8GHz tests were carried out at both CSM and Ashbourne for comparison, as it is anticipated that more wireless technologies will make use of the higher frequency bands in the future. The results from the 5.8GHz tests carried out using an omni directional antenna have shown close correlation with the 2.3GHz tests, with similar patterns and attenuation rates achieved in all of the various scenarios. It is expected that the general trend between the two frequencies is that 5.8GHz would offer slightly better range in straight tunnels and slight worse performance in non LOS situations. However, these differences are marginal and it is difficult to draw up conclusive evidence from these tests. The intention was more to investigate the feasibility of 5.8GHz wireless transmission in tunnels. Table 3.4, below, shows a comparison between the attenuation rates achieved at 2.3GHz and 5.8GHz in Ashbourne and each of the CSM Test Mine locations.

Table 3.4: 2.3GHz and 5.8GHz Tunnel Attenuation Rates (dB/m)

	Cross Section	Width	Height	2.3GHz Attenuation Rate (dB/m)	5.8GHz Attenuation Rate (dB/m)
Ashbourne Railway Tunnel Centre		7m at base 8m maximum	6m at centre	0.06	0.05
Ashbourne Railway Tunnel Left Wall		7m at base 8m maximum	6m at centre	0.05	0.04
Ashbourne Railway Tunnel Right Wall		7m at base 8m maximum	6m at centre	0.05	0.06
CSM Test Mine Tunnel A Centre		3.00m - 3.25m	2.50m - 2.80m	0.14	0.14
CSM Test Mine Tunnel B Centre		3.00m - 4.00m	2.50m - 2.80m	0.18	0.18
CSM Test Mine Tunnel B Wall		3.00m - 4.00m	2.50m - 2.80m	0.18	0.23
CSM Test Mine Tunnel C Centre		4.50m - 6.00m	2.00m - 2.20m	0.21	0.29
CSM Test Mine Tunnel D Centre		4.50m - 5.50m	2.30m - 2.80m	0.32	0.32

Table compiled by MRSL and author

3.3.8.2 Wireless Technologies Observations

Overview of Throughput versus Distance Tests

The range of wireless technologies tests carried out in the three different underground locations have shown that 2.4GHz wireless technology overall offers favourable transmission range within underground tunnel environments. The intention of taking throughput measurements were that degradation in wireless performance correlates directly to a reduction in signal strength. Overall, it is clear that the data correlates with the signal strength measurements observed in the CW transmission tests, where certain technologies were more optimal than others in these environments. Table 3.5, below, shows a summary of the performance of each of the tests locations: maximum throughput and minimum throughput against the headline data rate figures of each of the technology standards. The ranges achieved following the right angle bends at both CSM and MÜZ Test Mines are also shown. Also, the results from the MÜZ ‘East Tunnel’ location proved interesting in that there was significantly less degradation observed in a non LOS situation, with gradual curves, as observed with the CW tests.

Table 3.5: Representative Summary of Performance Limitations for WiFi Tests

	Headline Throughput (Mbit/s)	Maximum throughput (Mbit/s) achieved in any location referred to in this table	Throughput (Mbit/s) at maximum range of 250m in Ashbourne Railway Tunnel	Minimum throughput (Mbit/s) along Ashbourne Railway Tunnel	Throughput (Mbit/s) at maximum range of 190m in CSM Tunnel A	Minimum throughput (Mbit/s) along CSM Tunnel A	Distance (m) at which signal lost round 90° bend into CSM Tunnel B	Distance (m) at which signal lost round 90° bend into shallow curve MÜZ's Main Tunnel (at 105m)
Bluetooth V1.1, Class 1	**1.0**	**0.56**	**0.49 (88%)**	**0.38 (68%)**	**0.54 (96%)**	**0.40 (71%)**	**>24**	**>25**
802.11b	**11**	**4.8**	**4.5 (94%)**	**1.4 (29%)**	**4.0 (83%)**	**3.0 (63%)**	**18**	**15**
802.11g	**54**	**21**	**17 (81%)**	**11 (53%)**	**18 (86%)**	**15 (71%)**	**19**	**10**
SuperG®	**108**	**25**	**21 (84%)**	**9.2 (37%)**	**9.5 (38%)**	**9.5 (38%)**	**12**	**5**
SuperG® + BeamFlex™	**108**	**32**	**25 (78%)**	**19 (59%)**	**26 (81%)**	**24 (75%)**	**7**	**10**
Belkin pre-n	**108**	**35**	**21 (60%)**	**20 (57%)**	**18 (51%)**	**5.9 (17%)**	**24**	**20**
Draft 802.11n	**270**	**43**	**26 (60%)**	**18 (42%)**	**32 (74%)**	**24 (56%)**	**17**	**N/A**

Table compiled by MRSL

Table 3.6, below, shows the percentage of throughput reduction over the first 100m in the straight LOS tunnels, comparing each of the technology's performance. As in the CW tests, the Ashbourne railway tunnel tests demonstrated the least degradation in performance, and the MÜZ 'Main Tunnel' was the worst overall due to the various RF obstructions.

Table 3.6: Percentage Reduction in Data Throughput per 100m in the Straight Tunnels

	Bluetooth Class 1	802.11b	802.11g	Super G	Super G + BeamFlex	Belkin pre-n	Draft 1.0 802.11n
MUZ Main Tunnel (100m)	18	0	41	64	10	9	N/A
CSM Tunnel A (190m)	0	1	8	28	2	20	10
Ashbourne (250m)	4	4	7	6	6	8	10

Table compiled by MRSL

Wireless Technology Comparison

Summary graphs of the wireless technology tests have been presented in this Chapter, detailed graphs of each of the individual tests in each location are given in Appendix A.2. A brief description of the individual wireless technology performance is given below:

Bluetooth: In all the locations Bluetooth maintained a consistent link, degrading gracefully compared with other technologies, proving robust in non-LOS situations, and achieving longer range than the WiFi technologies. The results suggest there is significant merit in employing frequency hopping spread spectrum used in Bluetooth. Given that it only has modest throughput the technology would offer a resilient solution where high data throughput was not a priority.

802.11b: This older standard did not offer any high performance in terms of range or robustness compared with the higher throughput WiFi counterparts. Given that the technology has been superseded by 802.11g there is no reason to recommend this technology.

802.11g: The widely available 802.11g results showed modest all round performance in terms or range and non LOS, offering a modest throughput. This particular technology employs OFDM to achieve the higher throughput (compared to 802.11b), which in theory should increase robustness to multipath interference etc.

SuperG: This *de facto* standard is solely intended at improving throughput by using channel bonding. The performance in an underground tunnel environment was actually no better that standard ‘802.11g’ and in some cases worse.

SuperG plus BeamFlex: The Video 54 BeamFlex adaptive antennas performed better than standard 802.11g and SuperG in the straight tunnels. The adaptive antennas are attractive in a multipath environment. However, this technology did not perform well in non LOS situations.

Belkin Pre-N: The ‘pre-n’ MIMO technology behaved erratically giving relatively low percentage of throughput in close proximity, but giving optimal performance beyond a certain point. When a link was established it did result in good performance in terms of both range and non LOS resilience.

802.11draft-n: The recently released (in 2006) Draft 1.0 802.11n technology did not achieve anywhere near the headline throughput figures quoted (270Mbps – 300Mbps), yet it achieved the highest absolute throughput of all the tested technologies, and maintained a robust link in both LOS and non LOS situations. All the standards from 802.11g and higher use OFDM and technologies that employ MIMO antennas are further enhanced in a mine environment.

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Comparison versus Office and Open Air Performance

Figure 3.55, Figure 3.56, Figure 3.57 and Figure 3.58 below show straight tunnel throughput data versus distance in different locations: an open office, outdoors and straight tunnel. Comparisons are given in these Figures for 802.11b, 802.11g, SuperG and Belkin pre-n (except no open office data available for Belkin pre-n). The graphs show that the throughput data is either comparable or worse for the straight tunnel transmission during the first 50m or more. However a relatively consistent throughput was maintained over longer distances compared with the steady decrease in throughput shown in open office and outdoor environment. This fully supports the observations made in both the theoretical predictions and the CW transmission in that a tunnel will take the form of a waveguide and actually assist propagation.

The straight tunnel data was taken from the CSM Tunnel A. The open office data is taken from white papers published by WiFi chip manufacturers Atheros (2003, 2004). The outdoor data for 802.11b, SuperG and Belkin pre-n are from an independent study by Tom’s Networking (2004). These tests were not performed entirely outdoors, where the first 15m path was through plasterboard wall and an external brick wall, hence the initial data was not used. The data for 802.11g was taken from Buffalo (2005) where the path is assumed to be entirely outdoors.

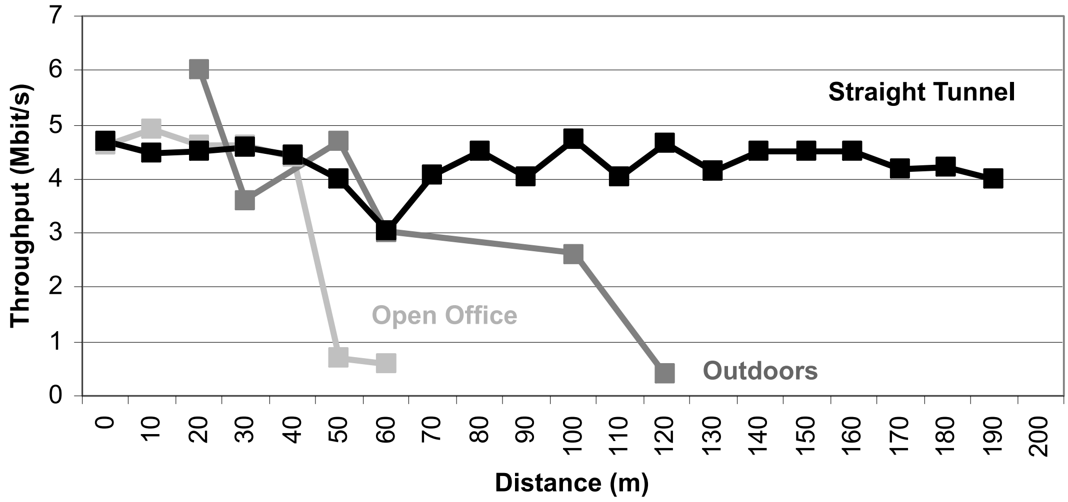


Figure 3.55: 802.11b in an Open Office, Outdoors and along a Straight Tunnel

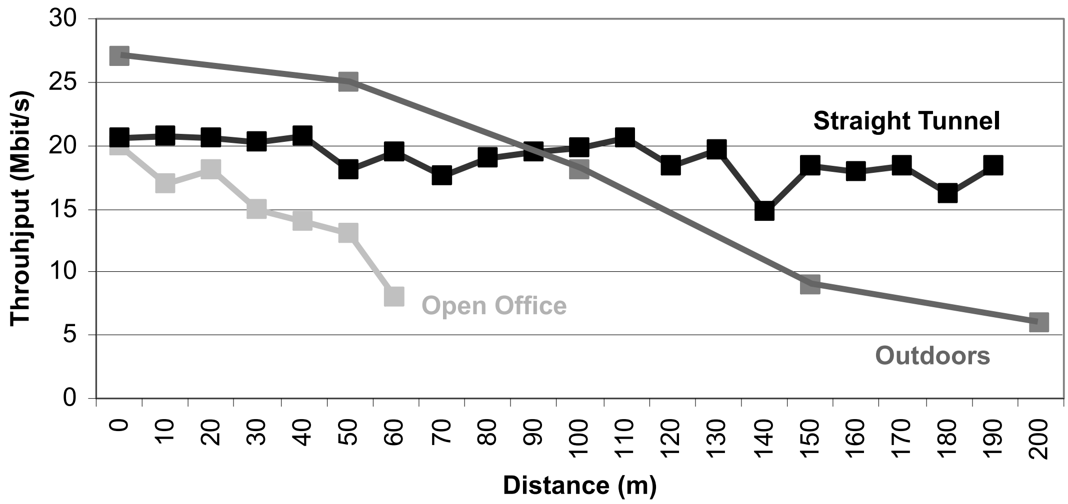


Figure 3.56: 802.11g in an Open Office, Outdoors and along a Straight Tunnel

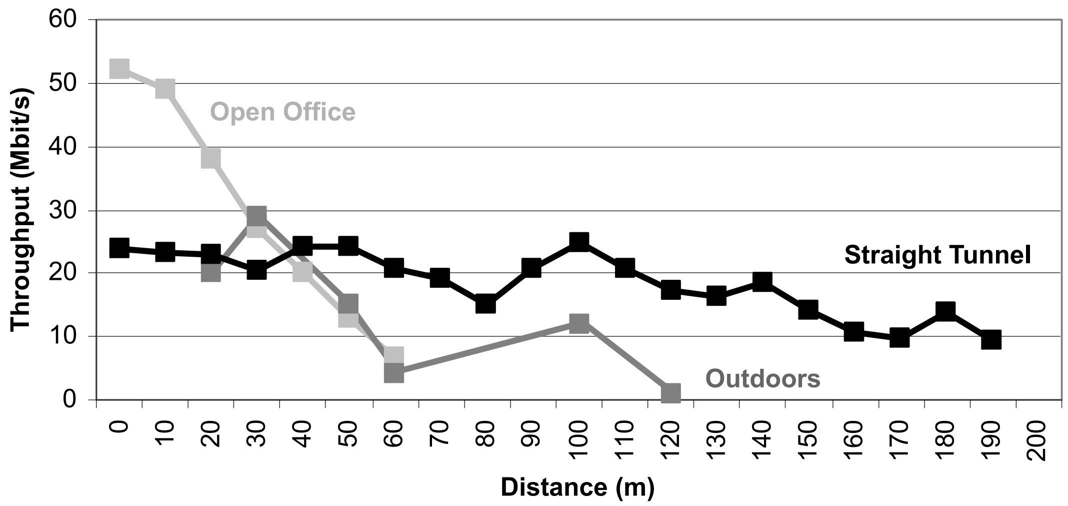


Figure 3.57: SuperG in an Office, Open Outdoors and along a Straight Tunnel

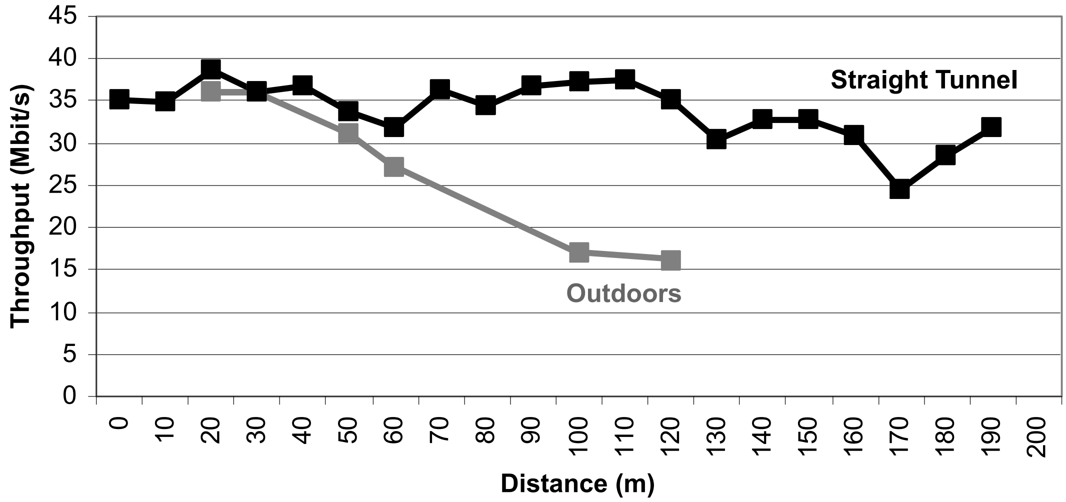


Figure 3.58: Belkin pre-n Outdoors and along a Straight Tunnel

3.3.8.3 Comparison with Waveguide Theory

Mode Attenuation

The theoretical analysis, presented earlier in Section 3.2.3, hypothesised that multiple modes will propagation in a tunnel. These can be either $E^{(v)}{}_{m,n}$ (electric components in the vertical plane) or $E^{(h)}{}_{m,n}$ (electric components in horizontal plane) modes, derived for a lossy dielectric waveguide model. The indices '*m*' and '*n*' indicate the number of half wavelengths in the horizontal and vertical direction respectively, running in any combination from zero to the highest m^{th} and/or n^{th} order mode determined by the tunnel cross section geomety cut-off frequency. If cross sectional dimension a > b, then the lowest order $E^{(h)}$ mode will be dominant, and if b > a then the lowest order $E^{(v)}$ mode will be dominant.

Using Equations 3.27 and 3.28, Figure 3.59, Figure 3.60, Figure 3.61, Figure 3.62 and Figure 3.63, below, show the mode attenuation rates due to refraction loss in the first 5 lowest order modes for Ashbourne, CSM Tunnels A, B C and D. Graphs are presented for $E^{(v)}{}_{0x}$, $E^{(v)}{}_{x0}$, $E^{(h)}{}_{0x}$ and $E^{(h)}{}_{x0}$ modes (modes with indices both *m* and *n* not equal to zero have increased attenuation, hence they are not represented here). In all the CW transmission tests, the antennas were vertically polarised for consistency, therefore the transmitting antennas would have predominantly coupled to the low order $E^{(v)}$ modes. However, it is impossible not to excite other modes therefore the signal will couple to other $E^{(v)}$ and $E^{(h)}$ modes. It was observed in the CW transmission tests that the attenuation significantly increased from Ashbourne to CSM, and that there was a smaller increase from CSM Tunnel A to B to C to D. The mode attenuation certainly correlates with the larger increase from Ashbourne to CSM. However, it is difficult to correlate the between the CSM tunnel data, based purely on mode attenuation.

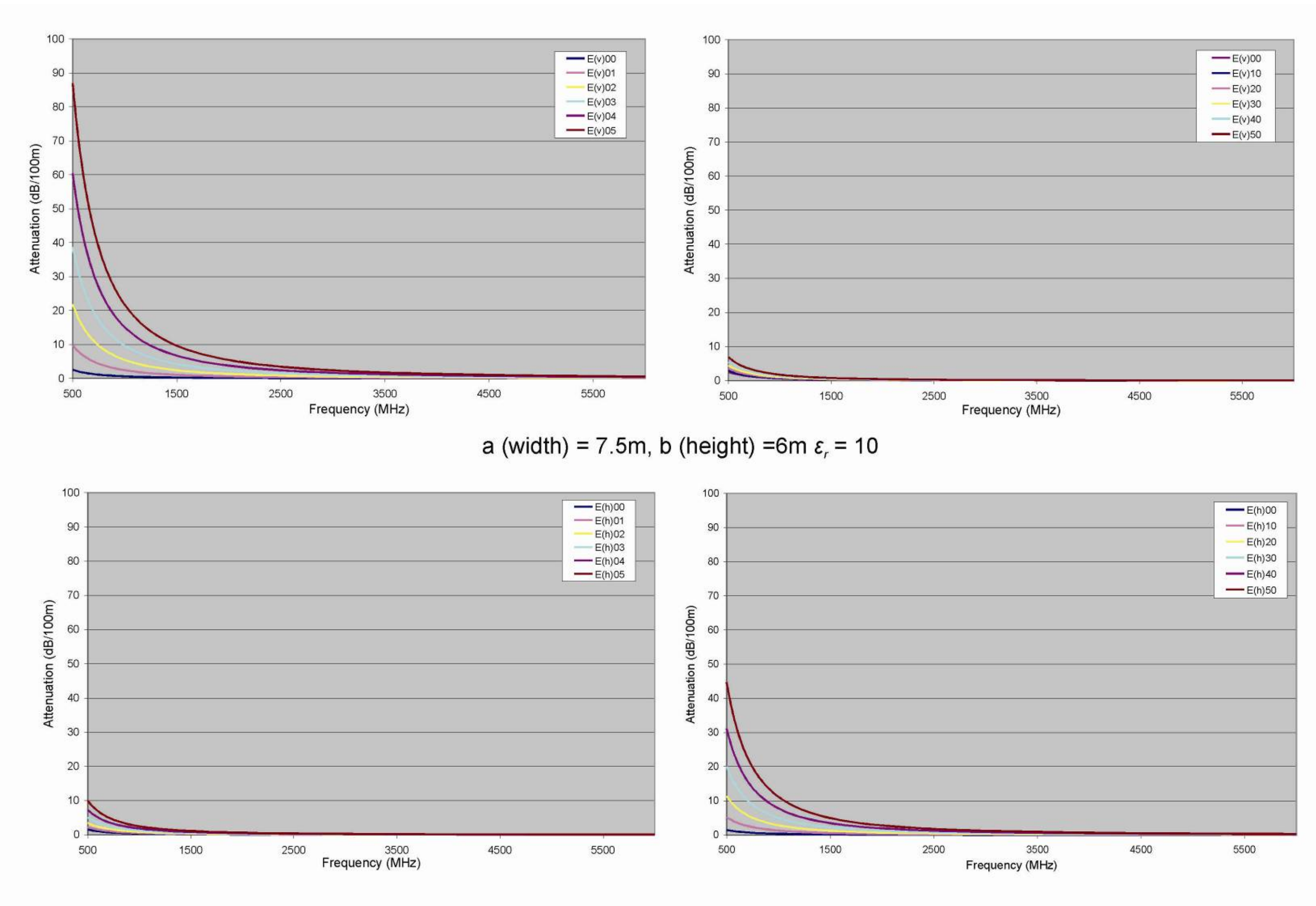


Figure 3.59: Ashbourne Waveguide Mode Attenuation

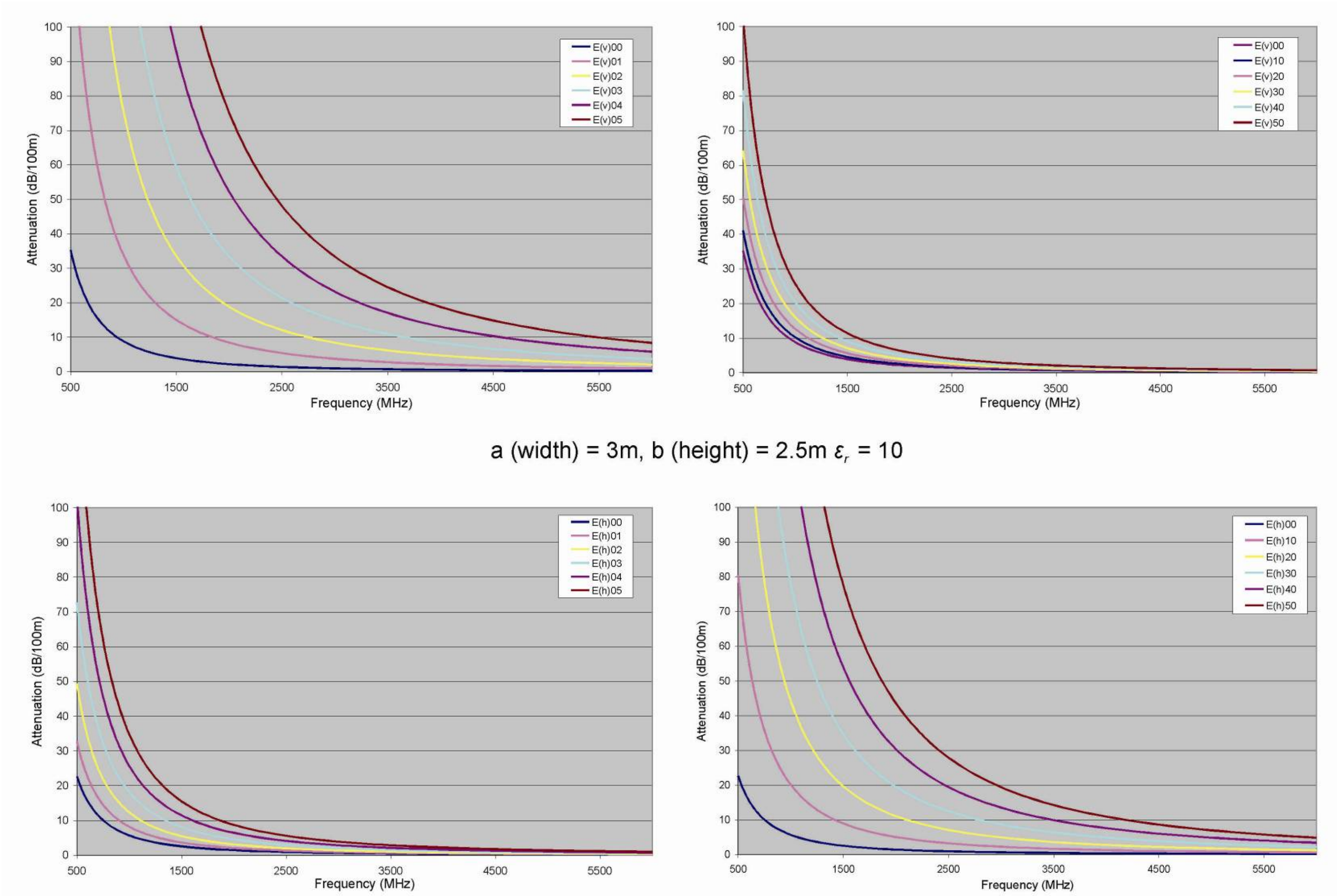


Figure 3.60: CSM 'Tunnel A' Waveguide Mode Attenuation

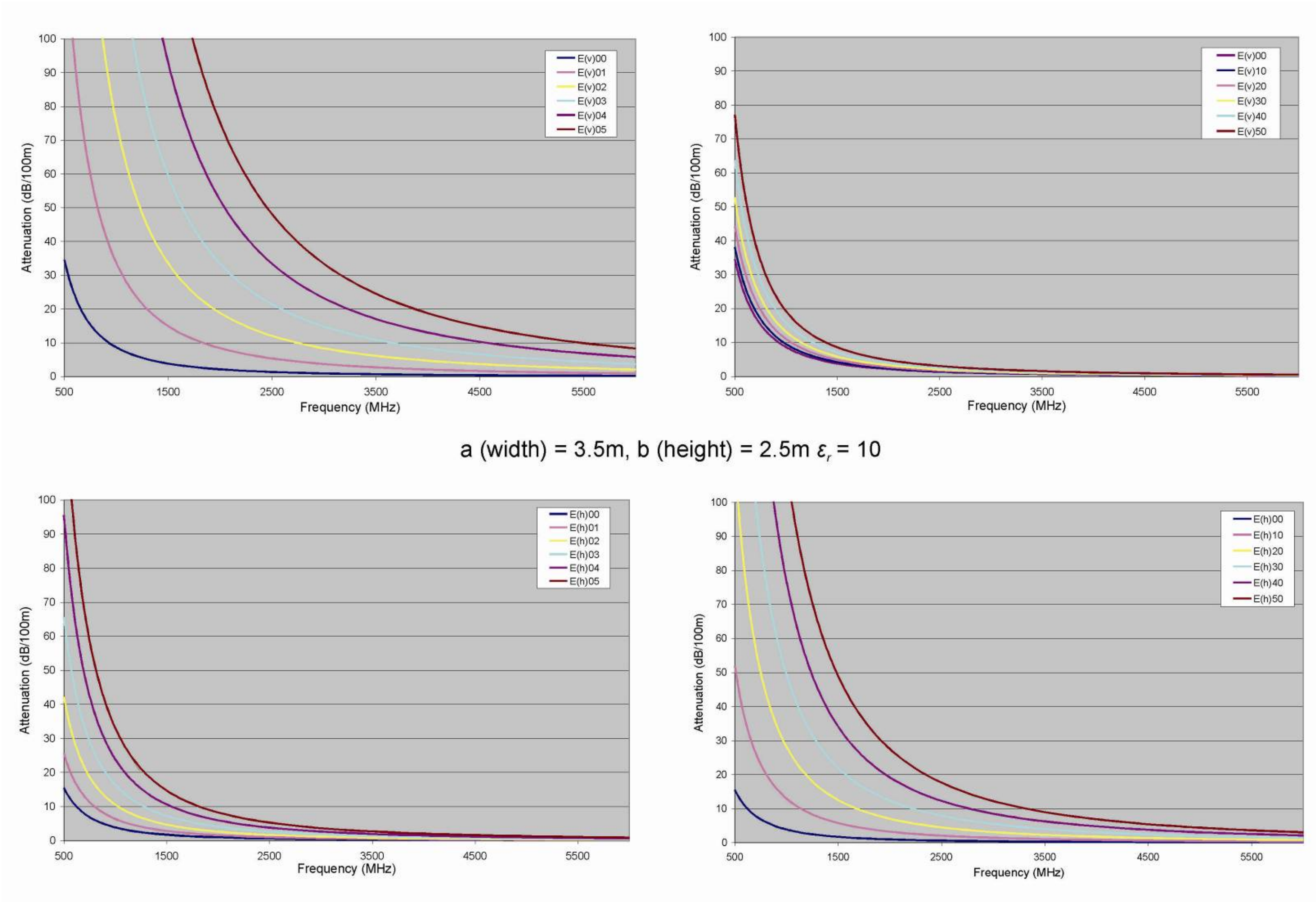


Figure 3.61: CSM 'Tunnel B' Waveguide Mode Attenuation

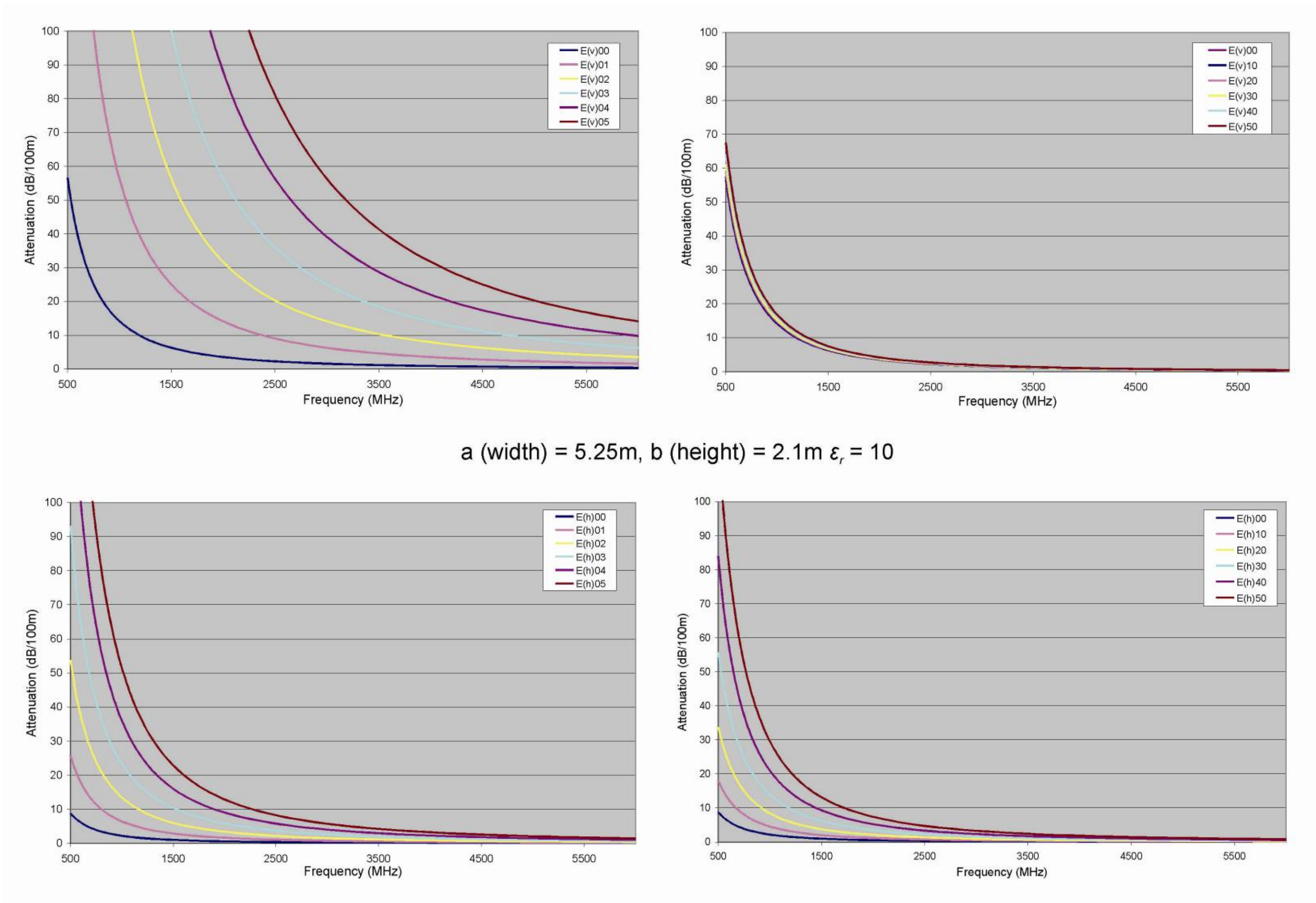


Figure 3.62: CSM 'Tunnel C' Waveguide Mode Attenuation

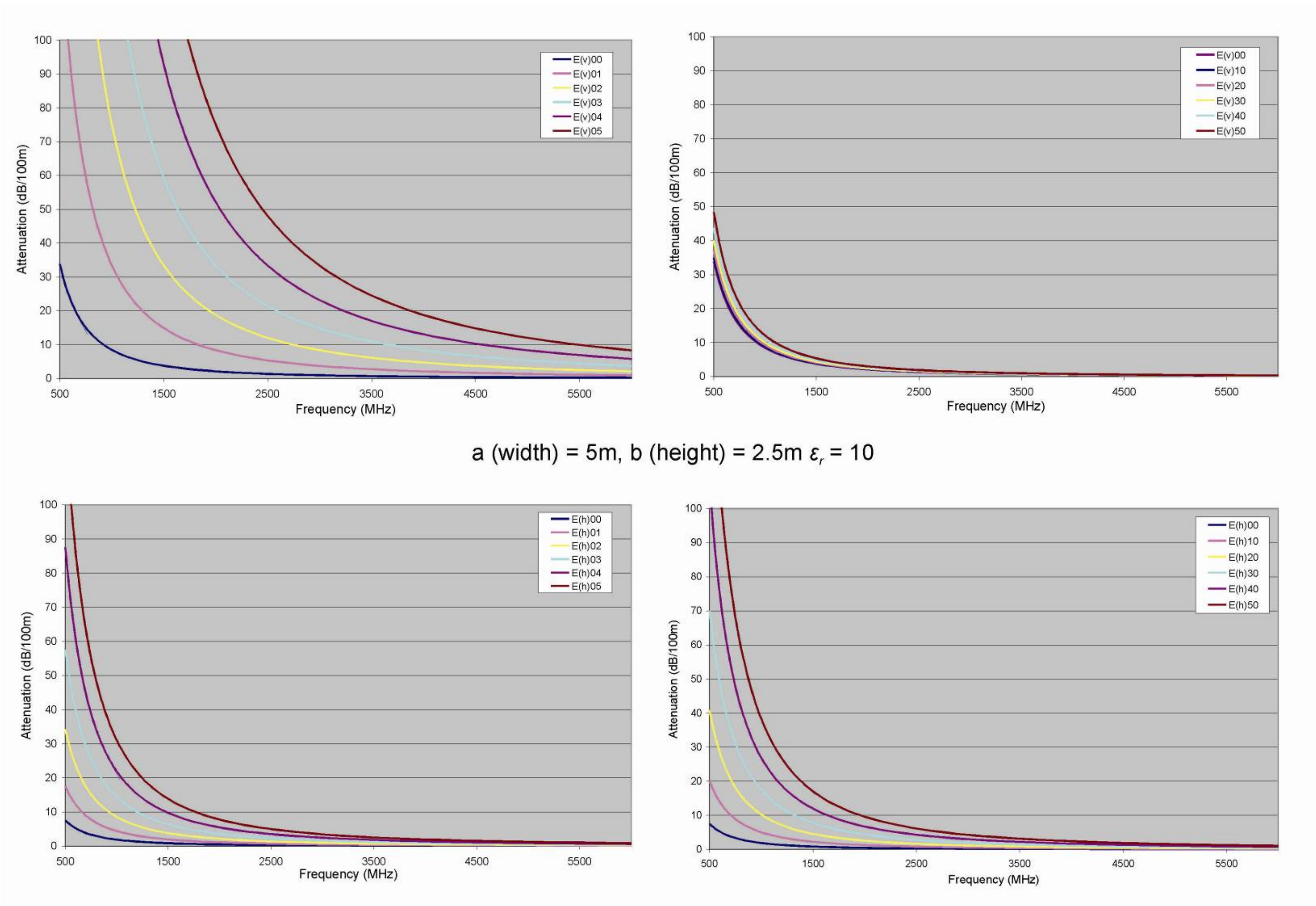


Figure 3.63: CSM 'Tunnel D' Waveguide Mode Attenuation

Intermodal Dispersion

While the transmitting antenna will predominantly couple to the low order $E^{(v)}$ or $E^{(h)}$ if the antenna is horizontally polarised), it is impossible not to excite other modes. Given the relatively large tunnel dimensions in respect to wavelengths, a large number of modes can propagate. For example, a tunnel of dimensions 3m x 3m, the indices '*m*' can equal anything up to 47 (for n= 0) and vice versa, or both *m* and *n* could equal 32. This would be a high order mode with 32 half-wave variations in the horizontal (*m*) direction and 32 in the vertical (*n*) direction.

The different modes have different phase velocities, which gives rise to standing waves, which can be observed as both constructive interference and destructive interference. This does offer a plausible explanation why we observed various fluctuations in tunnels, which were even perfectly straight with no obstructions, as in Ashbourne. Given the larger dimensions of Ashbourne, a higher number of modes would be permitted.

Another characteristic observed in all the CW propagation tests was an initial high rate of attenuation usually within the first 10m, then a low rate of propagation beyond this point. Figure 3.54, on page 109, gave an example for the CSM Tunnel A at 2.3GHz. The initial rate high rate was 1.88dB/m (or 188dB/100m) then the low rate beyond 10m was 0.11dB/m (11dB/100m). An explanation for this occurrence is due to the multi-mode propagation causing the intermodal dispersion. The high order modes, in fact, have a very high attenuation rate, for example the $E^{(v)}_{32,32}$ mode will have an attenuation rate in excess of 10dB/m. This means a significant amount of intermodal dispersion (or standing waves) due to the high order modes will diminish following approximately 10m. This would mean that increasing the tunnel dimensions would increase this initial rate attenuation, which is indicative of the results observed in the Ashbourne railway tunnel.

Additional Losses

As discussed in the theoretical analysis, tunnels are far from perfect waveguides and other factors besides refraction losses have to be taken into consideration. Table 3.7, below, shows calculated attenuation rates, which is the summation of the lowest order $E^{(v)}$ mode, wall roughness loss and wall tilt from Equations 3.27, 3.28 and 3.29 respectively. The measured attenuation rates in the various tunnels using omni-directional antennas are also shown. The $E^{(v)}$ mode refraction loss is calculated using tunnel cross-section dimensions (given in Table 3.4, page 111) with a 'worst case' relative permittivity $\varepsilon_r = 10$. The values used for rms tilt is $\theta = 0.5^{O}$, for Ashbourne, and $\theta = 1^{O}$, for the CSM tunnels. The values used for rms roughness is $h = 0.2$m, for Ashbourne, and is $h = 0.5$m, for CSM.

Table 3.7: Total Attenuation Rates at 2.3GHz and 5.8GHz Calculated vs. Measured

Test Locations	2.3GHz (dB/100m)		5.8GHz (dB/100m)	
	Theoretical	Measured	Theoretical	Measured
Ashbourne	2.65	5	6.34	4
CSM Tunnel A	15.76	14	27.19	14
CSM Tunnel B	15.16	18	26.95	18
CSM Tunnel C	20.06	21	28.59	29
CSM Tunnel D	15.41	32	27.002	32

The measured versus calculated attenuation rates demonstrate a degree of correlation. The significant increase in attenuation rates observed from Ashbourne to the CSM set of tunnels is shown to correlate well between the theoretical and measured results. However, it was observed that the attenuation rate increased from CSM Tunnels A into B into C into D at both frequencies showing the theoretical attenuation rates do not follow a similar pattern. The theoretical predictions are assuming each tunnel is identical in everything other than tunnel dimensions. However in practice the tunnels could vary significantly in terms of roughness, wall tilt, consistent cross-section dimensions and a range of other factors not taken into consideration. For example, pipes and cables occupied part of the tunnel sections, which may even increase the propagation guiding. The theoretical predictions do not take into consideration scattering effects due to gaps in the tunnel waveguide e.g. intersections, cavities/chambers. This would require a highly complex model to increase the accuracy of predicting the propagation attenuation rates.

Figure 3.64, below, shows the calculated losses for refraction, roughness, tilt and antenna coupling, from Equations 3.27, 3.28, 3.29 and 3.30, verses frequency. It can be seen that refraction loss and roughness decrease with frequency, tilt loss and antenna coupling loss increase with frequency.

Another observation from the theoretical model is that the losses were over estimated for 5.8GHz. It seems that the attenuation rates achieved at 5.8GHz was similar to that observed at 2.4GHz. An explanation for this is that the 'tilt loss' predicted as an increasing function with frequency, does not increase as dramatically as Equation 3.29 predicts. Zhang (2001) gives a modified equation for 'tilt loss', pointing out that these equations were originally derived as an approximation for lower UHF radio frequencies as opposed to microwave frequencies. Zhang's prediction is shown to correlate relatively well with theory in his paper at frequencies between 900MHz and 2GHz. Further work would be required here to compare this with the higher microwave frequencies.

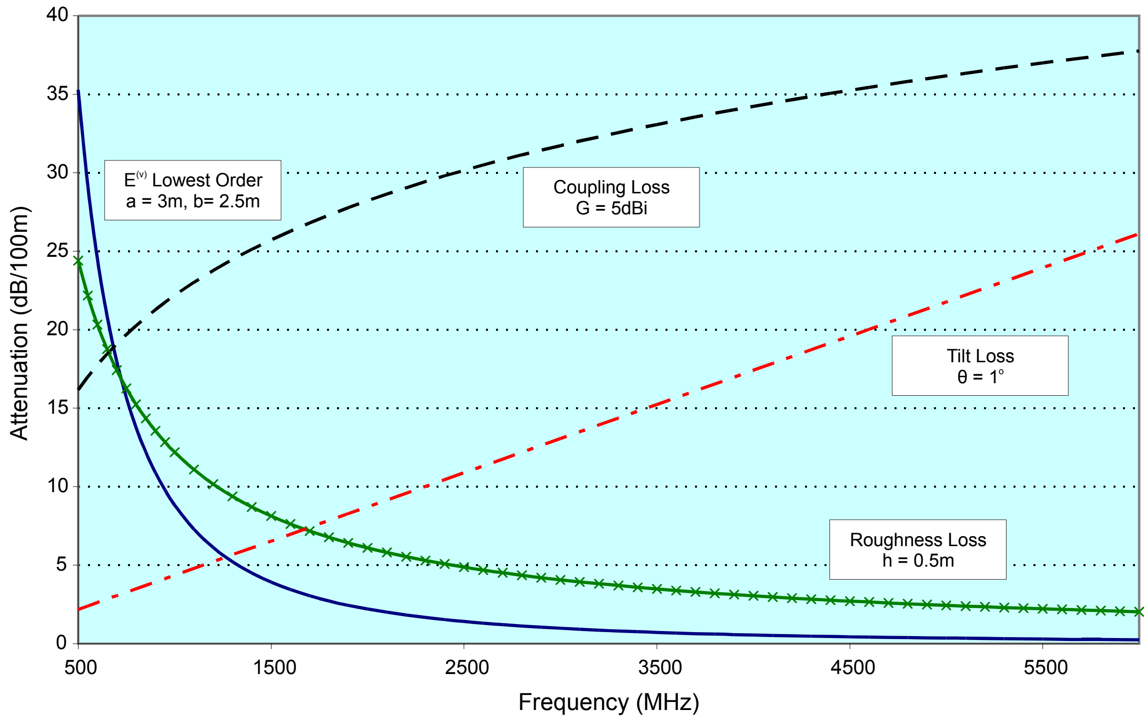


Figure 3.64: Calculated Tunnel Propagation Losses for Tunnel A

From Equation 3.30 we recall that the antenna coupling loss is given by

$$\frac{Pmn}{P_x} = \frac{2\pi ab}{\lambda_0^2 G} \sin^{-2}\frac{(m+1)\pi x}{a} \sin^{-2}\frac{(n+1)\pi y}{b}$$

For the lowest order mode at the centre of the tunnel, where x = ½ a and y = ½ b, the equation for antenna coupling loss becomes

$$\frac{Pmn}{P_x} = \frac{2\pi ab}{\lambda_0^2 G} \tag{3.32}$$

The various coupling losses for each of the test locations are calculated for each of the antenna gains used at 2.3GHz and 5.8GHz below in Table 3.8. These calculations take into consideration the quoted antenna gains only. They do not include the hypothesised more efficient coupling of the directional patch antennas which manifests itself as a higher gain in the tunnel environment, where we observed a notable improvement in performance using patch over omni-directional antennas. Antenna coupling loss increases with frequency, or with decreasing wavelength in regard to tunnel cross-sectional area. In fact the cross sectional area increases from CSM Tunnel A into B into C into D into Ashbourne Tunnel, therefore as shown the antenna coupling increases into each of these locations.

Table 3.8: Calculated antenna coupling losses for each test location and antenna gains

Test Locations	5dBi (2.3GHz)	9dBi (2.3GHz)	18dBi (2.3GHz)	11dBi (5.8GHz)
Ashbourne	37.2	33.2	24.2	39.2
CSM Tunnel A	29.8	25.8	16.8	31.9
CSM Tunnel B	30.3	26.3	17.3	32.4
CSM Tunnel C	31.1	27.1	18.1	33.1
CSM Tunnel D	31.6	27.6	18.6	33.7

Speculatively, it can be suggested this offers some correlation between the measured data shown in Table 3.7 earlier; however it is clear that it is more complex than this. Particularly given that directional antennas offer better performance than omni-directional antenna. Using a directional antenna, the energy is being more efficiency excited into the low order propagation modes. It can certainly be suggested from this that there is merit in considering circular polarisation. Anecdotal evidence suggests that circular polarisation couples more efficiently to the low-order propagation modes.

Limitations of Theoretical Modelling

The theoretical analysis presented has given further insight into certain characteristics observed during the various tests conducted. However, it is also recognised that the models discussed are still idealised and that tunnels vary significantly between environments or even within environments. There are a whole range of parameters to consider including, tunnel size / geometry, rock electrical properties, wall imperfections (roughness, tilt), scattering at junctions, antenna coupling, groundplane influences (water, metal work), RF screening, propagation around bends etc. Whilst some of these characteristics have been examined it would be a highly complex exercise to model UHF and SHF propagation in tunnels in any more depth, and is beyond the objectives of this thesis. Further work here would ideally require suitable electromagnetic modelling tools; there are currently a number available including Microwave Studio from CST (Computer Simulation Technology), COMSOL from Comsol Inc., SuperNEC from Poynting Software, and IE3D from Zeland Software. Hazdra at al. (2005) presents a useful review of EM microwave software modelling tools. The three most common numerical methods used to solve Maxwell's equations are Finite Element Method (FEM), Finite Difference Method (FDM) and Method of Moments (MOM).

3.3.9 Wireless Propagation Tests Conclusions

Extensive tests have been carried out using both ‘pure’ continuous wave (CW) transmission and a range of wireless technology tests. Three different locations have been used for comparison: disused railway tunnel, hard rock test mine and a coal mine replica test facility. The CW tests involved using both 2.3GHz and 5.8GHz transmission equipment and different antennas in the three locations. The wireless technology tests involved performing throughput versus distance for Bluetooth and WiFi technologies including: 802.11b, 802.11g, SuperG, SuperG (plus BeamFlex), 802.11pre-n (MIMO) and 802.11draft-n (MIMO). A number of interesting observations have been made.

The CW transmission tests have shown that at these microwave frequencies electromagnetic propagation in tunnels will take the form of a lossy waveguide. Comparisons have been made to the lossy dielectric waveguide model presented earlier in this Chapter. The CW tests have shown that low attenuation rates can be achieved over relatively long distances. In all situations there were two distinct propagation rates up to a critical point, usually around 10m, up to this point the attenuation rates were relatively high, and beyond this point low attenuation rates were achieved. This phenomenon has been explained through the presence of multiple waveguide propagation modes, where the high order modes with high attenuation rates would dissipate after a few metres.

The use of patch antennas was also shown to offer significantly improved performance compared with omni-antennas, significant improved non line-of-sight (non LOS) coverage was achieved. It was also shown that both 2.3GHz and 5.8GHz transmission characteristics are similar in tunnels. Given that 2.4GHz is currently widely available this is the natural choice in frequency. However, for various reasons including interference, 5GHz and upwards technology is becoming more widely available.

The aim of using the three locations was to compare a completely bare perfectly straight tunnel (Ashbourne), against a hard rock mine environment (CSM Test Mine) and a typical European coal mine environment (MÜZ). Similar performance and attenuation rates were achieved in each location. The exception to achieving low attenuation rates was in the MÜZ main tunnel, where there was significant cabling, pipes and metal equipment obstructing the transmission. As expected this had a higher degradation effect. The random fluctuations in received signal were also observed in all locations, and particularly so in the empty railway tunnel. These random peaks and troughs are explained by the presence of standing waves causing both constructive and destructive interference. In an additional interesting observation made at MÜZ was in low obstructed non LOS situations, where the gradual gradient tunnel bends and metal lining infrastructure seem to enhance the propagation.

The range of wireless technology tests has shown all 2.4GHz technology to offer a reasonable performance in underground environments. Technologies employing diversity, and in particular frequency diversity, has shown notable dominance over others e.g. technologies employing FHSS and OFDM. MIMO antenna configurations also seem to offer increased performance due to the fact it offers both directionality and antenna diversity. Comparing the tunnel performance with standard office and open air results has shown a distinct enhancement in transmission range distances due to the waveguide behaviour.

The results have shown good agreement with the waveguide theory discussed earlier, where some of the observations have been explained through waveguide characteristics. The limitations of the theoretical analysis have also been discussed, along with a brief discussion on the software modelling tools that would be required to conduct further work.

3.4 Summary

This Chapter has investigated subsurface electromagnetic propagation characteristics at UHF and SHF frequencies. The investigation has been carried out through literature review of previous theoretical and experimental work, theoretical analysis, and extensive practical tests. It has been shown that EM propagation at these frequencies in underground tunnels will behave as a lossy dielectric waveguide. Attenuation tends to decrease with increasing frequency. However, there are significant factors to take into consideration, which include: RF obstacles (e.g. vehicles), metallic infrastructure, presence of cables/pipes, water, tunnel size/geometry, antenna efficiency etc. Radio propagation tends to become increasingly restricted to line-of-sight at the higher frequencies, with the attenuation around corners being very severe. This investigation has shown that microwave frequencies are an optimal choice for robust wireless transmission in tunnels. However, at these frequencies it can be clearly seen that in order to achieve mine wide coverage active repeaters are needed, which can completely regenerate the modulated signal and discriminate against noise. New mesh wireless networking technology has a lot of potential in an underground environment; the use of this technology as a means of extending the underground coverage and increasing transmission resilience is introduced in the next Chapter.

Chapter 4: Mesh Networks in Underground Environments

The concept of mesh wireless networking is introduced in this Chapter, with particular respect to applications in underground mining. The characteristics of low power wireless mesh networking technology are examined relating to the new IEEE 802.15.4 and Zigbee technology. Details of tests carried out at Camborne School of Mines Test Mine facility and at Thoresby Colliery are presented. Finally the Chapter identifies potential applications using the low power wireless networking technology with particular respect to underground safety.

Wireless personal area networks (WPAN), e.g. Bluetooth, and low-rate WPAN (LR-WPAN) technology, e.g. Zigbee/IEEE 802.15.4, are a new breed of ISM band technology with the ability to set-up ad hoc (or mesh) network topologies. Bluetooth can support up to 8 devices in an ad hoc piconet, but slave devices can only communicate with the master. However, piconets can be joined to form what is called a scatternet. Whereas, IEEE 802.15.4 technology can support up to 255 nodes in a single mesh network. Bluetooth is designed, and well suited, for cable replacement applications to meet the demands of streaming video and high quality audio. LR-WPAN technology is a low rate, low power, and low cost alternative, aimed specifically at monitoring and control applications. It has a long battery life and places less demand on microprocessor power, enabling the devices to be smaller. The ability to set up large mesh network topologies greatly increases the robustness and survivability of a wireless network.

4.1 Mesh Wireless Networking Technology

In the past, wireless transmission has mainly provided point-to-point (e.g. connecting to a remote sensor or PLC) or point-to-multipoint data communications. In general, point-to-multipoint networks, forming a star topology (Figure 4.1), are very well suited to applications that require high speed, high data rates or wide area coverage (long range transmission). The IEEE 802.11 WLAN standard (transfer computer files, video) and the mobile phone (cellular) network are good examples of this. However, for industrial applications it is very important that the network is rugged, reliable and adaptable. A mesh network forms a multipoint-to-multipoint link, where a single node establishes a link with other neighbouring node within transmission range to form a mesh topology (Figure 4.2).

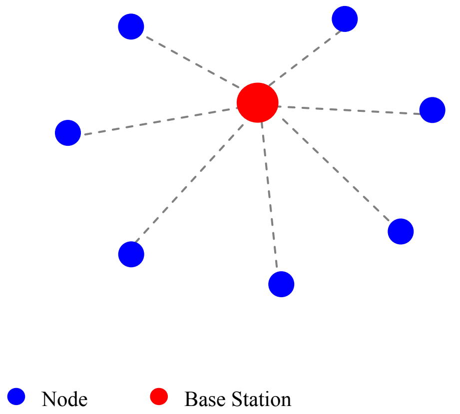


Figure 4.1: Wireless Star Topology (Point-to-multipoint)

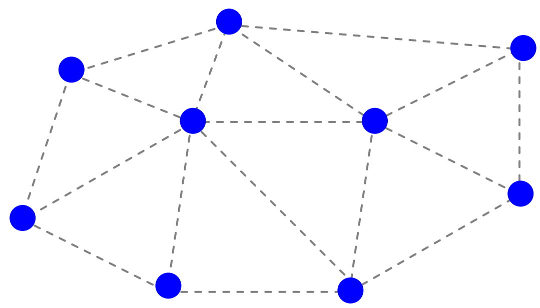


Figure 4.2: Wireless Mesh Topology (Multipoint-Multipoint)

A recent article published in an IEE magazine (Moss, 2004) discussed the great potential mesh (or ad-hoc) networks have to offer in future applications in many industry sectors. Research projects by MIT looking into a 'rooftop network' to share broadband Internet, and the installation of the Ember Corporation technology into a water treatment plant are mentioned. The paper also makes reference to another interesting project by BAE Systems, where a remotely controlled vehicle can deploy wireless ad hoc nodes to send data back from environments that may be too hazardous for humans to enter. In all, the article supports the potential and exciting applications in the use of mesh (ad-hoc) networks, summarising many of the advantages such as the ability to self-organise, self-heal, scalability and flexibility they have to offer.

Poor and Brent (2002) discuss the many advantages the 'mesh' networking configuration has to offer. These are summarised below.

Self-Configuring: The nodes in the mesh network are self-organising, and do not require any manual configuration of individual nodes. The network automatically discovers new nodes and incorporates them into the network without the need for a system administrator. This makes the network very flexible and efficient for installation and maintenance purposes.

Self-Healing: The self-healing properties of the network increase the overall network survivability. If a device in the network fails, data is re-routed through other adjacent nodes automatically.

Redundant: Due to the self-healing properties, a network can be deliberately 'over designed' by adding extra nodes to provide additional paths for sending data. This is an effective method for achieving redundancy.

Scalable: The mesh is also scalable as it supports large numbers of addressable end points. A mesh network can support up to 255 nodes. However, networks can be linked to increase this to thousands of nodes.

Reliability: These properties are all aimed at improving the overall reliability and adaptability of the mesh network. The mesh network is designed to adapt well in various environments, particularly if the environment is poor for radio propagation. Allowing for redundancy aims to improve the network survivability. Nodes in the mesh network also act as repeaters, which can be used to improve the transmission range and generally improving reliability.

4.2 Potential Underground Applications

The anticipated roles of wireless mesh network technologies underground include:

- Implementation of wire replacement schemes to sensors
- Vehicle and personnel zonal tracking and deployment monitoring (RFID replacement)
- High integrity stand-off control systems
- Provision of data, voice and data to mobile or flexible systems
- Local telemetry (e.g. 'vital signs') from individuals or groups
- Increased resilience of response in emergencies

Three examples, which have been identified for further consideration within this research are:

(a) Local telemetry of critical physiological parameters from rescuers and firefighters. This includes the possibility of monitoring core body temperature, heart rate and general activity.

(b) As a scheme to collect data from a multiplicity of sensors on mining machines and equipment. In this case, a potential application would include the telemetry of diagnostic data from machine condition sensors on a conveyor drive head scheme.

(c) Zonal location information – Active tracking of personnel and vehicles in an underground is highly valuable information, particularly from the safety and post incident emergency perspective.

4.2.1 Local Telemetry of 'Vital Signs'

A number of international incidents have been identified where otherwise healthy rescue personnel have collapsed from heat strain. Multiple fatalities were recorded in the Polish

Miwka-Modrzejow coal mine incident in February 1998, and the US Barrick Mieckle mine in October 2002. In each case, prevailing conditions involved high heat and humidity (Jones *et al.* 2003).

The report by Jones *et al.*(2003) discussed that heat stress is a multi-component hazard in many workplaces, including mining. Whilst psychrometric parameters and estimations of metabolic rate can be used to provide a general indication of heat burden, ultimately there is a requirement to monitor an individual's physiological parameters to determine, with any certainty, the proximity to safe working limits in severe conditions. Measurement of heat strain may include skin/oral temperature, body core temperature, weight loss from sweating and heart rate criteria. Focus is often given to the measurement of deep body core temperature, since there is a variety of previous research, which confirms that this is the most critical physiological parameter concerning physical activities carried out in hot and humid underground mine conditions.

Within this research, the use of Zigbee/IEEE 802.15.4 systems has been examined as a means of providing a low power, high integrity mesh network between local rescue team members or firefighters, and the local command and control centre. In underground mine rescue, the vital signs data could either be telemetered to the fresh air base using adaptations to the team's existing wired communications systems, or possibly to the team captain. In a surface firefighting environment, the benefits of multiple transmission pathways within the mesh network provide significant redundancy benefits, which are likely to translate into a general enhancement in coverage and resilience of firefighter communications.

4.2.2 Remote Machine and Sensor Telemetry

Another potential application is data acquisition from an array of sensors, which could typically be environmental monitoring, distributed temperature sensors, or machine diagnostic (condition monitoring) sensors on a complex mining sub-system. For example, this could be a conveyor head drive assembly or perhaps mobile plant. Where total data requirements are low then it is possible to anticipate the use of "fit and forget" battery-powered Zigbee-based sensors. This would offer significant benefits, with freedom from the problems of routing and protecting delicate cables. It is also possible to anticipate temporary fitment of transducers with inbuilt Zigbee data communications. These would offer the ability to simplify commissioning, model verification, and periodic machine performance tests.

The 'intelligence' and security built into the Zigbee/ IEEE 802.15.4 standard suggests further use in plant asset tracking and identification, and as a possible anti-theft measure. The very low power consumption, small physical size and mesh transmission capability allow devices to be inbuilt or physically embedded into machinery e.g. intelligent rock bolts.

4.2.3 Zonal Location Information

Current initiatives to implement high data bandwidth, 'backbone' data communication network schemes underground in UK Coal Mines (Ford 2006) will permit a number of intelligent sub-systems (or sub networks) to exploit the data highway. One generic subsystem is RFID (radio frequency identification devices, otherwise known as 'tags' or transponders). The primary applications for RFID devices are for deployment monitoring and tracking throughout a mine of mine personnel, materials and vehicles. The safety benefits are that the mine management can maintain a real-time view on exactly where personnel and equipment are located. In the event of an emergency or mine evacuation, a complete log of individual times and locations in a database can be quickly accessed permitting their status to be checked and the incident to be better managed. The status of personnel who routinely work or travel alone is important in this regard. Associated systems are feasible which will issue a warning against entry when hazardous areas are approached. Time and location information also boosts operational efficiency and effectiveness, in that key staff can be rapidly located and contacted, and deployment logistics can be updated in real time. Management of transport systems can be greatly improved if the location and status of vehicles and their materials/load can be monitored. The benefits of location and status information have been recognised for a number of years. However, efforts to implement RFID schemes have hitherto been compromised by high-cost, technical limitations and the proprietary nature of the systems. A number of active transmitter or transponder-based solutions have been introduced into mining for access control, vehicle and personnel deployment monitoring and zonal location. In each case hardware for local interrogation systems has been relatively cumbersome and costly to install. This is particularly the case for low frequency inductive tags, which require substantial coils to generate interrogation fields of appropriate magnitude and physical geometry. Electronic location determination systems employing tag-based technologies have to date been relatively expensive if a substantial number of tag reading points are required, which has limited their exploitation in the mining industry.

In principle, both Bluetooth and Zigbee technologies could meet an application requirement of providing an intelligent tag function, providing a lower cost replacement for older proprietary RFID technologies. The Zigbee/IEEE 802.15.4 specification technology appears to offer the best prospects for a low cost device able to provide a zonal detection capability with relatively low costs of implementation. The technology is well suited to intermittent data and applications requiring low latency data transmission (Zigbee has a network device recognition time of potentially ~30ms compared with up to 3s for Bluetooth). In terms of power considerations, Zigbee is designed to optimise slave power requirements, whilst Bluetooth has a power model comparable to a mobile phone (requires regular charging) and is designed to maximise smaller ad-hoc data streaming network functionality.

4.3 Mesh Routing in LR-WPAN

4.3.1 Upper Layer Network Formation Policies and Algorithms

The IEEE 802.15.4 LR-WPAN standard is essentially concerned with PHY and MAC layer implementation. The network and API (application interface) layers are handled within the Zigbee or proprietary stack implementation, generally in a dedicated microcontroller. The division of functions is shown in Figure 4.3. The algorithms associated with network formation and device association are performed by upper layers of the protocol, thus not defined in the IEEE 802.15.4 standard. The networking layer, or more specifically topologies and routing algorithms are discussed in this section relating the Zigbee standard or proprietary IEEE 802.15.4 standards based technology.

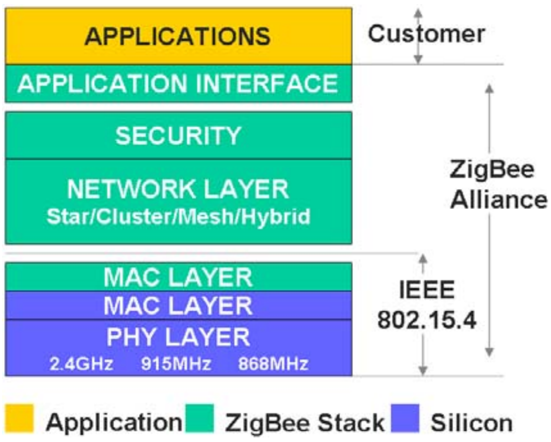


Figure 4.3: Division of functions between IEEE 802.15.4 and Zigbee

4.3.1.1 The Network Topology Decision

Since IEEE 802.15.4 is capable of supporting a large number of ad hoc network topologies, the optimal network topology depends on the intended application. Further, if the selected network topology is a peer-to-peer topology in which multi-hop communication is planned, then the choice and effectiveness of the routing algorithm must also be considered. Much of the following discussion is attributed to Gutierrez *et al.* (2004). Figure 4.4 and Table 4.1, below, summarise the major network topologies, including their strengths, weaknesses, and typical applications. It is noted that the choice of topology is generally not restrictive; most network topologies will function in a range of applications, however parameters such as message throughput and latency, and network device performance parameters such as power consumption need to be carefully considered.

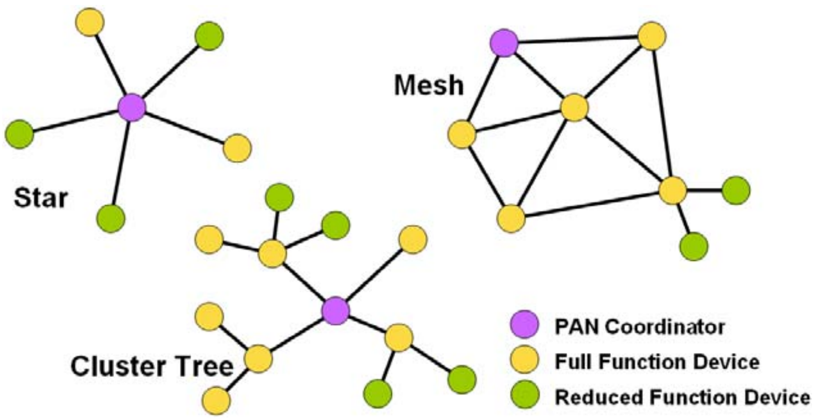


Figure 4.4: IEEE 802.15.4 network topologies

Table 4.1: Strengths, weaknesses and applications of wireless network topologies

Network type	Strengths	Weaknesses	Applications
Star	Low message latency. Centralised network control	Can cover only a limited physical area (single-hop communication)	Home automation. PC peripherals
Peer-to-peer	Can cover a large physical area (multi-hop communication)	Higher message latency	Wireless sensor networks, industrial control and monitoring
Flat	Simple network devices	Does not scale well as the number of potential destination devices increases	Wireless sensor networks
Cluster	Supports a larger number of potential destination devices	Uneven power consumption among network devices	HVAC systems
Cluster tree	Can support very large networks	Network maintenance overhead	Industrial control and monitoring

4.3.1.2 PAN Coordinator Selection

The first step in network formation is the selection of the PAN coordinator. There are several application-dependent scenarios as follows.

Dedicated PAN coordinator

In certain situations, it is clear that only one device, the gateway device, needs to be connected to an outside network, where this device is also the PAN coordinator. The network can be designed with only one FFD in the network (as the PAN coordinator), with the rest of the network populated with RFDs. In such a network, only one device is eligible to become the PAN coordinator. This greatly simplifies the network thus also reducing the power budget of remote devices.

Event-determined PAN coordinator

It is desirable in some applications to employ a large number of identical devices, where any one of which may become the PAN coordinator. This could be a dynamically changing network, every device must be an FFD. The assignment may be triggered by an external event, e.g. by the user.

Self-determined PAN coordinator

An example of this type of application is a location-determining network. The purpose of this network is to determine the relative location of each network device, possibly by means of a distributed algorithm. In this type of application, there may be no external gateway, so any network device may serve as the PAN coordinator. One way of forming this type of network is to employ a form of power-on-network formation, in which the upper layer of each device instructs the MAC to begin an active channel scan upon device power-up. The first FFD device to complete this scan becomes the PAN coordinator.

4.3.1.3 The Use of Beacons

The IEEE 802.15.4 standard defines beacons for use in network discovery. Beacons are useful for coordination and synchronisation of an active network, and in applications for which it is desirable to minimise coordinator-to-network device message latency. However, beacons have disadvantages. For example, if no messages are expected from the coordinator to the network device, and only light traffic is expected from the network device to the coordinator, then beacon transmissions will waste the power of the coordinator, and reception of the beacons will waste the power of the network device. A solution is to stop the beacon transmissions and have the network device asynchronously transmit its (infrequent) data frames as they are generated. This approach is relevant if the network is in a star configuration, and the PAN coordinator may be externally powered. In this case, the PAN coordinator may operate constantly in receive mode, while the battery-powered network devices need only expend significant energy when it transmits a state change to the PAN coordinator. As a result, the battery life of the network device may be extended. This applies even if occasional coordinator-to-network device traffic is expected, requiring the network device to poll the coordinator for data.

4.3.1.4 The Star Network

Star network topologies are a good design choice for applications that need to cover a limited physical area, so that a single device (the master) may be in range of all other network devices (the slaves), e.g. standard WiFi topology. IEEE 802.15.4 star networks must employ an FFD as the coordinator; however, the other network devices may be either FFDs or RFDs.

Since star networks by their nature are single- and double-hop networks, message latency can be lower than in multi-hop networks. If latency is a critical performance metric of the desired application, a guaranteed time slot (GTS) may be assigned by the PAN coordinator to reserve time for a particular network device, thus avoiding network contention. In this way, an IEEE 802.15.4 star network can provide maximum message latencies as low as ~16 ms. It is possible to extend a single GTS to enable a single network device to have the entire channel bandwidth, potentially in excess of 115 kbps for the 2.4 GHz band, for relatively high-bandwidth applications.

Message routing in star networks is rather different to message routing in peer-to-peer mesh networks. The PAN coordinator of a star network can hear all network devices and directly controls access to the shared channel. Routing in star networks is viewed as occurring in the MAC layer, as packet switching, rather than in the network layer as part of a peer-to-peer message routing algorithm. The advantages of routing at this level is implementing simple message relaying and potentially higher throughput as the message ‘overhead’ is reduced.

4.3.1.5 Flat Mesh Network Topology

A ‘flat’ mesh network is the simplest type of peer-to-peer mesh network. A network composed of a number of identical network devices, not all of which may be in range of any one device. Messages may be relayed from source devices to destination devices via a large number of routing algorithms. A principal problem to be overcome in a flat mesh network design is the problem of addressing. Because the network is logically flat (i.e., there is no hierarchy) and there is no other grouping or organisation of network devices, the address of a network device does not provide clues to the route needed. Further discussion is given later in the section. It is noted that the technical field of network route discovery and route maintenance is complex and there are inherent trade-offs between static and dynamic (convergence) performance and device complexity (and thus device stack size). Nevertheless, many routing algorithms have been devised for such networks, a few of which are discussed below.

Flooding

The simplest method of routing messages in flat mesh topology is to broadcast messages to all network devices. Whilst this would ensure that the message reached the destination, it is inefficient, especially for large networks. Broadcasting messages to unintended recipients simply wastes power. This method is not commonly used in practical networks to transmit data traffic, although it is needed in nearly all networks for at least some control and status message traffic functions. This could also be a useful override safety feature in a mesh network.

The Bellman-Ford algorithm

The Bellman-Ford algorithm requires all network devices to maintain a routing table that contains routing costs for the optimum route to all other network devices, plus the address of the first device in that route. Usually the routing metric is the number of hops, although more complex, multiple cost metrics can be used. Devices maintain their tables by exchanging them with all devices within their range, and then comparing entries by destination. Although an efficient routing algorithm, the Bellman-Ford algorithm suffers from poor dynamic behaviour. If a communication link is broken, its convergence behaviour to derive the updated route metrics is slow and potentially unstable in certain circumstances. Also, the routing tables must have as many entries as there are network devices in the network; therefore the costs to exchange them actually limit the size of the network.

The GRAd (Gradient Routing for Ad hoc networks) algorithm

The GRAd algorithm requires all network devices to maintain a cost table that lists the routing cost to each potential destination device (as opposed to the Bellman-Ford algorithm which lists all network devices). Messages are broadcast by the source to all network devices in range, along with the cost value to the destination found in the source's cost table. Neighbouring devices hearing the broadcast message, and having a routing cost for the destination less than that sent by the source (and therefore presumably closer to the destination), waits for a random period and then rebroadcasts the message, listing its own routing cost. Acknowledgment is passive; the acknowledgment to the transmitting device is detection of their transmission by a neighbouring device. All others ignore the message, except to record the routing cost and destination sent by their neighbour, which they use to update their cost tables. In this way, the message slides down a 'cost gradient' to its destination. EmberNet mesh networking technology (discussed later), employs GRAd routing algorithm. This technology was originally developed by MIT University, resulting in the formation of the company Ember Corporation Poor and Brent (2002).

4.3.1.6 Cluster Network Topology

In some applications the routing in a flat network has limitations unavoidable limitations, for example where some devices do not need to form fort of the logical structure, particularly static sensor network type applications. The cluster network is one approach to improve network efficiency. In a cluster network, there is the concept of a 'parent-child' relationship between network devices. The network forms, as do all IEEE 802.15.4 networks, with the PAN coordinator as the first device in the network. When a new device associates to the PAN coordinator (and therefore to the network), it becomes the child of the PAN coordinator, and the PAN coordinator becomes the parent of the new device. Should a second device come into range of the first network device (but, perhaps, out of range of the PAN coordinator), the second device may join the network as a child of the first device. Network devices may have many children (and grandchildren), but only one parent.

The structure of the cluster network is controlled to some extent by the PAN coordinator, which retains authority over network association (regardless of which network device a prospective member may contact). The PAN coordinator may prohibit, for example, a prospective member from joining the network at a device distant (many hops away) from the PAN coordinator, while allowing other prospective members to join closer to the PAN coordinator, in order to encourage a ‘flatter’ cluster structure and control the latency of messages sent in the network.

A significant advantage of cluster networks for wireless sensor network applications is the small size of the network device routing tables, compared to those of hierarchically flat networks. In general, for flat networks, a table entry is required for every potential destination; for a cluster network, the routing table may be much smaller because destinations not found in the table are still routed, via the parent. A small table size reduces the memory requirement of the network devices, which can be a material factor in the product cost.

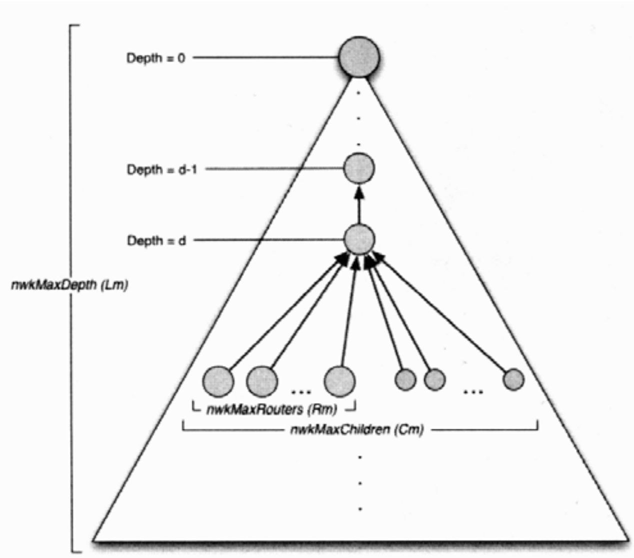
A disadvantage of cluster networks is the non-uniform distribution of message traffic among the network devices. Some devices, especially those logically close to the PAN coordinator, may have significantly higher traffic than devices further away from the PAN coordinator, leading to unequal battery life among network devices. Should the power supply of a device become exhausted, a network partition could occur. Several methods have been proposed to mitigate this effect, including the rotation of PAN coordinator duties among alternative network devices and the use of multiple routing table entries for the same destination.

4.3.1.7 Cluster Tree Network Topology

The address space of IEEE 802.15.4 MAC is capable of supporting a large number of network devices. However, as the number of network devices continues to grow, even the routing tables of devices in a cluster network may grow to an impractical size, because a device’s routing table must contain an entry for each of its offspring (child, grandchild, etc.)

To address this issue, hierarchy may be employed. A large network may be broken up into several, smaller clusters, connected in a hierarchical tree. An example is a ‘cluster-tree’ network, where a large network is composed of smaller clusters, each with a coordinator. The

PAN coordinator may have rules governing network formation. These rules may take the form of a limit on the number of devices in a cluster, a limit on the number of hops any device may be from a coordinator, or a more sophisticated algorithm. The logical, short address of a network device in a cluster-tree network is a hierarchical address consisting of two parts, a cluster identifier and a network device identifier. In the cluster-tree network, the PAN coordinator may still transmit network status request messages. One way to do this is to have the network status request messages route, as in the cluster network, to the ends of the branches (the 'leaves' of the tree). The network status response message is also handled in the same way. This takes advantage of the address hierarchy to reduce the size of the network status response message, which, in a large network, may otherwise be impractical. The addressing scheme adopted by the Zigbee 1.0 standard primarily assumes cluster tree-based addressing (Zigbee Alliance, 2004). The scheme is shown in Figure 4.5 below.



Routers at depth d+1 separated by:

$$Cskip(d) = \frac{1 + Cm - Rm - Cm \cdot Rm^{Lm-d-1}}{1 - Rm}$$

Address of nth end device at depth d+1:

$$A_n = A_{parent} + Cskip(d) \cdot Rm + n$$

Figure 4.5: Cluster Tree-based addressing used in Zigbee 1.0 standard

[*Source*: Zigbee Alliance (2004)]

4.4 Evaluating LR-WPAN in Underground Mining

4.4.1 Ember Evaluation Kit

Following the review of Zigbee/IEEE 802.15.4 development systems it was decided that the Ember Evaluation kit (Figure 4.6 below) was the most suitable evaluation tool for the project at the time. The EM2420 Evaluation Kit and four EM1020 modules were purchased to evaluate the potential and feasibility of a low power wireless network in a mining environment. Particular focus should be on the functionality and RF performance of the network, and considering potential applications.

Figure 4.6: Ember Evaluation Kit and Modules

Hardware: 12 EM2420 Modules plus antennas
4 EM1020 Modules plus antennas
2 AC power adaptors
2 Serial adaptor cables
AAA Batteries

Software: Ember Studio Lite – Network and Node Management Software

Requirements: PC with Microsoft Windows 2000 or XP Operating System

4.4.1.1 Radio Module Characteristics

Both the EM1020 and EM2420 radio modules have a lot to offer, each being robust, low power, efficient and cost effective (Table 4.2 and below). The EM1020 operating at lower frequency has a longer range than the EM2420, but it does not offer as much bandwidth. The EM2420 is fully IEEE 802.15.4 compliant and is compatible with the Zigbee standard. The EM1020 is completely non-standard i.e. it is not an IEEE 802.15.4/Zigbee device.

Table 4.2: EM1020 Radio Module Characteristics

Frequency Band	Between 402-470MHz, and 804-940MHz. Evaluation module set at 868 MHz.
Power Requirements	17.6mA RX 2µA sleep 2.3V - 3.6V power supply
Receiver performance	RX sensitivity examples at a Bit Error Rate of .1% -100dBm for 76.8kbps at 868-915MHz
TX Power (Max)	+5dBm
Data Rate	Data Rate 0.45 - 153.6kbps Output Power -20dBm - +5dBm
Modulation	FSK, GFSK, or OOK
Range	The typical line of sight range is 300 metres when operating at 868/915 MHz.

Table 4.3: EM2420 Radio Module Characteristics

Frequency Band	16 channels of operation in the 2.4GHz worldwide ISM band. 5MHz channel spacing.
Power Requirements	20.7 mA TX @ 0 dBm 19.7 mA RX / Idle 0.5µA Sleep 2.3V - 3.6V power supply
Receiver Performance	RX sensitivity of better than -90 dBm at 1% packet error rate for a 20 byte payload.
TX Power (Max)	0dBm
Data Rate	250kbps
Modulation	OQPSK Modulation, Direct Sequence Spread Spectrum (DSSS) in accordance with the IEEE 802.15.4 specification.
Range	Line of sight range of 75 metres.

4.4.1.2 EmberNet Embedded Networking Software

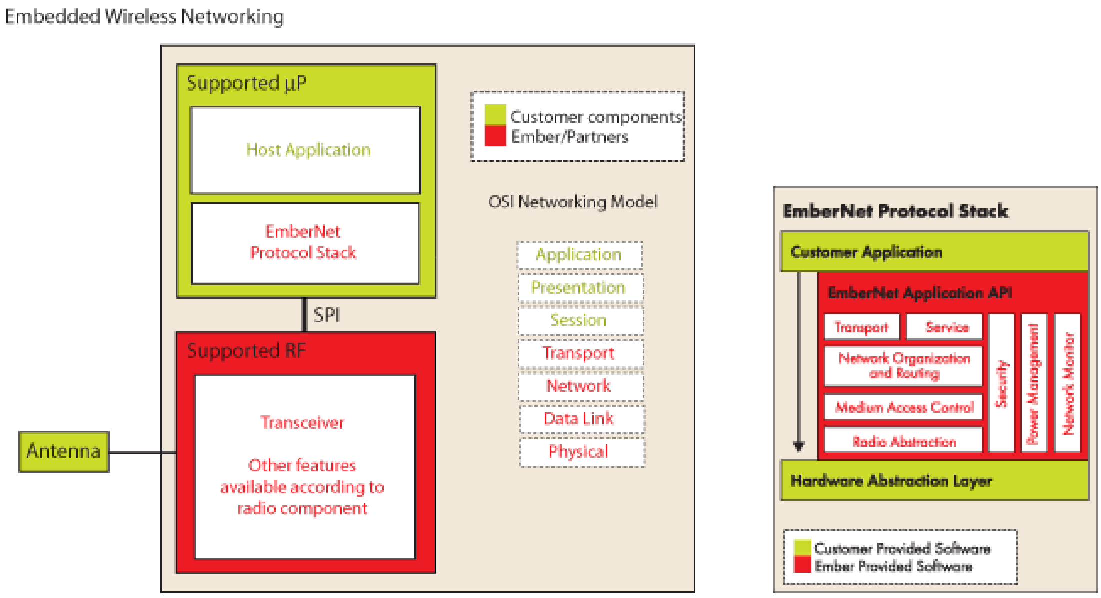


Figure 4.7: EmberNet Stack
[*Source*: www.ember.com]

The EmberNet software stack (Figure 4.7) is a self-healing, self-organising embedded networking platform delivering the connectivity between the EM1020/EM2420 modules. EmberNet is a proprietary low power wireless networking platform developed by Ember Corporation. The stack employs GRAd routing to achieve the peer-to peer mesh links.

The decision to use EmberNet for this research project was partly do to the fact that Zigbee is still at the very early stages of release, whereas the Ember technology seems to be more established in the wireless networking market. Another key feature of the EmberNet platform is that there is a strong emphasis placed on the network's ability to survive through the self-healing and self-organising mechanisms. Issues such as reliability and survivability are considerations in the Zigbee standard. Many companies are working together through the Zigbee alliance to develop the standard (Ember Corporation being one of them). Fully operating Zigbee devices are beginning, or are due, to be released very soon. EmberNet was seen as a low power wireless network solution ready to be implemented immediately. It was also anticipated that given the close relationship between EmberNet and Zigbee networking stack, any research work conducted using the Ember technology should also closely to the Zigbee standard.

For maximum flexibility and reliability EmberNet has been designed for a flat 'mesh' network topology. However, due to the nature of EmberNet it does enable flexible networking by allowing various other topologies: peer-peer, star, mesh or superstar (combined star/mesh).

4.4.1.3 Ember Evaluation Kit Testing Programme

The test procedure was as follows:

Stage 1: Evaluate the modules and software tools in an indoor laboratory environment.

Stage 2: Conducted extensive field tests to examine the parameters identified in Section 2.4.4. The field trials took place within the test mine at Camborne School of Mines (CSM) over 6 weeks. A plan of the CSM Test Mine is shown in Figure 4.8 below.

Stage 3: Conducted trials in a colliery (In collaboration with UK Coal Mining Ltd). This required one day of testing. The colliery tests also involved significant preparation time prior to the tests in order to meet Mine Manager's rules .

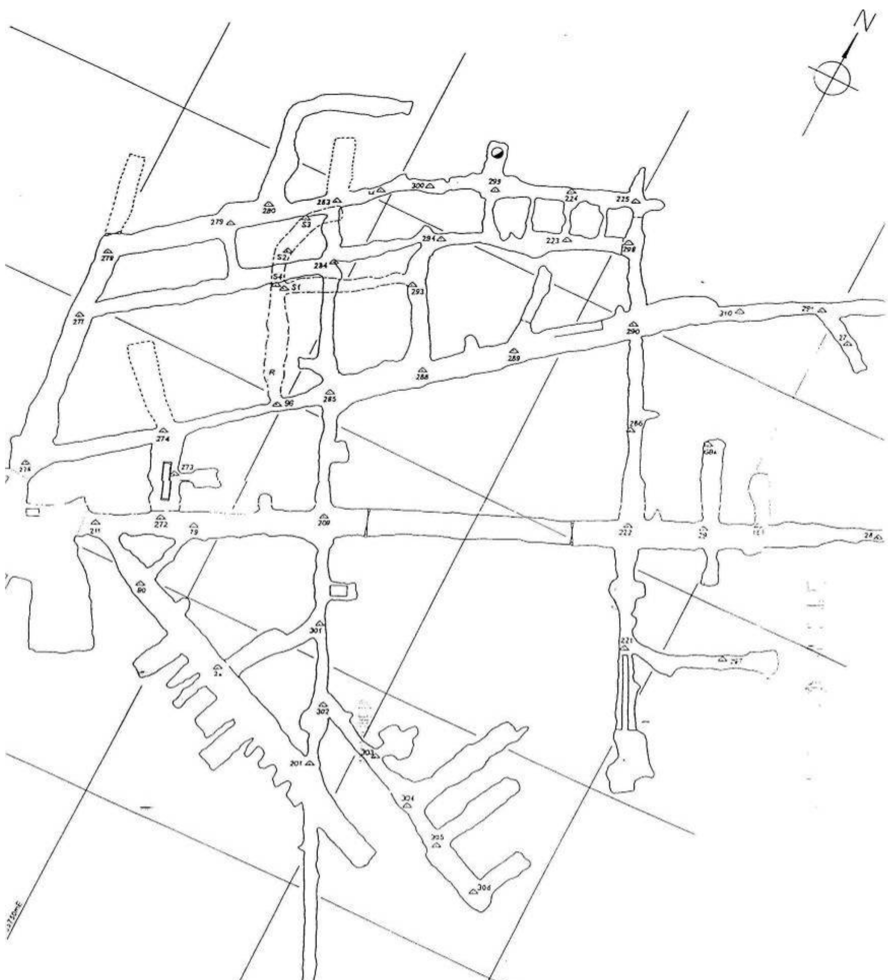


Figure 4.8: Plan of Tunnels at CSM Test Mine (50m Scale)

CSM Test Mine Physical Preparation:

The Test Mine at CSM was very suitable for carrying out field trials of the evaluation kit. The mine is hard-rock (Granite); therefore it does not have the same intrinsic safety concerns as in coal mining i.e. no methane gas etc, making it an ideal equipment testing facility. The main issues concerned in preparing the kit is ensuring that measures are taken to make the modules are moisture and dust resistant.

Colliery Testing Physical Preparation:

For evaluation purposes the kit had to be passed under the Mine Manager's Rules to be taken into a non-regulation 19 zone. A non-regulation 19 zone in a colliery is an area that has been approved as having very low levels of flammable gas/dust. Certain equipment is permitted to operate in these areas, which may not meet full intrinsic safety regulations, under Manager's Rules. Factors that will have to be taken into consideration for the Ember modules are listed below:

- Power Supply Requirements
  - Batteries
  - Means of isolation
  - Max voltage, max current
- RF Power Level (<500mW)
- Enclosure
  - Plastic case size (<100cm^2)
  - Anti-static
  - Environmental protection (Moisture/Dust)

Appendix A.4 contains full details of the preparatory work undertaken in conjunction with the Mine Managers Rules drawn prior to the Zigbee/EmberNet coal mine tests.

Test Parameters

Essentially two sets of test parameters were examined in evaluating low power wireless networks underground: the networking functionality/performance and the RF performance. The results obtained from testing the modules, along with the analysis work, were aimed at gaining an understanding of ultimately being able to optimise RF transmission and performance of a wireless network underground.

RF Performance:

The aim was to examine the physical performance and limitations of a low power wireless network operating at both 868 MHz and 2.4 GHz. The following variables were considered during the testing phase:

- RF Transmission
    - Operating frequency
    - RF Power
    - Transmission Scheme
- Environmental
    - Tunnel wall - geometry/complexity/roughness
    - Groundplane influences (geological, electrical equipment, machinery)
- Optimal Performance
    - Transmission Range
    - Positioning/orientation
    - Multiple transmission pathways (redundancy)
- Fading
    - Path Loss/Range
    - Multipath
    - Scattering loss at junctions

Network Functionality/Performance:

The network functionality and performance phase of testing overlaps with the physical RF testing. In order to ensure that the network is operating effectively there has to be a reliable radio link between the nodes. The aim of this testing phase was to evaluate the performance and limitations of the EmberNet low power networking platform. Although EmberNet is a proprietary standard the results are applicable to other Zigbee and related low power wireless networks, given the close relationship and functionality. The following characteristics were evaluated during the test phase.

- Network Topology
- Survivability (Mesh Network)
    - Self-configuring
    - Self-healing
- Network Performance and Data Transmission
    - On board sensors (battery power, temperature, accelerometer)
    - Power Management Scheme

Ember Evaluation Kit Performance Measurement:

The Ember Studio Lite software supplied with the evaluation kit has two main test features to measure the statistical performance of the modules: ping test and trace route test. These were the two main methods used to measure the RF and network performance of each module.

Ping: Test performance between two nodes in a multi-node network that cannot directly hear each other (i.e. over 1 hop away) or test the strength of the radio link between two nodes that are in RF range within each other.

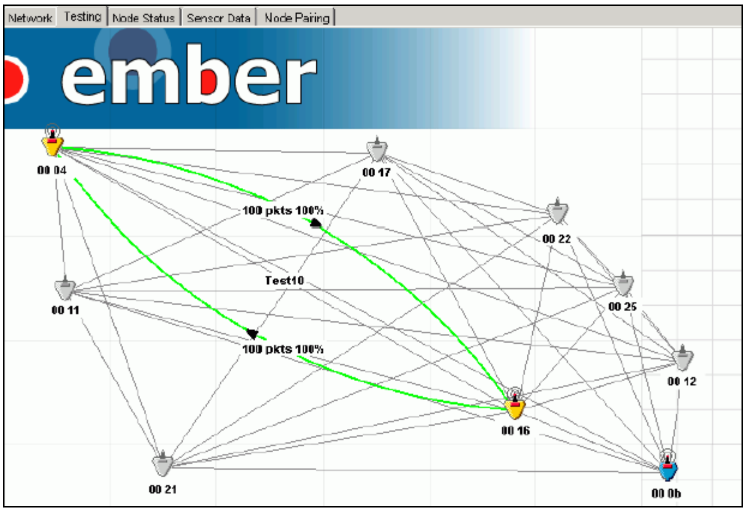


Figure 4.9: Ping Test Example

Trace Route: Determines the statistical route that a series of packets travelled to get from one specific node to another.

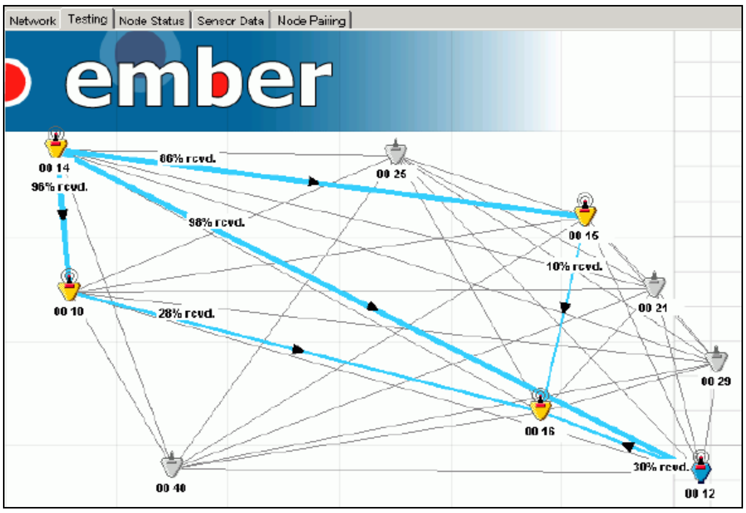


Figure 4.10: Trace Route Test Example

The software also allows certain variables to be adjusted (e.g. packet size/delay and transmission power). When conducting a ping and trace route test using in the Ember support software, the default options were used as follows; number of packets =100, packets size =25 bytes and packet delay =250 milliseconds. The results in Table 4.4 below show the success rates for packet size, while holding a constant 250 ms delay, and the optimal packet delay, while holding a constant 25 bytes packet size. The default settings are broadly consistent with optimal packet success rate.

Table 4.4: Effect of Packet Size and Packet Delay on Packet Success Rate

Variable	Value	Success Rate for the Send-to-Receive Portion	Success Rate for the Receive-to-Send Portion
Packet size (bytes)	5	100%	100%
	10	100%	100%
	20	100%	100%
	40	100%	100%
	60	100%	95%
	80	100%	83%
Packet Delay (ms)	80	75%	60%
	120	99%	84%
	160	100%	97%
	200	100%	100%
	250	100%	100%
	300	100%	100%
	350	100%	100%
	400	100%	100%

[*Source*: www.ember.com]

4.5 Hard Rock Test Mine Trials

These tests formed part of an overall investigation in the feasibility of low power mesh technology, also known as LR-WPAN, in an underground environment. The aim of these tests using the EmberNet modules was to evaluate the overall performance, behaviour and efficiency of Zigbee/IEEE 802.15.4 related LR-WPAN technology in an underground environment. A number of tests are reported, which demonstrate the mesh networking behaviour of Ember EM1020 and EM2420 wireless mesh networks within the hard rock test mine facility, operating at frequencies of 868 MHz and 2.4GHz respectively. Whilst the modules at ~0.9 and 2.4 GHz use different RF techniques, the intention of using two module types was to contrast behaviour at two specific frequencies. The test procedures generally involved the establishment of a 'gateway' station with control software at a suitable location underground (Figure 4.11 below) and then locating the network nodes around the mine as required.

Figure 4.11 Network ‘gateway’ station set-up and Ember module

Key: *Map Scale* 50m Grid.

Modules: Gateway:  Network Node: 

Link Line Quality:

- Good signal strength (76 - 100 % packets)
- Fair signal strength (51 - 75 % packets)
- Poor signal strength (26 - 50 % packets)
- Very poor signal strength (0 - 25 % packets)

***RF Transmission Power*:** EM2420 = 0 dBm EM1020 = +5 dBm

4.5.1 Network Performance

4.5.1.1 1020 (868 MHz) Network Performance Test Results

A wireless network using four EM1020 (868 MHz) modules was set up in the mine (Figure 4.11). Nodes 0311 and 031d had the furthest separation, establishing a very poor link. A ping test between these nodes (Figure 4.12 & Figure 4.13 below) shows that only 76% of packets were received in the send-to-receive portion and 78% in the receive-to-send portion.

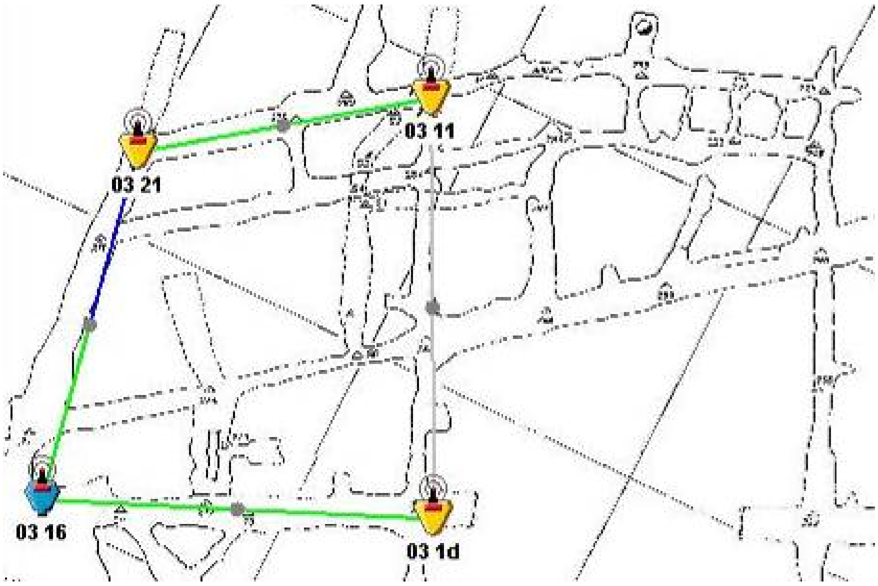


Figure 4.12: 1020 Network 1

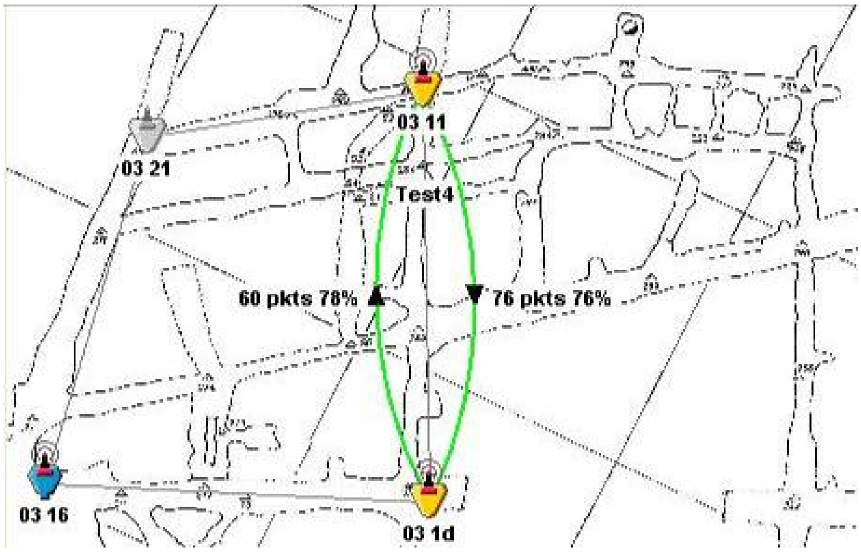


Figure 4.13: 1020 Network 1 – Ping Test (0311 to 031d)

Table 4.5 shows the percentage of the link quality between each node in the network. Table 4.6 contains the results of ping tests between each node, where it correlates with the link quality data in the first table as expected.

Table 4.5: Neighbouring Nodes and Link Quality – 1020 Network 1

Node	Neighbouring Nodes	Link Quality
0316	0321, 031d	99%, 100%
0321	0316, 0311	96%, 99%
031d	0316, 0311	100%, 25%
0311	0321, 031d	99%, 45%

Table 4.6: Ping Test Results – 1020 Network 1

Node	Packets Out (→) Send-to-Receive			Packets Return (←) Receive-to-Send		
	TX	RX	%	TX	RX	%
0316 → 0321	100	100	100%	100	100	100%
0321 → 0311	100	100	100%	100	100	100%
0311 → 031d	100	76	76%	76	60	78%
031d → 0316	100	100	100%	100	100	100%

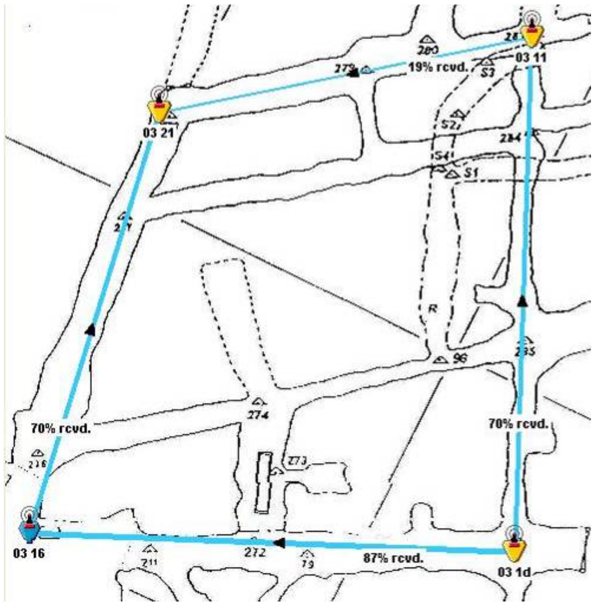


Figure 4.14: 1020 Network 1 – Trace Route (031d to 0321)

A trace route test from node 031d to node 0321 (Figure 4.14, above) demonstrates how some data packets are automatically re-routed via neighbouring better quality links, thus making the network more rugged and survivable. This demonstrates one of the key attributes of mesh wireless network technologies. 87% of the data packets are received from 031d to 0316, and 70 % is received from 031d to 0311. In all, 70 % of the data packets find their way to 0321 via node 0316 and 19 % via node 0311 totalling 89%.

4.5.1.2 2420 (2.4 GHz) Network Performance Test Results – Network 1

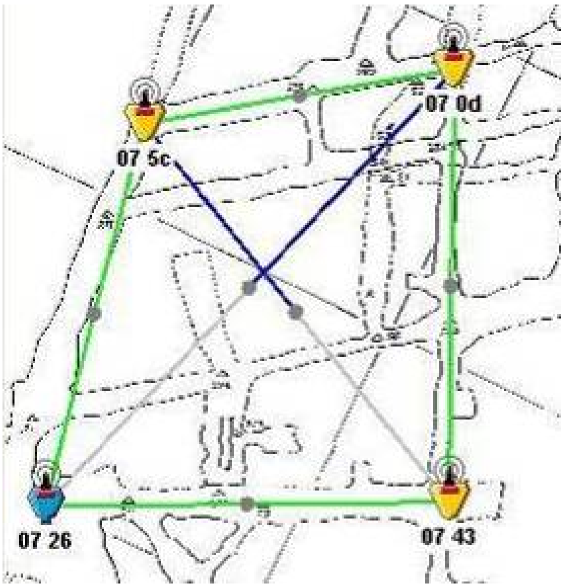


Figure 4.15: 2420 Network 1

A network of four EM2420 modules (Figure 4.15, above) was set up in the test mine in the same position as in the '1020 Network 1' test. A strong signal link between each of the nodes was seen immediately, showing the EM2420 modules to be more robust in this environment. Weak signal lines suggest that there is non-line of sight propagation between the nodes, which does not appear to occur when using the EM1020 modules.

Table 4.7: Neighbouring Nodes and Link Quality – 2420 Network 1

Node	Neighbouring Nodes	Link Quality
0726	075c, 0743	100%, 99%
075c	0726, 070d, 0743	100%, 100%, 91%
070d	0726, 075c, 0743	98%, 97%, 99%
0743	0726, 070d	100%, 99%

Table 4.7, above, shows the number of neighbouring nodes and corresponding link quality for each node in the network. The ping tests shown in Table 4.8, below, support the good quality signal strengths observed between each node, as the results are ~100 % for each. The ping test is a measure of the percentage of packets reaching A to B within a network; therefore ping test measurements beyond a single hop were not recorded

The trace route test from node 075c to 0743 (Figure 4.16, below) is a perfect demonstration of packets being randomly routed through the network. 59% of the packets or sent via 0726 to 0743 and the remaining 41% is sent via 070d to 0743.

Table 4.8: Ping Test Results – 2420 Network 1

Node	Packets Out (→) Send-to-Receive			Packets Return (←) Receive-to-Send		
	TX	RX	%	TX	RX	%
0316 → 0321	100	100	100%	100	100	100%
0321 → 0311	100	100	100%	100	100	100%
0311 → 031d	100	100	100%	100	100	100%
031d → 0316	100	100	100%	100	100	100%

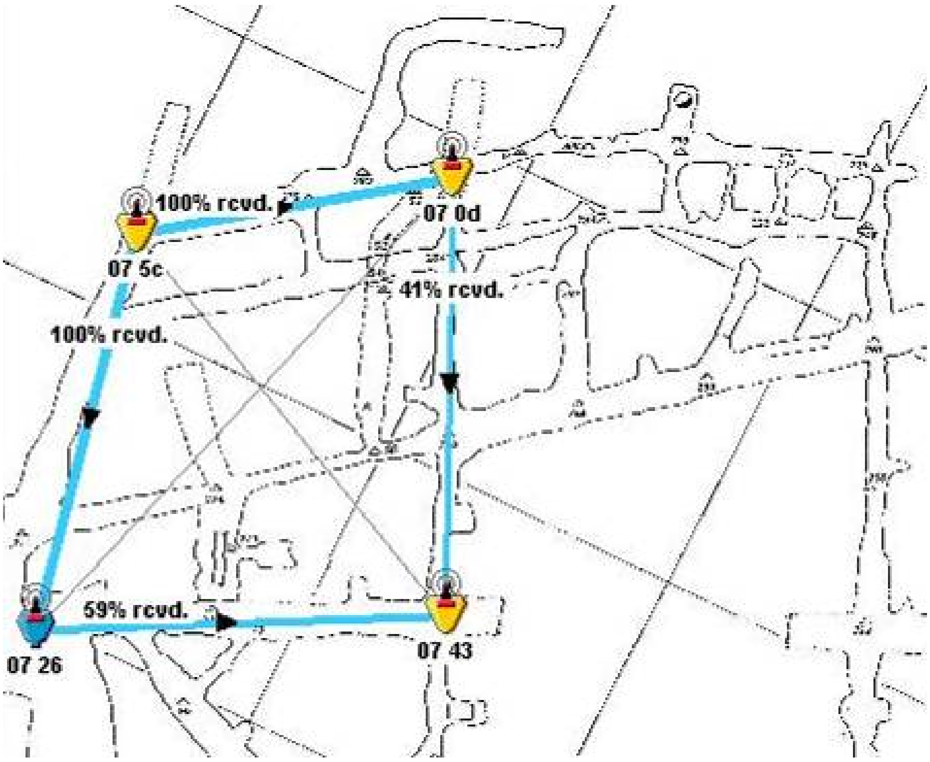


Figure 4.16: 2420 Network 1 – Trace Route (075c to 0743)

4.5.1.3 2420 (2.4GHz) Network Performance Test Results – Network 2

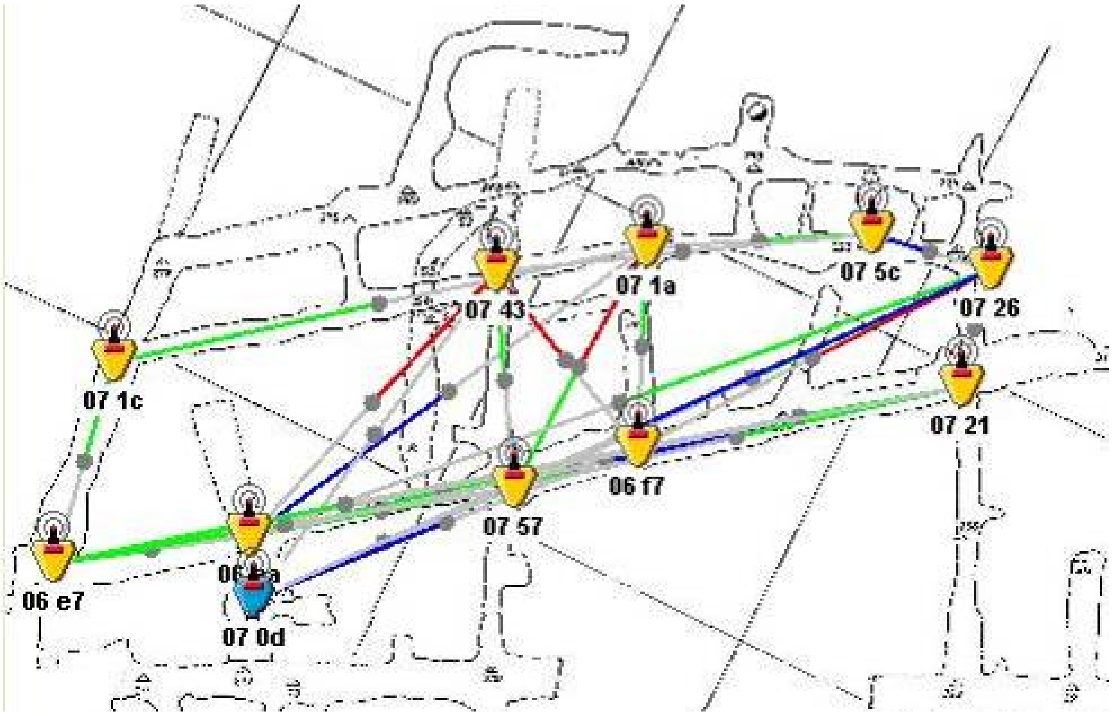


Figure 4.17: 2420 Network 2

The ‘2420 Network 2’ test (Figure 4.17, above) gives an example of a wireless network with nodes operating in relatively close proximity. There are a number of weaker signal lines between nodes indicating that non line of sight propagation is occurring. There is a slight bend between 071a and 075c, and brick wall with only a small opening for ventilation between 075c and 0726, which is why a weaker signal is present there. A selection of ping tests was performed between certain nodes to verify the integrity of the network (Table 4.9, below).

Table 4.9: Ping Test Results – 2420 Network 2

Node	Packets Out (→) Send-to-Receive			Packets Return (←) Receive-to-Send		
	TX	RX	%	TX	RX	%
06e7 → 06f7	100	100	100%	100	100	100%
06f7 → 0721	100	100	100%	100	100	100%
0721 → 0726	100	100	100%	100	100	100%
0726 → 071a	100	100	100%	100	100	100%
0743 → 071a	100	100	100%	100	100	100 %
071a → 06f7	100	100	100%	100	100	100 %
071a → 06ea	100	98	98%	98	95	97%

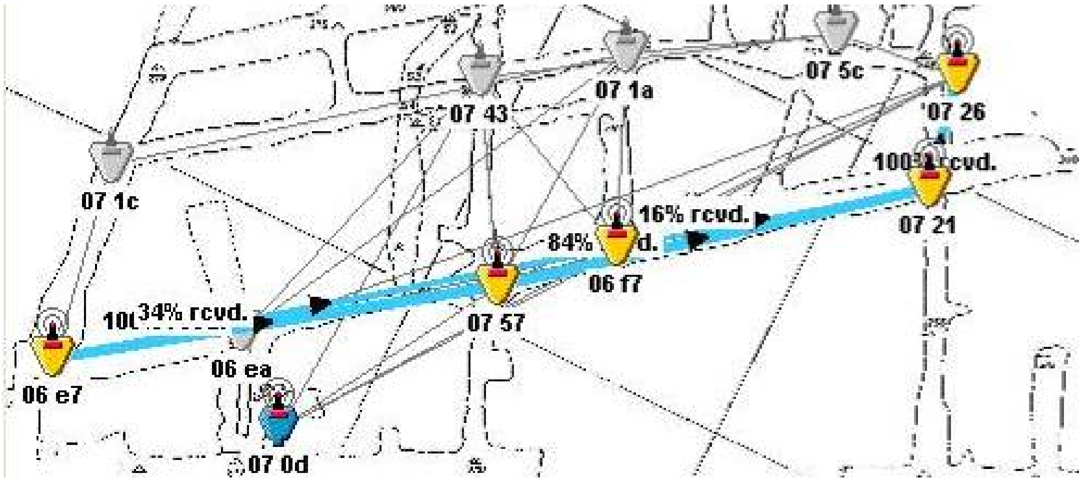


Figure 4.18: 2420 Network 2 – Trace Rout Test (06e7 to 0726)

The trace route test (Figure 4.18, above) again demonstrates how packets are randomly routed through the mesh network via the best available links. To give an explanation of the test, 06e7 sends data to both 0757 and 06f7. 84% of the data is sent from 0757 to 0721 and the remaining 16% from 06f7 is sent to 0721. Finally, all the data (100%) is then forwarded from 0721 to 0726.

4.5.1.4 2420 (2.4GHz) Network Performance Test Results – Network 3

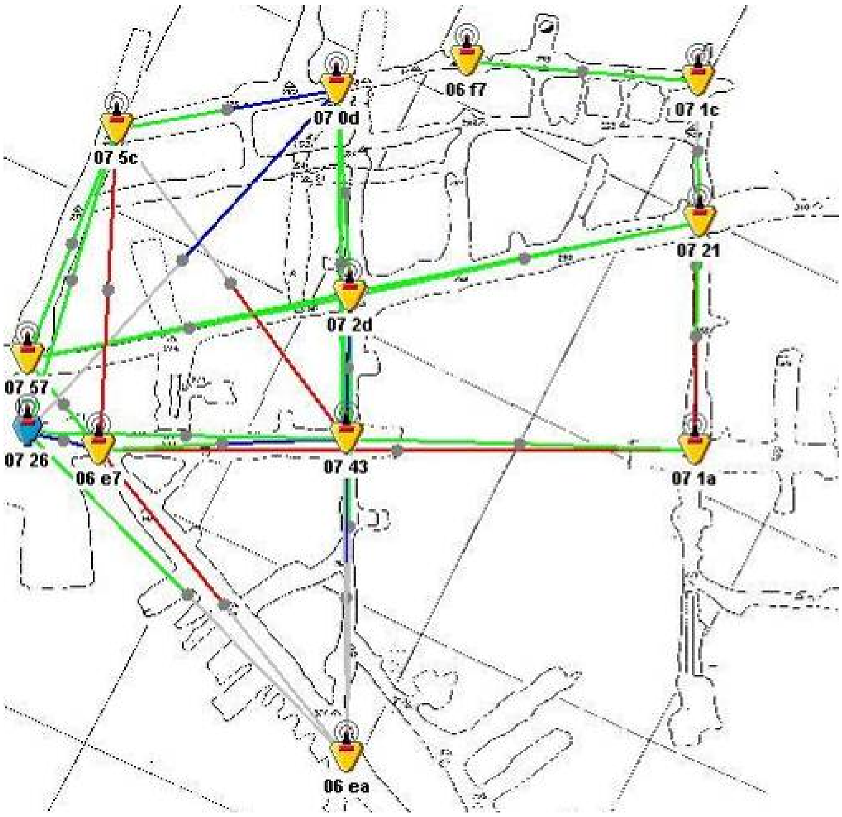


Figure 4.19: 2420 Network 3

The '2420 Network 3' test (Figure 4.19, above) demonstrates a larger network; with the 12 EM2420 modules distributed widely around the test mine. It shows that the 12 modules can almost span the distance of the whole test mine. Obviously, to achieve full coverage in every mine drivage, additional modules would be required.

Note: The area between nodes 0743 and 071a is open, allowing line of sight propagation between the modules. A partial collapse in the tunnel is present in this area. No propagation is achieved between nodes 070d and 06f7 as this area is filled completely with compacted mineral. The ping tests (Table 4.10, below) indicate good quality links except for the link between 06ea and 06e7, particularly on the send-to-receive portion. The trace route tests, 06f7 to 070d (Figure 4.20, below) and 06f7 to 06ea (Figure 4.21, below), again demonstrate the robustness of the wireless network.

Table 4.10. Ping Test Results – 2420 Network 3

Node	Packets Out (→) Send-to-Receive			Packets Return (←) Receive-to-Send		
	TX	RX	%	TX	RX	%
070d → 06f7	100	100	100%	100	100	100%
0721 → 071a	100	100	100%	100	100	100%
071a → 0743	100	100	100%	100	100	100%
0743 → 06ea	100	100	100%	100	100	100%
06ea → 06e7	100	51	51%	51	49	96%

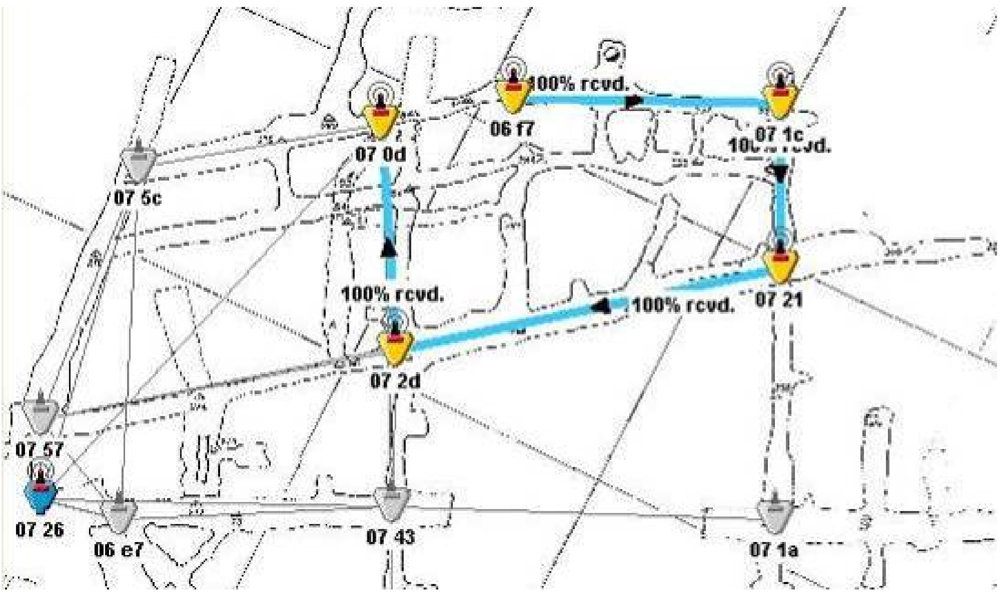


Figure 4.20: 2420 Network 3 – Trace Route 1 (06f7 to 070d)

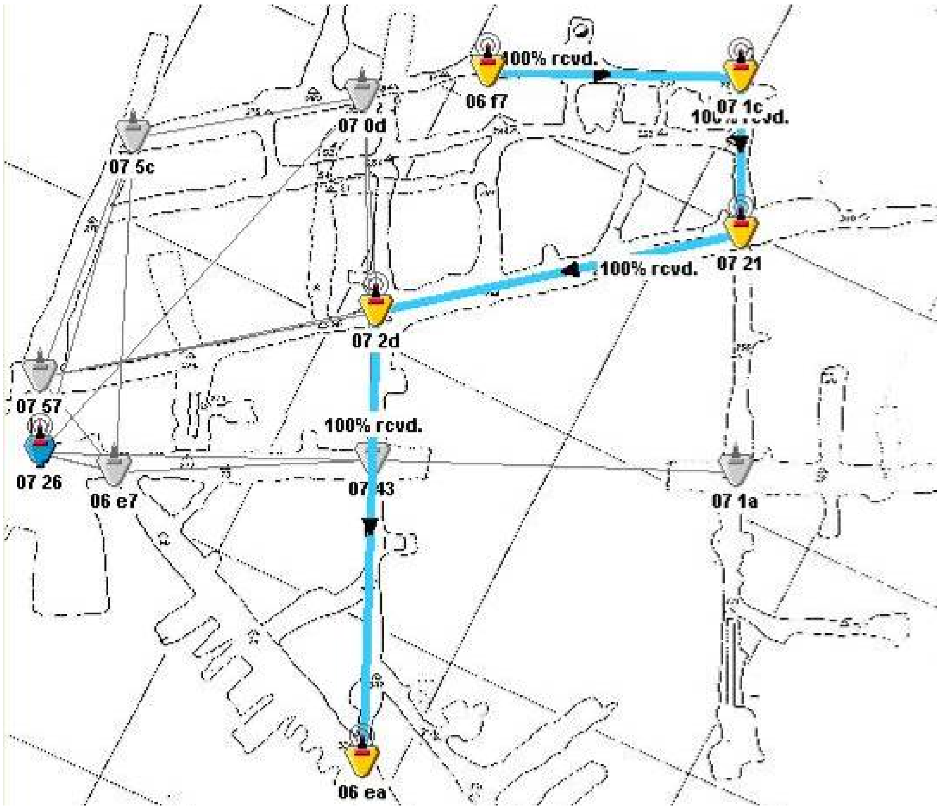


Figure 4.21: 2420 Network 3 – Trace Route 2 (06f7 to 06ea)

4.5.2 RF Performance

The aim of this testing phase was to investigate the RF performance characteristics of 868 MHz and 2.4 GHz ISM band technologies operating underground. The EM1020 (868 MHz) and EM2420 (2.4 GHz) modules have differing operating frequencies and transmission techniques. The EM1020 modules employ FSK (Frequency Shift Keying), whereas the EM2420 modules employ the IEEE 802.15.4 PHY (physical layer), which defines OQPSK (Orthogonal Quadrature Phase Shift Keying) using DSSS (Direct Sequence Spread Spectrum) technique. The differing transmission characteristics were also taken into consideration, as far as is practicable, when evaluating the performance of these modules underground.

The results gathered include an investigation of the underground operating range, effects of tunnel wall proximity, body shielding, module/antenna orientation and the presence of a typical metallic mine vehicle roadway obstruction. These tests are summarised here.

4.5.2.1 Underground Range

The range between two radio modules in a straight tunnel was measured at the point where the statistical percentage of packets received began to fall below 100% causing the link to fail. An accurate distance was recorded using an EDM (Electronic Distance Measurement) device. The

EM2420 modules, operating at 0 dBm, had a range of 79m before packet delivery failures were recorded. The EM1020 modules, operating at +5dBm, achieved a range in excess of 135 m.

4.5.2.2 Tunnel Proximity and Body Shielding

The aim of these tests was to investigate the effect of radio module proximity to the tunnel wall within the test mine. In some tests 'body shielding' with a person physically standing in front of the receiver, was introduced for further investigation. These tests, importantly, simulated how transmission might be affected if a PAN device was worn or carried about the person. To be fully representative, the test subject wore typical mine workwear, PPE and caplamp. All the tests were conducted between two modules (EM1020 or EM2420); one gateway connected to the PC and one the receiving (RX) node. The RX node was placed in various locations as noted in Figure 4.22, below, at a distance of 20m from the gateway module. The cross-section diagram of the tunnel is not to scale, it is intended to show the module proximity to the tunnel rib walls. The dashed line indicates the roughness of the tunnel wall, where in some circumstances when a module was placed adjacent to the wall, it was partially or completely shielded by rock mass. The RF transmission power for all of the tests, using both the EM1020 and EM2420, were set to 0 dBm unless otherwise stated.

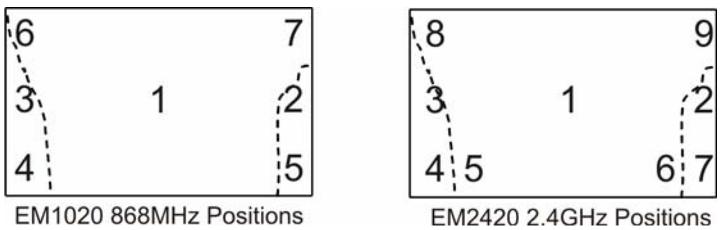


Figure 4.22: Proximity to tunnel wall tests.

The results for the EM2420 and the EM1020 are shown in Table 4.11 and Table 4.12, below, respectively. Both sets of tests show that when the modules were placed in regions where there was a significant amount of protruding rock mass, the signals were weakened. From these results it is difficult to distinguish which module type performed better here. Regarding body shielding effects, the EM1020 modules at this distance could not establish a link at all when a person blocked the transmission path. The results show that the EM2420 modules are more robust to the effects of body shielding than the EM1020 modules. The effect of tunnel proximity is inconclusive and may need further investigation. It is also noted that the tests mine walls are substantially free of metallic infrastructure, unlike typical coal mine environments. This aspect required further consideration. The effect of tunnel wall proximity was investigated further during the CW transmission tests in Chapter 3.

Table 4.11: EM2420 Tunnel Wall Proximity Results

RX Module Position	TX Power	Body Shielding	Ping Test	
			TX to RX (%)	RX to TX (%)
1	-10 dBm	N	90%	100%
1	-10 dBm	Y	Failed	–
1	0 dBm	Y	92%	100%
2	0 dBm	Y	100%	100%
3	0 dBm	Y	Failed	–
3	0 dBm	N	52%	100%
4	0 dBm	N	98%	100%
5	0 dBm	N	Failed	–
6	0 dBm	N	100%	100%
7	0 dBm	N	100%	100%

Table 4.12: EM1020 Tunnel Wall Proximity Results

RX Module Position	Body Shielding	Ping Test	
		TX to RX (%)	RX to TX (%)
1	Y	Failed	-
1	Partial	Failed	-
1	N	92%	100%
2	N	79%	21%
3	N	100%	94%
4	N	70%	100%
5	N	100%	100%
6	N	100%	100%
7	N	Failed	-
8	N	100%	100%
9	N	100%	100%

4.5.2.3 Presence of Intervening Machinery (Dump Truck)

Two modules were set up underground as shown in Figure 4.23, below, with the Gateway TX module attached to a PC laptop and a RX module located in various positions around a dump truck located in the position indicated in the diagram. Figure 4.24, below, shows the typical disposition of the dump truck and the tunnel to the rear of this. In terms of procedure, firstly two EM1020 modules were used with a 0 dBm Transmission Power, then the test was repeated with two EM2420 modules at 0 dBm TX power. The results are given in Table 4.13 and Table 4.14, below. The recorded module positions are relative to the TX module transmission path towards the vehicle obstacle. The modules were positioned vertically central to the tunnel axis unless otherwise stated.

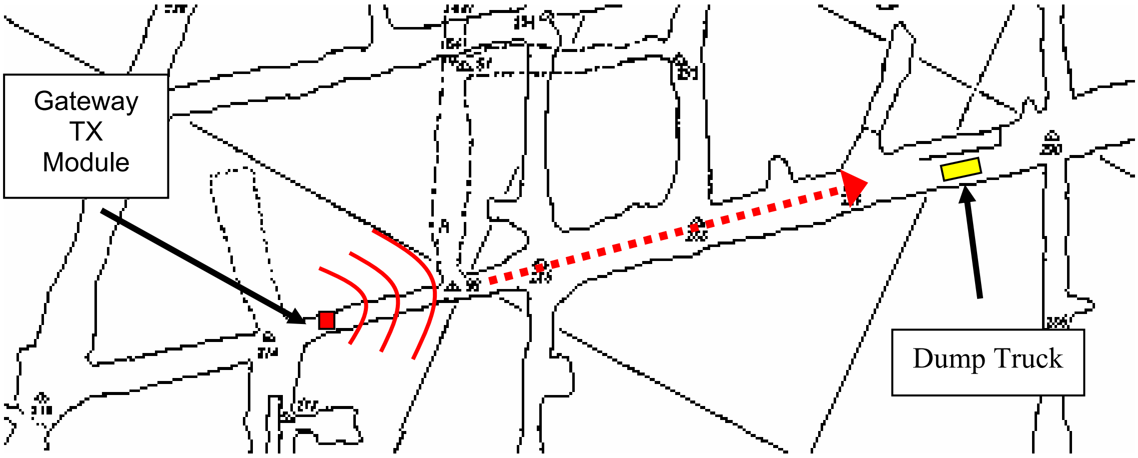


Figure 4.23: Dump Truck Proximity Test

Table 4.13: EM1020 (868 MHz) Dump Truck Proximity Results

RX Module Position to Dump Truck Obstruction	Ping Test TX to RX (%)	Ping Test RX to TX (%)
Front	100%	100%
Right	6%	100%
Left	93%	100%
Behind	Failed	-

Figure 4.24: Transmission tests around dump truck roadway obstruction

Table 4.14: EM2420 (2.4GHz) Dump Truck Proximity Results

RX Module Position to Dump Truck Obstruction	Ping Test	
	TX to RX (%)	RX to TX (%)
Front	100%	100%
Right	100%	100%
Right: 2nd Test	Failed	–
Left	100%	100%
Left: 2nd Test	92%	97%
Behind	100%	100%
Behind: Low	100%	100%
Behind: +5m	100%	100%
Behind: +5m Low	100%	100%
Behind: +10m	99%	96%
Behind: +10m Low	99%	97%
Behind: +15m	91%	100%

The 868 MHz EM1020 module completely failed once it passed the vehicle. A 900MHz wireless headphone set (analogue, FM) was tested in a similar set up for comparison. Again, when the vehicle obstacle was reached the link became very poor.

The 2.4 GHz EM2420 modules were very robust in operation around the vehicle. A good quality link was established beyond the obstacle, even when lowering the RX module closer to the ground to further increase the screening effect. However, both sets of modules became unreliable to the right of the vehicle, where there was reduced clearance between the vehicle and the tunnel wall.

4.5.2.4 Orientation

Two EM2420 2.4 GHz modules were used to explore the effects of orientation variation of the module unit and antenna. The test was set up using the modules spaced at a distance of 20 metres, with the transmission power lowered to –10 dBm for both the transmitting unit, TX, (attached to PC) and the receiving (RX) unit.

The results show that the orientation of the module units does not have any significant effect on the performance of the radio transmission. However, the orientation of the antenna is an important factor. The ideal orientation is that the antennas for each unit are the same. Antennas polarised at 90˚ difference have demonstrated a significant degradation in performance.

Table 4.15: Antenna and Module Unit Orientation Results (V-Vertical, H-Horizontal)

TX Unit Orientation		RX Unit Orientation		Ping Test	
Antenna	Module	Antenna	Module	TX to RX (%)	RX to TX (%)
V	V	V	V	100	100
V	V	H	V	75	49
V	V	V	H	100	100
V	V	H	H	77	76
H	H	V	V	60	81
H	H	H	H	100	100
45˚ – Opposite orientation				83	79
45˚ – Same orientation				100	100

4.5.3 CSM Test Mine Results Summary

4.5.3.1 Network Performance Tests

Previous research concerning theoretical analysis predicted the lower UHF frequency to have better range and coverage around corners. The network performance tests have clearly shown that the EM2420 radio modules are more robust than the narrowband EM1020 modules, encouraging slight 'non line-of-sight' propagation. However, the EM1020 modules clearly have a better range in a strict line of sight situation, at least in the test mine environment. The main difference between the radio characteristics of the two modules, other than operating frequency, is that the 868MHz modules use FSK modulation, and the 2.4 GHz modules employ DSSS and O-QPSK modulation. DSSS (direct sequence spread spectrum) does appear to make the transmission more immune to interference and multipath effects. The trace route tests for all the networks demonstrated the survivability and robustness of the wireless networking modules. The random routing of data through the best available links is similar to how data packets are randomly routed through the Internet.

A very interesting finding was that the packet analysis software indicated that the EM2420 could establish very weak non line-of-sight links within a network. This was demonstrated in '2420 Network tests 1, 2 and 3' (Section 4.5.1). This has shown that some radio waves are propagating along and around corners, suggesting that the waveguide effect is occurring, although, the signals were very weak due to the significant attenuation occurring at the bends. Non-line of sight signals were not observed for the lower frequency 868MHz modules. This issue requires further investigation, and possibly indicates penetration of electromagnetic waves through modest rock depths at certain locations.

4.5.3.2 RF Performance Tests

To summarise the RF performance tests, the 868 MHz modules had greater line of sight range than the EM2420 modules. However this was completely restricted to line of sight geometry, since any obstacles, e.g. body shielding, rock mass and vehicles, severely constrained the signal link. The EM2420 modules proved to offer significantly more rugged and reliable transmission behaviour underground. Good quality links were established in slight non-line of sight situations, and where there was body shielding and the presence of a vehicle obstructing the path. On balance, the tests provided a reasonable degree of confidence that 2.4 GHz ISM band LR-PAN wireless technologies can coexist underground, and would demonstrate favourable local propagation behaviour.

4.6 Underground Coal Mine Trials

Tests were carried out in conjunction with UK Coal Mining Ltd at Thoresby colliery in Nottinghamshire to investigate feasibility and RF performance of a low power wireless mesh network within a ‘working’ coal mine. These trials were the final stage within the overall investigation and feasibility study of ISM band high-frequency wireless mesh technology operating within an underground mine. The EM2020 (2.4 GHz) radio modules and EmberNet mesh networking software were used to carry out the field trials. It was decided not to pursue any further trials using the EM1020 (868 MHz) radio modules given the more optimal performance of the higher frequency EM2420 radio technology in general, and hence the 2.4 GHz technology is of key interest for further development.

The use of non-approved equipment was permitted in the coal mine under Mine Manager’s Rules in accordance with UK EAW Act, Regulation 19.2(g). As part of the process of drawing up the Manager’s Rules, a full risk assessment was carried out and further safety and protective measures were introduced to the modules. An inspection of the equipment and production of the Mine Manager’s Rules were carried out by a third party company, HSEC Ltd.

The following points/constraints were raised during the risk assessment:

- Over constraints of Tests
  - Use only in outbye intake or only where atmosphere is measured to have no / minimal CH_4 concentration.
  - Direct supervision of UK Coal Engineer
  - All equipment to be logged in / out of the mine

- Position of all radio beacon units, and subsequent re-positioning to be clearly marked on a plan.

- Module Placement
  - More fixed measures can be taken for placement of devices e.g. tie wraps
  - Personnel will act as 'Centuries' to monitor cluster of network devices e.g. 3 or 4 devices within a certain ‘zone’.
  - Location must be physically logged on an underground plan in addition to the network monitoring software. The software will detect failure and store the location of the particular module.
  - The on-board LED’s, indicating the beacon functionally are in constant operation, further increase to visibility of the modules underground.
  - All equipment logged in and out of mine:

- Hardware:
  - Switch - Rotary switch has central "on" positions, with the two outer positions corresponding to "off". Rotary ==> cannot be knocked into "on" position. Central-on ==> easy to verify switch is off, simply by twisting to one extreme or the other.
  - Battery - The only required battery source is the external 4xAA battery pack. No internal batteries used.
  - ABS plastic enclosure used mast have clear label stating ‘do not rub with dry cloth’.

Details of the equipment preparation made to meet the requirements identified in risk assessment are given in Appendix A.4.

The aim of this testing phase was to investigate the network and RF performance of the mesh network system in a ‘real’ and possibly one of the harshest underground environments, with high electrical power machinery and an extensive metallic infrastructure present.

4.6.1 Network Performance Tests

A high-density cluster of meshed network devices was established around a belt conveyor drive, as shown in Figure 4.25, below. The aim of this test was to demonstrate a potential 'real' application scenario of smart wireless sensors operating in close proximity to a machine/plant, reliably collecting and transmitting telemetry data. The EM2420 radio modules were placed in various positions around the belt conveyor drive, a typical belt conveyor drive is shown in Figure 4.26, below.

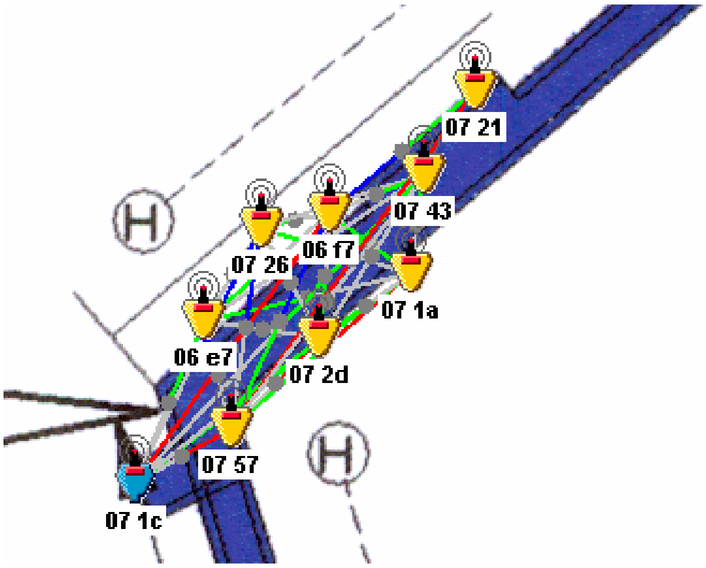


Figure 4.25: Belt Conveyor Drive – High Density Network Evaluation

Figure 4.26: Typical Belt Conveyor Drive

It was demonstrated (Figure 4.25) that multiple redundant pathways could be established between every wireless node. The ping test (Figure 4.27, below) between node 0721 and 0757 resulted in 100% transmission reliability. The EM2420 2.4GHz network demonstrated a high resilience and rugged data transmission system behaviour when operating in close proximity to high powered machinery and significant metallic infrastructure. This suggests that a 2.4 GHz Zigbee system will be suited to several potential applications including; high-integrity stand-off control systems and underground smart sensor telemetry.

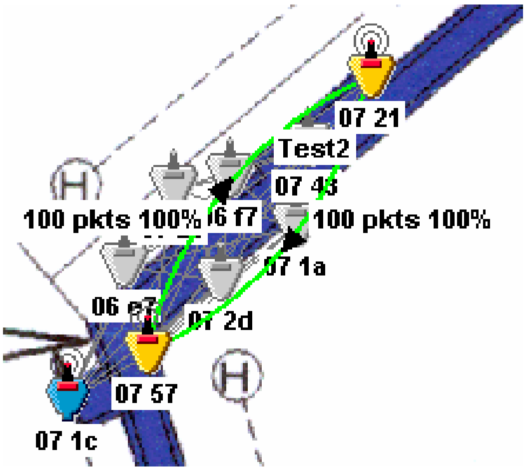


Figure 4.27. Belt Conveyor Drive – Ping Test

4.6.2 RF Performance Tests

A ‘daisy chain’ mesh network was established as shown in Figure 4.28, below, with each node spaced approximately every 25m. The aim of this test was to demonstrate a means of further increasing linear range in a mine drive or tunnel by using each node as a repeater, and to confirm the feasibility of rapid deployment of a temporary communications network system e.g. rescue team network. The test demonstrated that rapid deployment of such a network can be successfully established in this type of environment. However, it became clear that proximity of the devices with the tunnel floor and walls could affect significantly the RF performance. Significant degradation was observed when network nodes were place adjacent to the tunnel wall or directly on the ground.

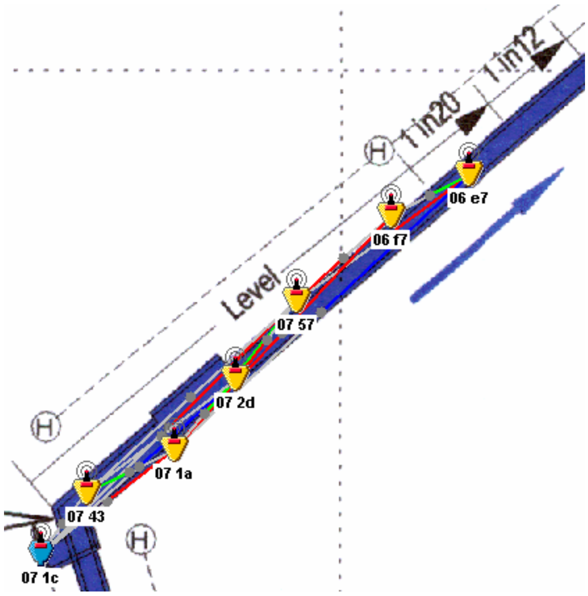


Figure 4.28. 'Daisy Chain' Test

The test methodology used in the previous CSM Test Mine tests to record the operational range between two EM2420 radio devices was used in the coal mine tunnel tests. The range was recorded between the two devices at the point where the statistical percentage of packets successfully received commenced falling below 100%. The gateway node (blue) was stationary and the second standard network node (yellow) was moved along at regular intervals in the tunnel (Figure 4.29, below). An operational range in excess of 150 m was recorded. This greatly exceeds both the operational range in open air and the underground hard rock test mine range (around 80m). It should also be noted that both nodes were located in a central position within the roadway. The recorded range of >150m was also maintained over both '1 in 20' and '1 in 12' roadway inclines; therefore the link was non line-of-sight in the vertical plane. This would suggest that the waveguide effect is being enhanced due to the metallic roof supports.

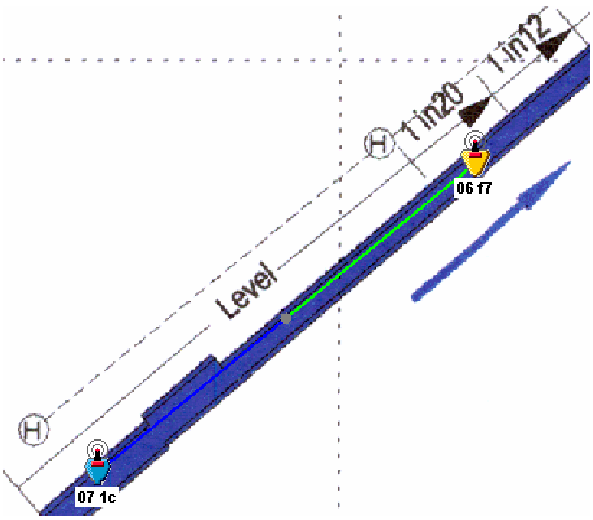


Figure 4.29. Operational Range Test

4.7 Additional tests using high-gain antennas

Further tests were carried out at CSM Test Mine using higher gain antennas in order to investigate whether the performance of the low power mesh wireless network could be enhanced.

The following equipment was used during the tests:

- EM2420 EmberNet Evaluation Kit – 12 x 2.4GHz modules and network management software.
- USR5481 5dBi Reverse-SMA Omni Directional Antenna (from US Robotics)

The radiation patterns for the 5dBi omni directional antennas are shown below in Figure 4.30. Given that omni directional antennas have increased directional gain in the horizontal plane, as opposed to an isotropic radiator. Based on observations made during the CW measurements (Chapter 3), antennas with increased directionality couple more efficiently to the waveguide mode. It is also noted that direction patch antennas would perform better still, yet they are impractical in this situation as more than one direction is required in many instances.

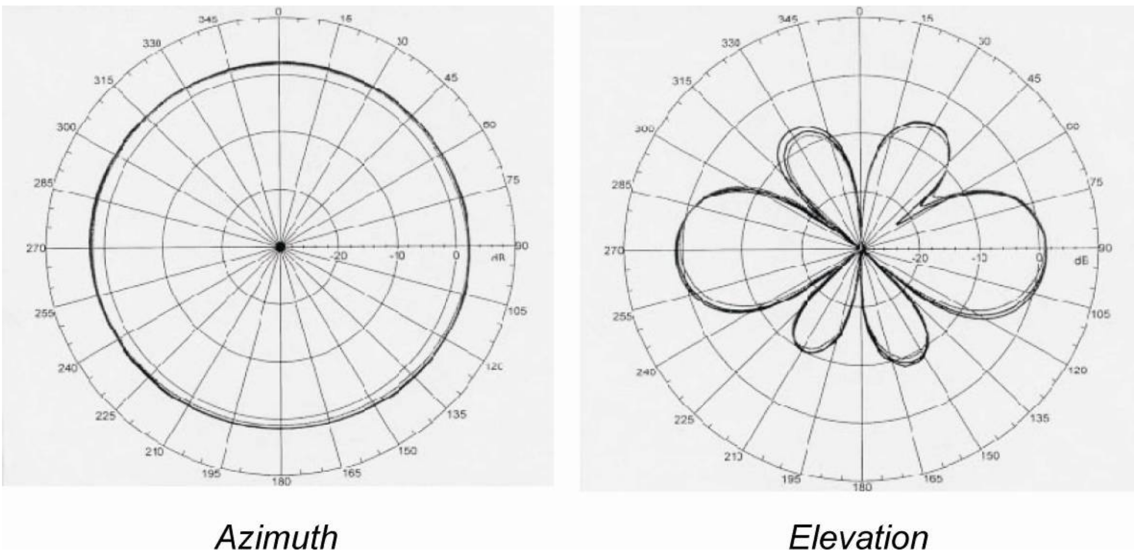


Figure 4.30: USR5481 5dBi Omni Antenna Radiation Pattern

The mine-wide mesh network was established, as shown in Figure 4.31 below, placing nodes in exact geographical locations as in the previous mine wide test at CSM using standard 2dBi monopole antennas (see Figure 4.19 on page 154). The 5dBi omni-antennas clearly enhance the link quality between each of the various nodes, compared with the previous test. In addition to this there are an increased number of non line-of-sight signals present.

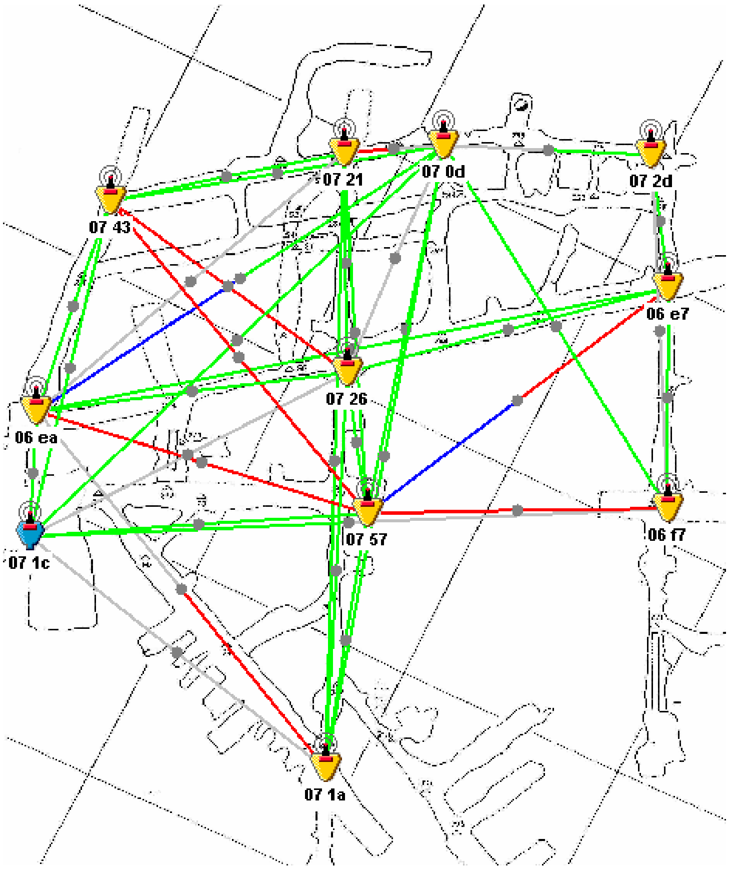


Figure 4.31: Mine-Wide Mesh Network – 2.4GHz, 5dBi Omni Antennas

Blocked Passageway Scenario:

In interesting scenario is between nodes 0721 and 070d (Figure 4.32), where the passageway is >90% blocked with rock material. This location is in fact a drawpoint, however, this scenario is also representative of a roof-rock fall. This was also investigated during the previous EM2420 test (Figure 4.20, page155). Using the 5dBi, a weak signal is present this time between the two nodes. A ping test between the two nodes demonstrates that 100% packets are transmitted and received. However, the ping test does not take into account the route taken.

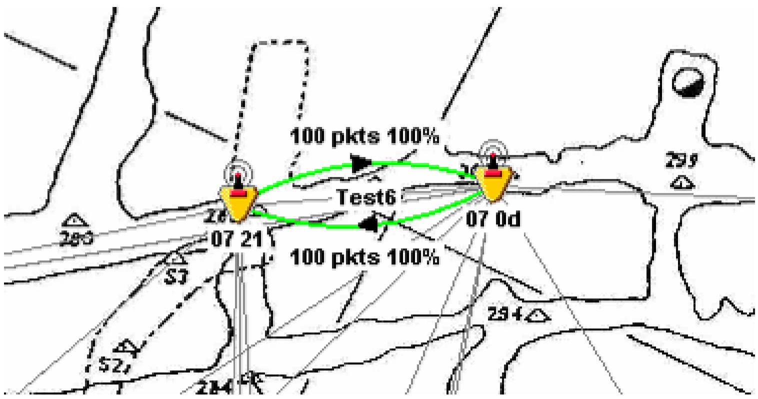


Figure 4.32: Ping test – Between nodes 070d and 0721

Figure 4.33, below, is a trace route test between these nodes demonstrating the actual route used in transmitting data from node 070d to node 0721. This demonstrates the survivability of this type of network, where the GRAd routing algorithms pick the optimal route (least cost) regardless of geographical location. Radom routing of packets via other best available routes is also demonstrated.

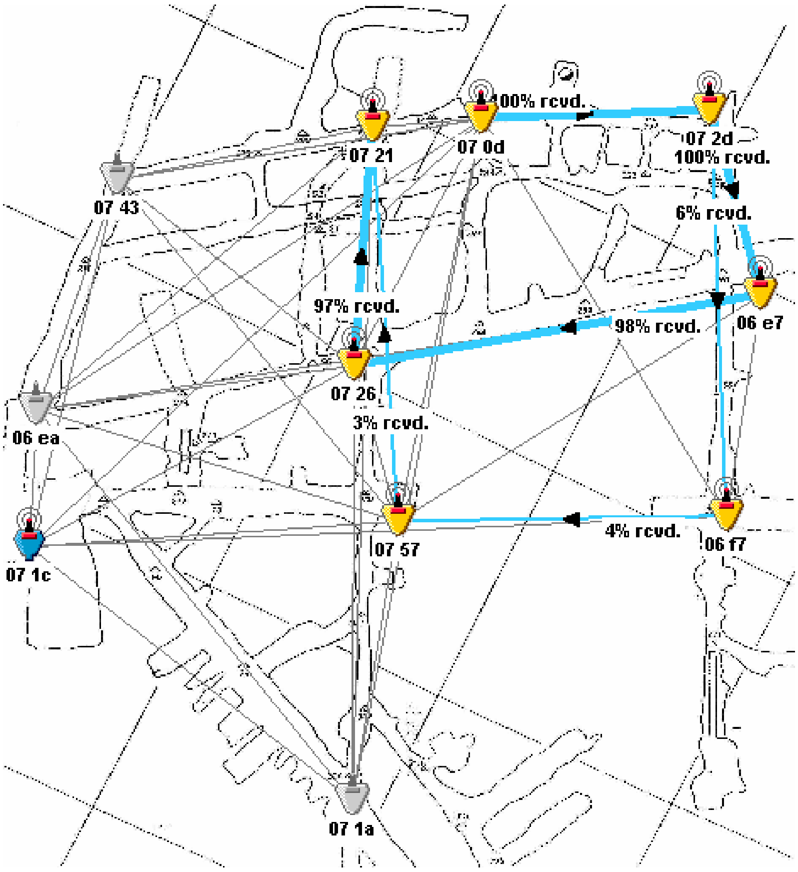


Figure 4.33: Trace Route Test - Node 070d to 0721

4.8 Conclusions of Underground Wireless Mesh Tests

Wireless mesh network tests have been carried out using EmberNet LR-WPAN technology, which is closely related to the new Zigbee standard. Tests have been carried out at both the CSM Test Mine (hard rock) and a UK colliery. Conclusions of the tests are summarised below:

CSM Test Mine Wireless Mesh Network Tests:

- Tests were carried out using both 868 MHz (EM1020) and 2.4GHz (EM2420) EmberNet mesh networking technology
- The 868 MHz system proved to have poor resilience underground. Although the recorded operational range in excess of 100m was achieved, it was completely restricted to line-of-sight (LOS).

- The 2.4 GHz system proved very robust -
  - Increased resilience in both LOS and non LOS and screening effects (body shielding and vehicle)
  - Maximum operating range of 80m.
  - IEEE 802.15.4. 2.4GHz PHY employs DSSS, which is inherently more immune to multipath effects
- Waveguide effect observed, particularly in the 2.4GHz tests where weak non line-of-sight signals detected.

Coal Mine Tests:

- 2.4 GHz mesh network demonstrated high resilience and good quality links in the presence of -
  - Significant metallic infrastructure
  - High power electrical machinery
- Demonstrated potential 'real' application scenarios operating in close proximity to machines and plant e.g. a distributed belt conveyor drive application.
- Transmission performance:
  - Significant degradation in performance observed when nodes are placed on floor or directly adjacent to tunnel wall
  - Enhanced waveguide effect - Placing nodes in the centre of the tunnel actually enhanced operational range, recording a range in excess of 150m. It also maintained good quality links into a non line-of-sight tunnel section, through '1 in 20' and '1 in 12' inclines.

4.9 Summary

This Chapter has introduced the concept of using mesh wireless network as a means of achieving a robust and resilient wireless network in an underground environment. Particular attention as been given to LR-WPAN, which is a group of low power wireless mesh technology relating to new IEEE 802.15.4 and Zigbee standards. Potential applications have been discussed, along with various routing and network topologies. A range of tests have been carried out using EmberNet mesh technology, closely relating to the Zigbee standard, examining the performance, feasibility and potential applications underground. Extensive tests were conducted at CSM Test Mine (hard rock mine) and limited tests were conducted at a UK colliery in conjunction with UK Coal. These results, along with the findings from the wireless propagation tests and investigation presented in Chapter 3, show that 2.4 GHz mesh networking technology is an optimal choice in critical high integrity safety applications in underground environments.

Chapter 5: Mesh System for Rescue Personnel in Harsh Environments

This Chapter examines the potential use of mesh LR-WPAN networks in confined space environments for a potential application, monitoring the 'vital signs' of rescue personnel. Details of practical tests that were carried out in conjunction with the London Fire Service evaluating the feasibility and network performance within a 'built' confined space environment are also presented.

5.1 Overview

Effective ground communications can be a critical success factor in rescue activities such as mines rescue or firefighting. One emerging related aspect is a recognised need to gather and transmit data of rescue personnel 'vital signs', with body core temperature being increasingly recognised as a key physiological indicator. This Chapter describes field trials using low power wireless mesh networking technology which were conducted at London Fire Brigade (LFB) Southwark fire training centre, as part of an investigation into the potential use of low power mesh systems to gather 'vital signs' data in emergency situations.

MRSL has been currently examining thermal physiological measurements and relating to this research is considering developing wireless mesh technology specifically geared towards rescue applications. One particular area being examined is the potential of Zigbee (or LR-WPAN) systems to provide a low power, high integrity mesh network between local rescue team members in an emergency situation. The aims of the LFB training centre trials were to evaluate the performance of a low power mesh network within a demanding indoor radio propagation environment and to examine the feasibility of relaying vital signs telemetry from within the building to a command centre.

5.2 Vital Signs Telemetry

In Chapter 4, vital signs telemetry was identified as being a key potential application in this research. A report by Jones *et al.* (2003) highlighted there are key vital signs to monitor when the body is under extreme critical stress including heart rate and body core temperature. Figure 5.1, below, indicates that when undertaking work in severe climatic conditions, body core temperature can rise rapidly, approaching a regression-based figure of ~100mK per minute of activity.

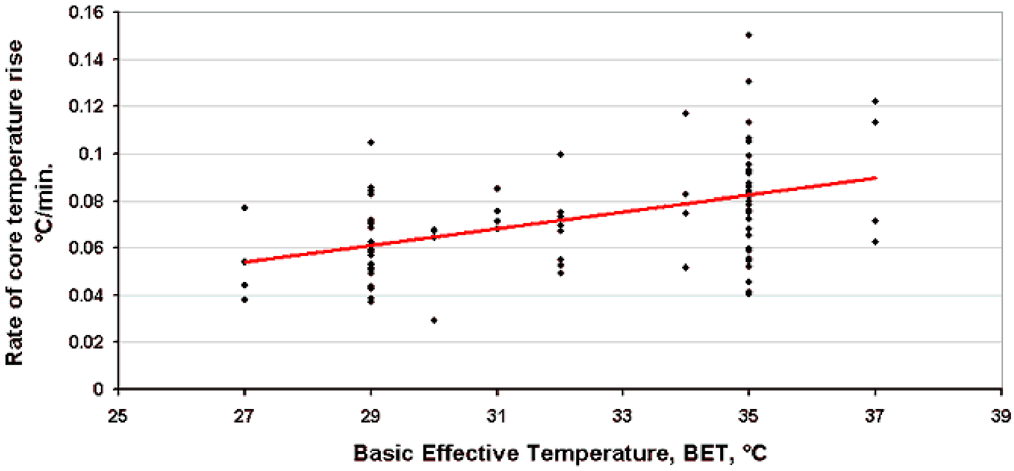
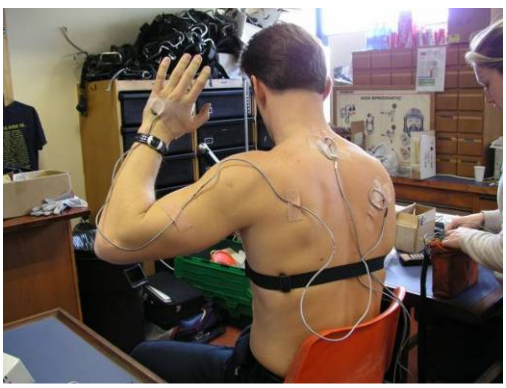


Figure 5.1: Core body temperature rise observed in simulated underground evacuations in hot and humid conditions

[*Source*: Jones *et al.* (2003)]

There are a number of methods to monitor these vital signs, the most common being skin attached sensors. The human ear can actually give one of the most convenient and accurate body core temperature. Devices of this nature are being practiced more commonly in medicine. Figure 5.2, below, shows an example of work being conducted by the Fire Service to monitor heart rate and skin temperature. The subject in the photograph as also ingested a radio telemetry lozenge, which as part of this evaluation work. However, a disadvantage of this system is the amount of wiring and additional equipment requiring the rescue person to carry additional weight. Even the data from the lozenge has to be collected locally, i.e. in close proximity to the human body. Sensors with in-built RF telemetry are seen to significantly enhance this type application in minimising the amount of excess equipment a rescue member would carry.



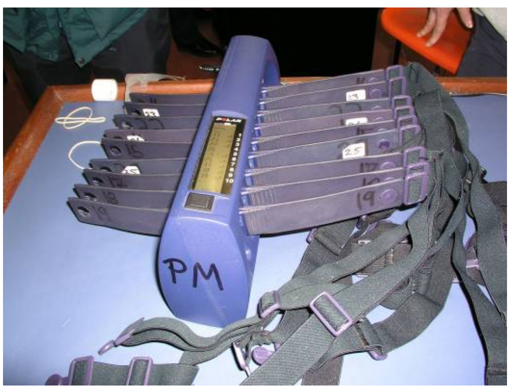


Figure 5.2: Examples of Heart Rate and Skin Temperature Monitoring – Fire Service

[Photo courtesy of D.Gibson]

5.3 Southwark Building Trials

The LFB Southwark fire training building (Figure 5.3) is arguably a 'worst case' environment for a wireless device due to the fact that the interior is steel-lined to withstand intense heat. The presence of steelwork causes multiple signal reflections causing multipath interference for radio propagation and will also introduce a screening effect for point-to-point links around the building. The aim of the exercise, given the relatively limited timescales was to establish the wireless mesh technology performance in this type of environment, examining the feasibility of gathering vital signs data of rescue personnel via low power 'meshed' telemetry.

Figure 5.3: (a) LFB Southwark Training Centre (b) Main door

Figure 5.4: (a) 2nd Floor 'Bedroom' (b) 1st Floor 'Garage'

The fire training facility comprises four floors and a basement with various rooms modelling parts of a typical domestic, office or light industrial setting. Figure 5.4**,** above, gives examples of the steel-lined rooms within the building.

Test Radio Module Characteristics:

The field trials were conducted using EmberNet EM2420 (Zigbee related) mesh networking technology, operating at a frequency of 2.4 GHz with the following characteristics:

Table 5.1: EmberNet Radio Characteristics

Operating Frequency	2.4 GHz
Modulation	OQSPK (1)
Spread Spectrum	DSSS
Data Rate	250 kbps
Transmission (TX) Power	0 dBm (1mW)
Operational Range	75 metres (open air)

(1): Offset quadrature phaseshift keying with half-sine chip shaping

Network Map Key:

Modules: Gateway:  Network Node: 

Link Line Quality:

- Good signal strength (76 - 100 % packets)
- Fair signal strength (51 - 75 % packets)
- Poor signal strength (26 - 50 % packets)
- Very poor signal strength (0 - 25 % packets)

5.3.1 Results

5.3.1.1 LFB Training Centre Network 1 – 1^{st} Floor

The first network test was set up, as shown in Figure 5.5, below, with the gateway module attached to a laptop situated adjacent to the main door with 10 other network modules placed in different positions around the 1^{st} Floor of the building. The network demonstrated good coverage in relatively close proximity. Good quality signal links are indicated between neighbouring nodes with multiple redundant links across the network, weaker signal links are present when passing through steel walls as expected.

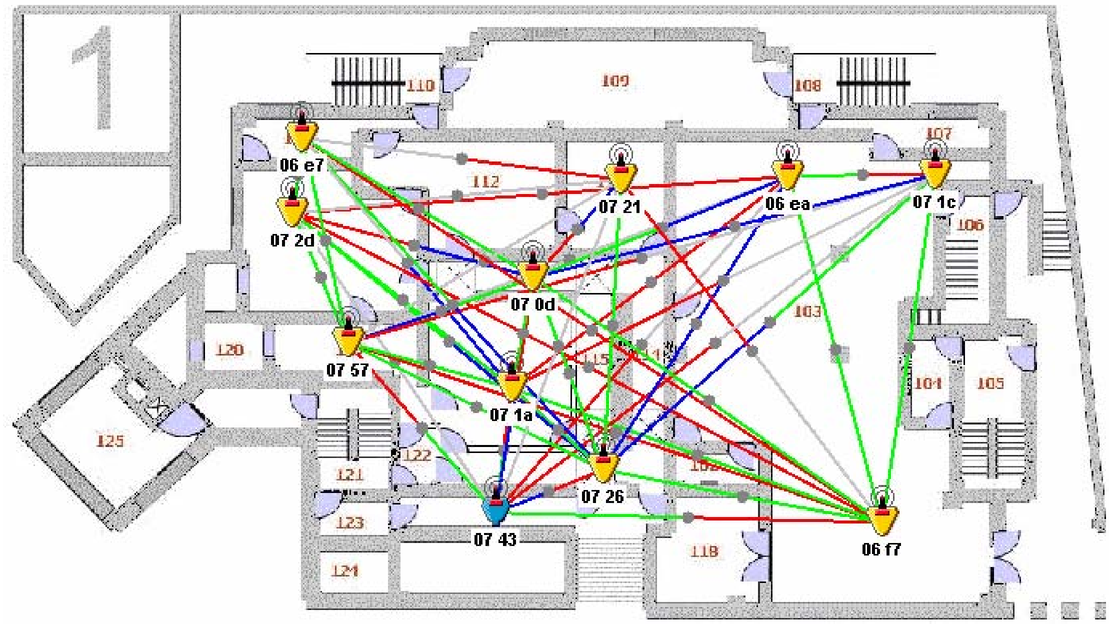


Figure 5.5: Southwark Training Centre Network 1 [Floor 1]

A trace route test between node 06f7 and node 06ef, shown in Figure 5.6, below, demonstrates how packets of data are randomly sent across the network via best quality available links. Random packets data are sent from 06f7 for a set time frame, the data is then sent to both 070d (97%) and 0726 (98%). 49% of the data arrived via 070d and 43% via 071a totalling 92%. with, 8% of packet loss.

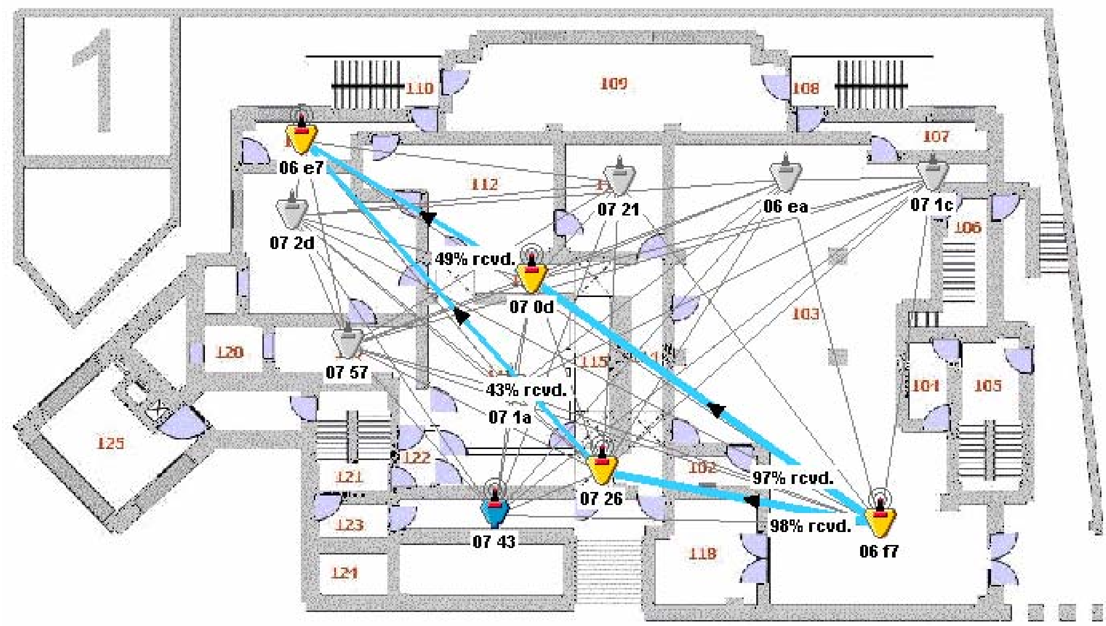


Figure 5.6: Southwark Training Centre Network 1 – Trace Route Test (06f7 → 06e7)

A ping test gives a measurement of the signal performance between two nodes, by sending and returning 100 packets between two nodes in a set time frame. A good quality link, e.g. in open air within a nominal operating range, would return 100%. Therefore, the percentage of the packets sent and returned gives a statistical representation of the signal strength, or signal noise between two nodes.

Figure 5.7, below, demonstrates a good quality link through walls is present between the gateway and node 0757.

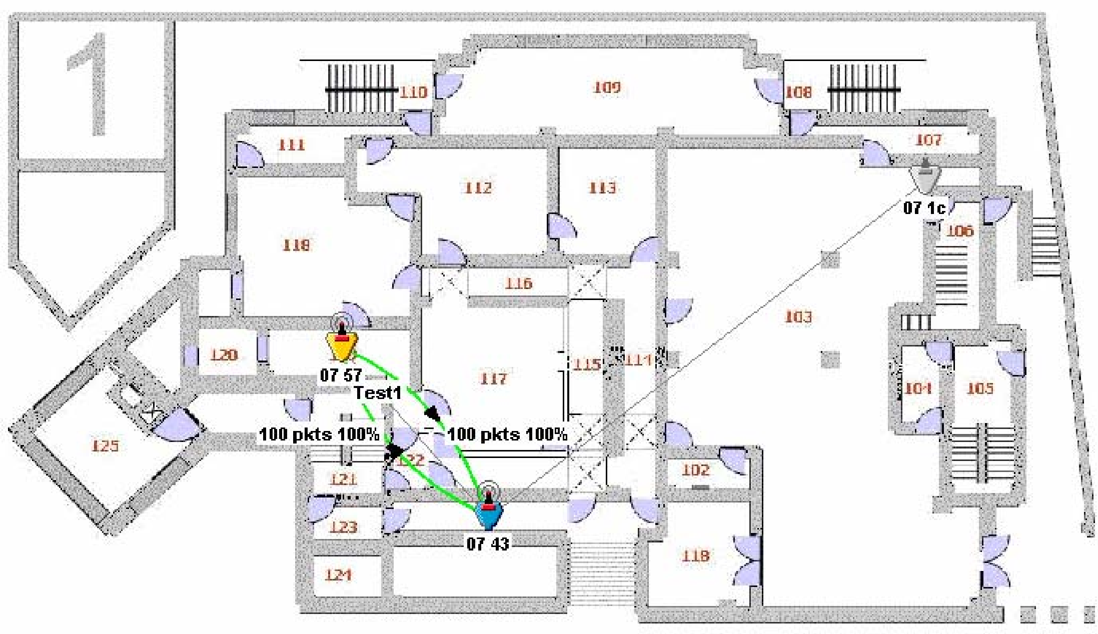


Figure 5.7: Southwark Training Centre Network 1 – Through-Wall Ping Test

Whilst most tests employed static network configurations, a limited number of dynamic tests were conducted with a moving subject. As a demonstration exercise, acceleration data was gathered from node 071c within the network. An accelerometer on board the module measures orientation in space, in terms of acceleration in the X- and Y-axis. During the exercise, the module node was carried from its position within the network to outside the main door, where the gateway module was situated. The data gathered from the accelerometer is shown in Figure 5.8 below. The exercise has shown that data can be gathered dynamically from a mobile device within the mesh network. However, the Ember evaluation software employed is unaware that the device is mobile and a routing algorithm would need further development to compensate for this. This could also include a simplified proximity detection capability, to indicate that the device is mobile or where it is located in relation to the other nodes within the mesh network.

Note: The accelerometer is not calibrated; therefore the data recorded is not accurate. The results were gathered solely for indicative purposes.

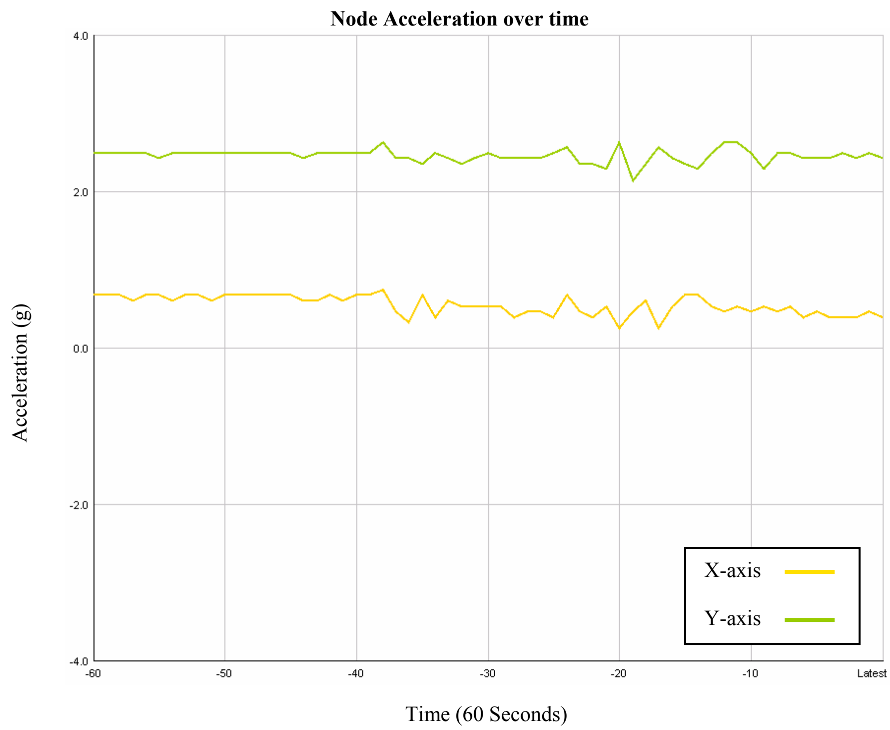


Figure 5.8: 071c node accelerometer data, mobile subject

As a general observation, the mesh network has shown good resilience in a complex multipath environment with relatively low transmission power at 0 dBm (or 1mW) ERP. The 1st floor network demonstrated that a robust mesh network could be established within relatively close proximity i.e. room-to-room transmission. The network began to fail when transmitting through multiple walls. Although, the number of redundant transmission pathways present would increase the ruggedness and network survivability. The simple accelerometer exercise demonstrated that data could be easily transmitted across this type of network. However, further work is needed, as discussed, to overcome the issue of gathering dynamic rather than static data from the modules.

5.3.1.2 LFB Training Centre Network 2 – 1st and 2nd Floor

Another network was set up with the gateway situated adjacent to the main door as previously, and various other nodes distributed around the 1st and 2nd floor, as shown in Figure 5.9 (page 179). A relatively robust network was established between the two floors with all nodes being seen except for node 0721, which was situated outside on the balcony. A steel door between the 0721 and the 070d (top of stairs) and the balcony itself directly above the gateway module seemed to cause a severe screening effect. Whereas, node 06ea, situated further was just visible to the network.

Ping tests were taken between node 0757, situated on the first floor and neighbouring nodes above on the second floor to test the performance from floor to floor. As shown in the table below, the test between 0757 and the node directly above (072d) returned an 86% link for the send-to-receive portion and a 96% for the return, demonstrating a relatively strong link from floor-to-floor, see Figure 5.10 (page 180). However, nodes not directly above the reference module could not establish a reliable link for the test, resulting in a 0% response.

Through Floor Test:

Table 5.2: Through Floor Test

Node	Packets Out (→) Send-to-Receive			Packets Return (←) Receive-to-Send		
	TX	RX	%	TX	RX	%
0757 → 072d	100	86	86 %	86	83	96 %
0757 → 071a	0	0	0 %	0	0	0 %
0757 → 0743	0	0	0 %	0	0	0 %

5.3.1.3 LFB Training Centre Network 3 – 1st to 4th Floor

The final network scenario was set up using the gateway module in the same position with the other network nodes distributed across the 1st, 2nd, 3rd and 4th floors, as shown in Figure 5.11 (page 181). This network test was clearly operating at the limits of the modules. A relatively reliable network was established up the stair well up to the 3rd floor. Interestingly, the transmission link of the node at the top of the stair well on the 4th floor is completely bypassing the nodes located on the 3rd floor and is only communicating with the modules further away. This is clearly a scenario where the metallic infrastructure is having a complex effect on transmission. The other two nodes on the 4th floor are not able to establish a reliable link.

In all, this network is operating at and above the limitations of the low power modules operating at 1mW transmission power. Extending the network coverage beyond its limitations clearly causes the mesh network to start behaving erratically and is increasingly influenced by the proximity of the metal structures etc. Therefore, a denser network and possibly increased transmission power is required in order to reliably achieve full building coverage. The results from network 2 and 3 suggest that a linear 'daisy chain' approach of establishing multi-floor coverage within this type of environment would be an appropriate approach.

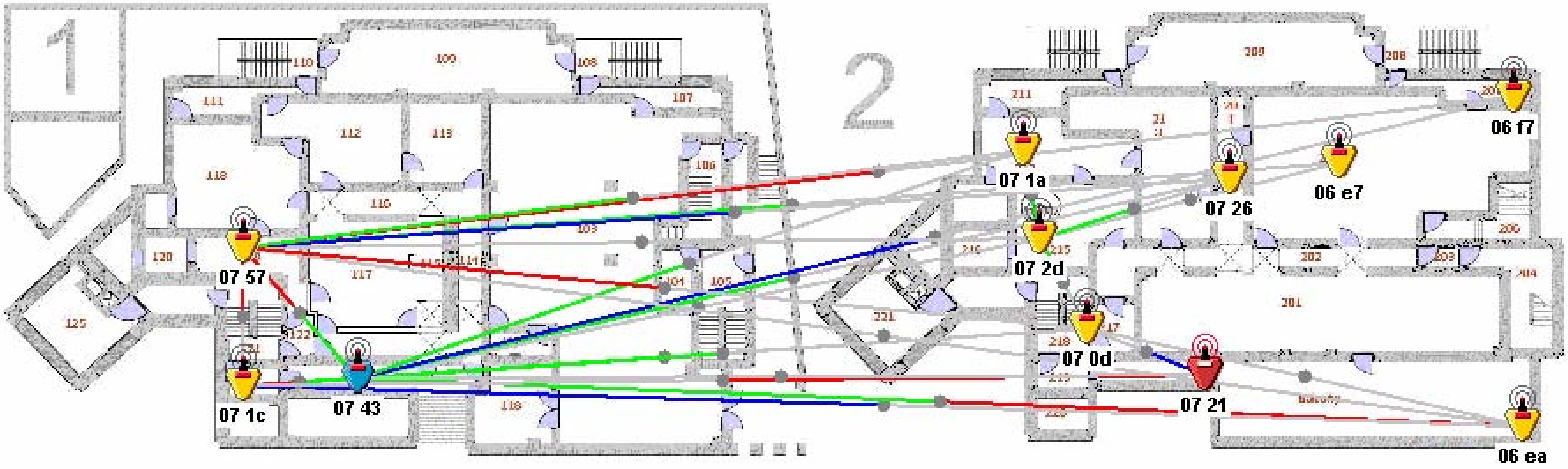


Figure 5.9: Southwark Training Centre Network 2 [Floors 1 → 2]

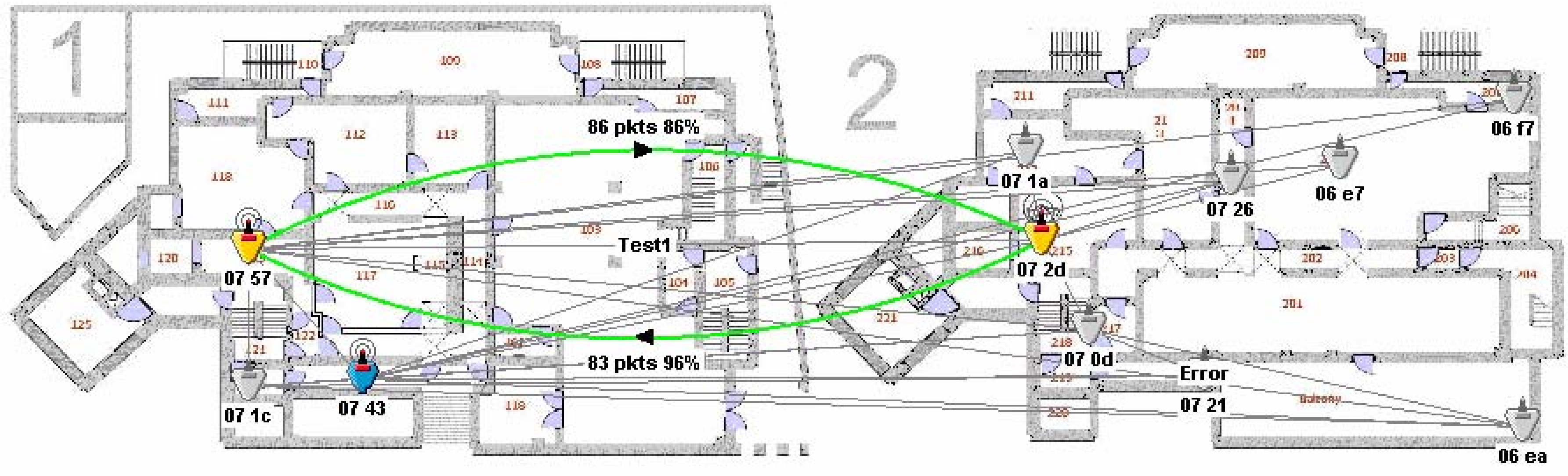


Figure 5.10: Southwark Training Centre Network 2 – Ping Test (0757 → 072d)

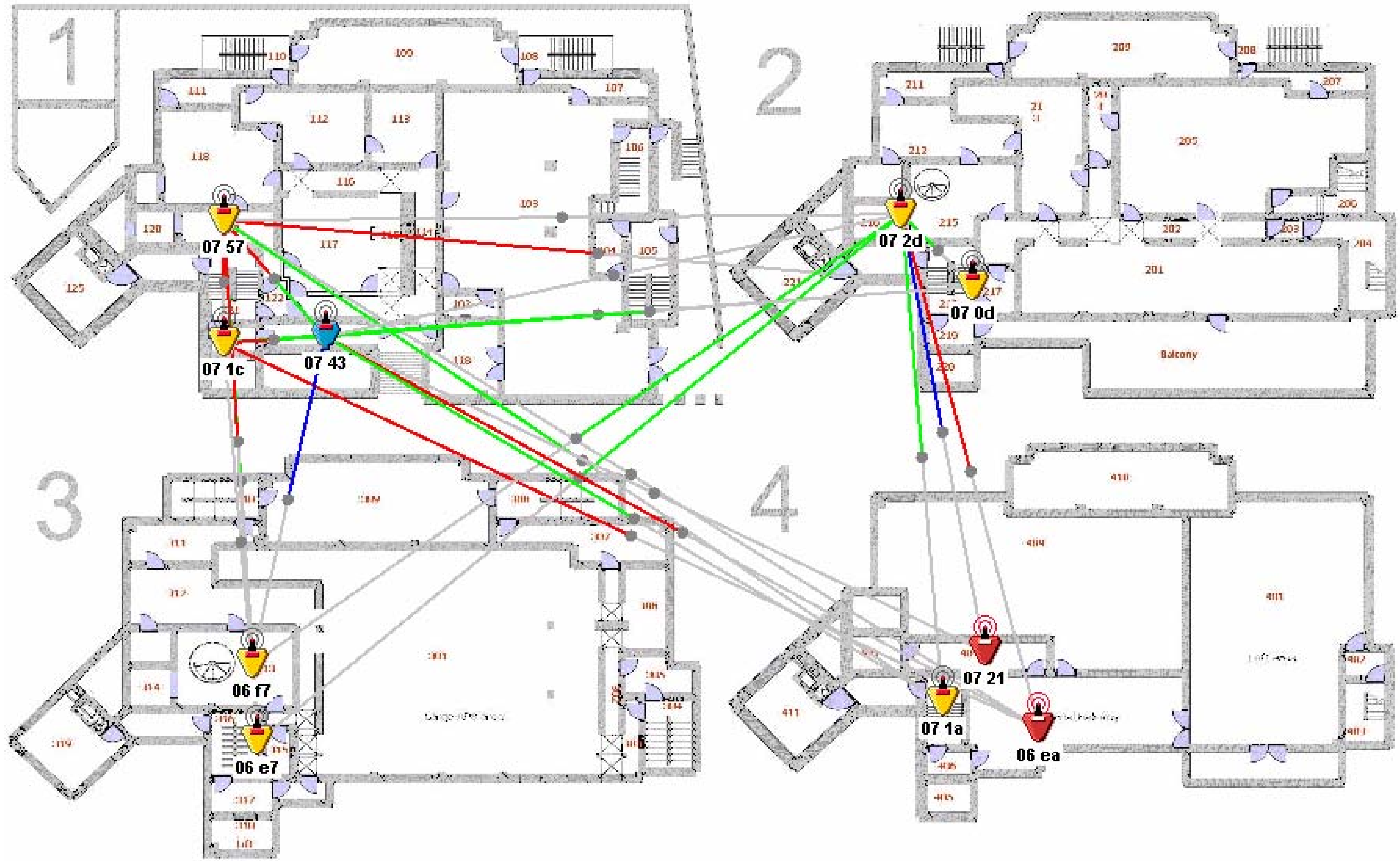


Figure 5.11: Southwark Training Centre Network 3 [Floors 1 → 4]

5.3.2 Discussion on Packet Loss

The trials were conducted using an Ember EM2420 evaluation kit, which is a useful tool for evaluating general Zigbee network behaviour, but which has shown sub-optimal performance in certain situations. Our trials of the Ember network have shown that, in some circumstances, there can be significant packet loss during ping tests, and the evaluation software frequently reports that individual nodes are no longer functioning. Clearly, we are operating at the limits of the system, which is very low powered, and affected by the proximity of metallic structures. Any practical system will need to function in these ‘difficult’ radio environments. The mesh control algorithm (for routing and transmission control) also needs to be able to provide a means of maintaining high priority transmission pathways.

In a sense, packets of data are "supposed" to get lost during a ping test, which is merely a simple transmission of a data packet. For transmitting 'real' data across a network, a higher-level protocol would be used, which requested re-transmission of failed data packets. Even a network where only a small fraction of packets are successfully transmitted can be used to transmit accurate data, although at a limited speed. In other words the statistics of a ping or trace route are not a measure of the reliability of data transfer. If 10% of packets are successful this implies that data transmission speed is 10% of the fastest possible speed, not that 90% of data will be corrupted. A simple point-to-point radio-modem telemetry system will generally fail if any of the data is corrupted. Clearly the advantage of a mesh network is not only that it is a mesh, but that the data is transmitted in packets; it can be re-sent if there is a failure and the packets can be re-assembled in the correct order at the receiver. For this reason a mesh network may be useful even when the possibility of configuring it as a true mesh (with multiple data paths) is limited, e.g. in a linear tunnel environment or ‘daisy chain’ link

5.3.3 Southward Trails Conclusions

Summary of LFB Southwark Fire Training Centre Field Trials

In summary, the mesh network trials at the fire training building have demonstrated that meshed networks offer increased transmission resilience versus comparable point-to-point links. Operating at a low transmission power of 1mW, a relatively dense network across Floor 1 demonstrated a rugged mesh network could be readily achieved. Transmission across several floors or through several walls within the metal-lined building stretched the mesh network to its limitations, where particularly in the final test across the whole building, the network began to behave erratically. There is a clear indication that the proximity of metallic structures is influencing the radio transmission.

The in-building trials at the training centre are a ‘worst case’ scenario for a wireless device to operate in due the steel-lined interior. The results have shown that low power wireless mesh networking technology can feasibly operate reliably within this type of environment, however, there are a number points to make:

- Meshed networks have increased transmission resilience verses traditional point-to-point links.
- High node density and short transmission distances are beneficial.
- A linear or ‘daisy chain’ approach would be a suitable approach to achieving floor-to-floor coverage.
- Network path selection and packet routing control algorithm performance is critical to overall system performance.

The transmission tests at Southwark demonstrated a somewhat reduced transmission range compared with the various laboratory and underground trials. Further studies are required to characterise built environment behaviour of low power personal area wireless networking technologies. The cardinal points of a targeted programme of further studies are identified overleaf for further consideration.

Considerations for Further Work

Ultimately, the goal of conducting research into improving fireground communications performance must involve identifying simpler, more resilient technology that will work in a diverse range of built environments, including tunnels. The size, reliability, cost and performance balance of these systems also needs to be matched to Fire Service procurement standards. As with most emergency equipment and apparatus, fitness for purpose, (hazardous area) approvals and human factor attributes are important design and development issues. Communications demands in a large fire incident can also be onerous, with a particular requirement to ensure transmission resilience to many parties, freedom from channel blocking and prevention of command centre 'overload'. Recently, the need to telemeter 'vital signs' and firefighter status information to command centres has been reinforced.

The proposed next step is to focus on specific aspects of wireless mesh communications behaviour, towards developing a better understanding of the potential gains offered by using a mesh topology approach against existing Fire Service radio systems. Towards gaining a better appreciation of variability and the limitations of mesh communications in build structures, testing will need to be conducted in a representative selection of building types.

The tests at Southwark training centre, supported by underground mine tests, direct that attention be given to the following technical avenues:

1. Investigation of the role, algorithm design and metrics required of wireless mesh operating software to ensure high integrity communications.
2. Investigation of the performance gains achievable by the following procedural and design specification changes:
    a. Node deployment procedures (physical separation, geometrical constraints etc).
    b. Increased transmission power (with an optional 10 dBm to increase unit-unit range).
    c. Resistance to multi-path effects through enhanced propagation using various classes of 'smart' antenna.
3. An evaluation of the feasibility of providing an intelligent proximity detection algorithm within the network (versus manually placing nodes on pre-loaded maps).
4. An assessment of the feasibility of integrating digital data transmission and speech communications using voice over IP (VoIP) data communication protocols and techniques. This would also need to assess any increase in nett energy consumption and overall battery demands.

5.4 Summary

In extreme conditions, particularly heat and humidity, the human body can rapidly decline when under a large amount of physical excursion. There have been a number of incidents around the globe where otherwise rescue personnel have collapsed due to heat strain (Jones *et al.* 2003). Key 'vital signs', such as heart rate and body core temperature, can be monitored to ensure the rescuer is not reaching a critical point. This Chapter has introduced work undertaken by both Mines Rescue Service (Jones *et al.*, 2003) and the Fire Service in resolving this issue. Currently systems under evaluation are wired sensors or a local RF lozenge is ingested. Complete wireless telemetry offers the potential to significantly reduce the amount of excess equipment a rescue team member would have to carry in implementing this type of system. A mesh type network has the potential to provide both the rescue team captain and a central ground control the facility to monitor individuals. Details of mesh network performance tests carried out in conjunction with the London Fire Service within an in-built environment have also been presented.

Chapter 6: Underground Smart Sensors and Telemetry

The application development of distributed smart sensor networks and remote telemetry with a 3D surveying instrument is discussed in this Chapter. Distributed wireless mesh smart sensors have a number of interesting applications including: environmental monitoring, belt conveyor drive sensors, other machinery diagnostics, and control (remote telemetry). Two proof-of-concept applications have been developed; an application to gather remote sensory data across a mesh wireless network, and an application to control a 3D surveying instrument, as an example of remote telemetry. The 3D surveying control software was developed in conjunction with another research project at Camborne School of Mines, which is developing a robotic surveying vehicle for unsafe mine environments. These applications were developed to a proof-of-concept stage; full details are given in this Chapter.

6.1 Outline and Objectives

Underground smart sensors and remote telemetry were key applications identified earlier in this research (Chapter 4), using low power mesh networking technology. The aim of the work presented here was to develop the 'smart sensor' and 'remote telemetry' applications to a proof-of-concept stage. The aim 'smart sensor' application was to develop a generic method of gathering remote sensory across a mesh network, in turn being able to log the data. In addition providing a means of transferring the data to another, or larger network, infrastructure e.g. Ethernet or the Internet. The aim of the 'remote telemetry' application was to provide a means of establishing robust, rapidly deployed, wireless telemetry with a 3D surveying instrument deploying using a robotic vehicle to survey underground mine stopes in hazardous areas.

6.2 Underground wireless mesh smart sensors

6.2.1 Motivation

Wireless mesh 'smart sensor' networks in an underground mine could be used in environmental monitoring, machine diagnostics, or provide distributed temperature monitoring on a belt conveyor drive for fire safety. Another similar closely related application is the 'vital signs' telemetry (Chapter 5), where sensors are distributed around a rescue team of personnel and the data collection point would be fed either to the team captain or ground control base station.

There are a number of key advantages in using a mesh wireless system for smart sensor type applications. They can be quickly installed, or even rapidly deployed if necessary. There is flexibility in semi-mobile type systems e.g. belt conveyor drive, where the downtime in moving equipment is minimised. It also provides the scope for scalability and additional functionality (e.g. localisation). The elimination of large amounts of cabling, and simplifying installations also has implications in lowering cost.

Details of the development of proof-of-concept' underground mine sensory data acquisition using a mesh network is presented in this section. This application gathers remote smart sensor data, e.g. temperature or other environmental data, across the wireless mesh network back to a 'sink' node. The sink node can either be the gateway device to a PC or network infrastructure, or several sink nodes could potentially be used to remotely log data in a larger network infrastructure. A separate windows application has also been written to log the sensory data either directly to a PC or remotely across a TCP/IP network. An overview smart sensor application is shown in Figure 6.1 below.

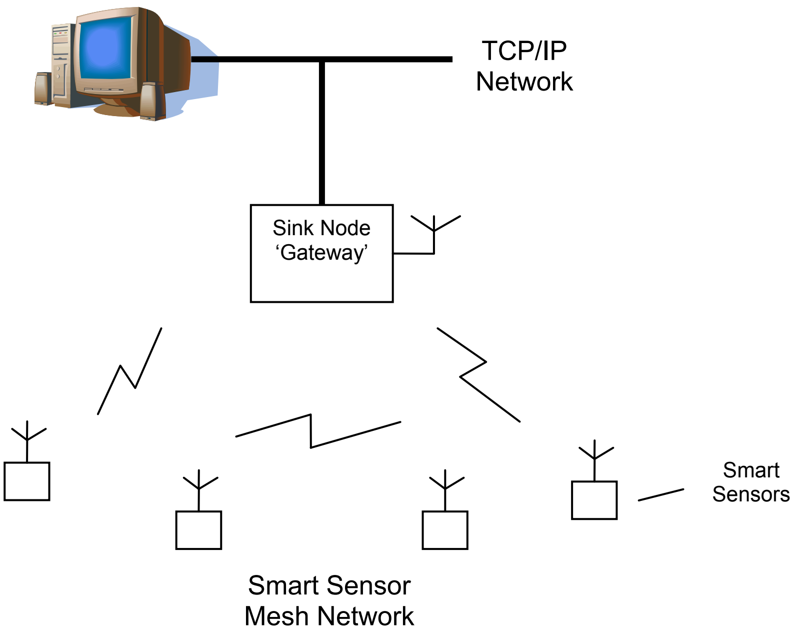


Figure 6.1: Wireless Mesh Smart Sensor Application Overview

6.2.2 Hardware and Development Tools

The applications have been developed using Ember EM2420 EmberNet Development Kit and associated software tools. Details of the hardware and software development tools are given below.

6.2.2.1 Hardware

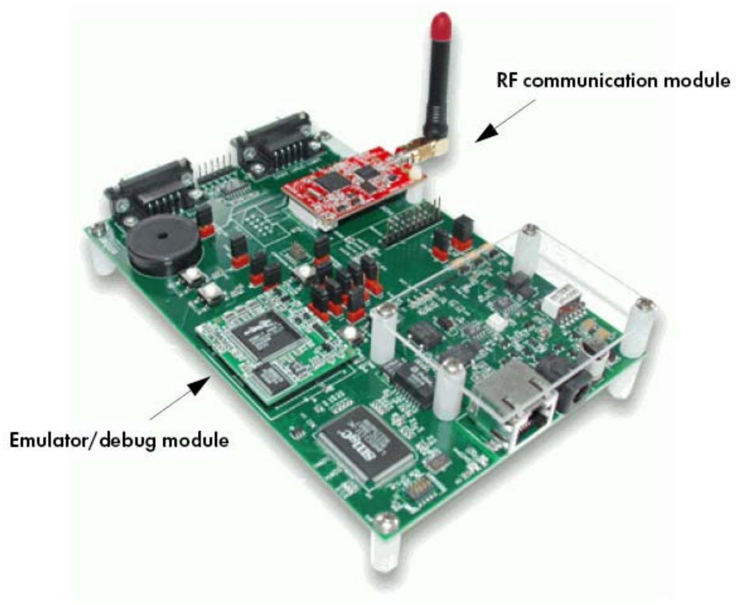


Figure 6.2: EM2420 Development Boards

- 12 EM2420 Development Boards – Includes:
  - 12 x EM2420 Radio Communication Modules
  - 12 x Break-out boards with Serial and TCP/IP interface
  - Power-over-Ethernet Injector Supply
- Sensors
  - National Semiconductor LM20 Temperature Sensor
  - Sensor Technics HCXM100D6 Barometric Pressure Transducer

A layout of the EM2420 Radio Communication Modules is shown below in Figure 6.3. The module comprises a separate EM2420 radio transceiver (U5) and ATmega128L microcontroller (U2).

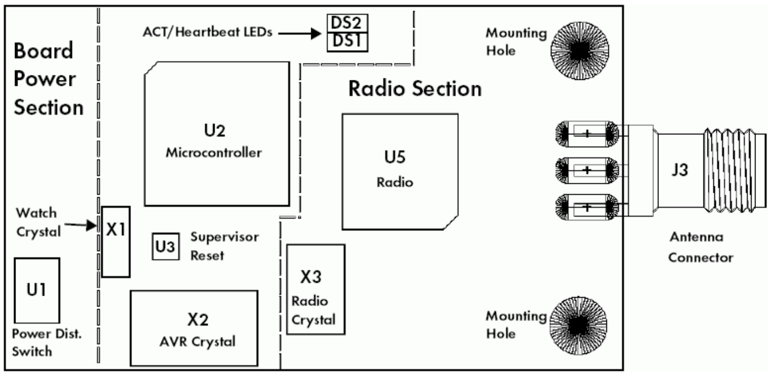


Figure 6.3: EM2420 RCM

EM2420 Radio Transceiver Features:

- 2.4 GHz IEEE 802.15.4 compliant RF transceiver with baseband modem, MAC support, and networking stack.
- DSSS baseband modem with 2MChips/s and 250 kbps effective data rate.
- Suitable for both RFD and FFD operation
- Low current consumption (RX: 19.7 mA, TX: 17.4 mA)
- Low supply voltage (2.1 – 3.6 V) with integrated voltage regulator, (1.6 – 2.0 V) with external voltage regulator
- Programmable output power
- 128(RX) + 128(TX) byte data buffering
- Digital RSSI / LQI support
- Battery monitor

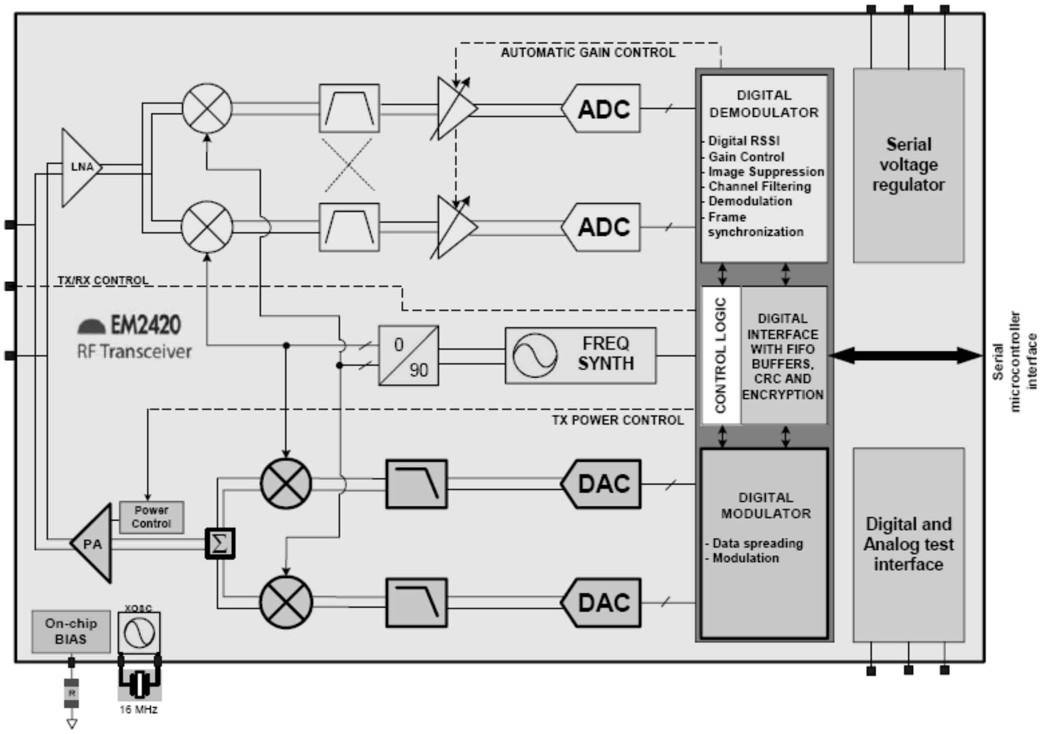


Figure 6.4: EM2420 Radio Transceiver

ATmega128L Microcontroller Features:

- High-performance RISC, Low power AVR® 8-bit Microcontroller
- Peripheral Features –
    - 8 Channel 10 bit ADCs,

- UART and SPI,
- PWM Channels

- 128K Flash Memory
- 4K EEPROM
- 53 I/O Programmable Lines
- 2.7V to 5.5V Power Supply
- Up to 8MHz Operating Speed

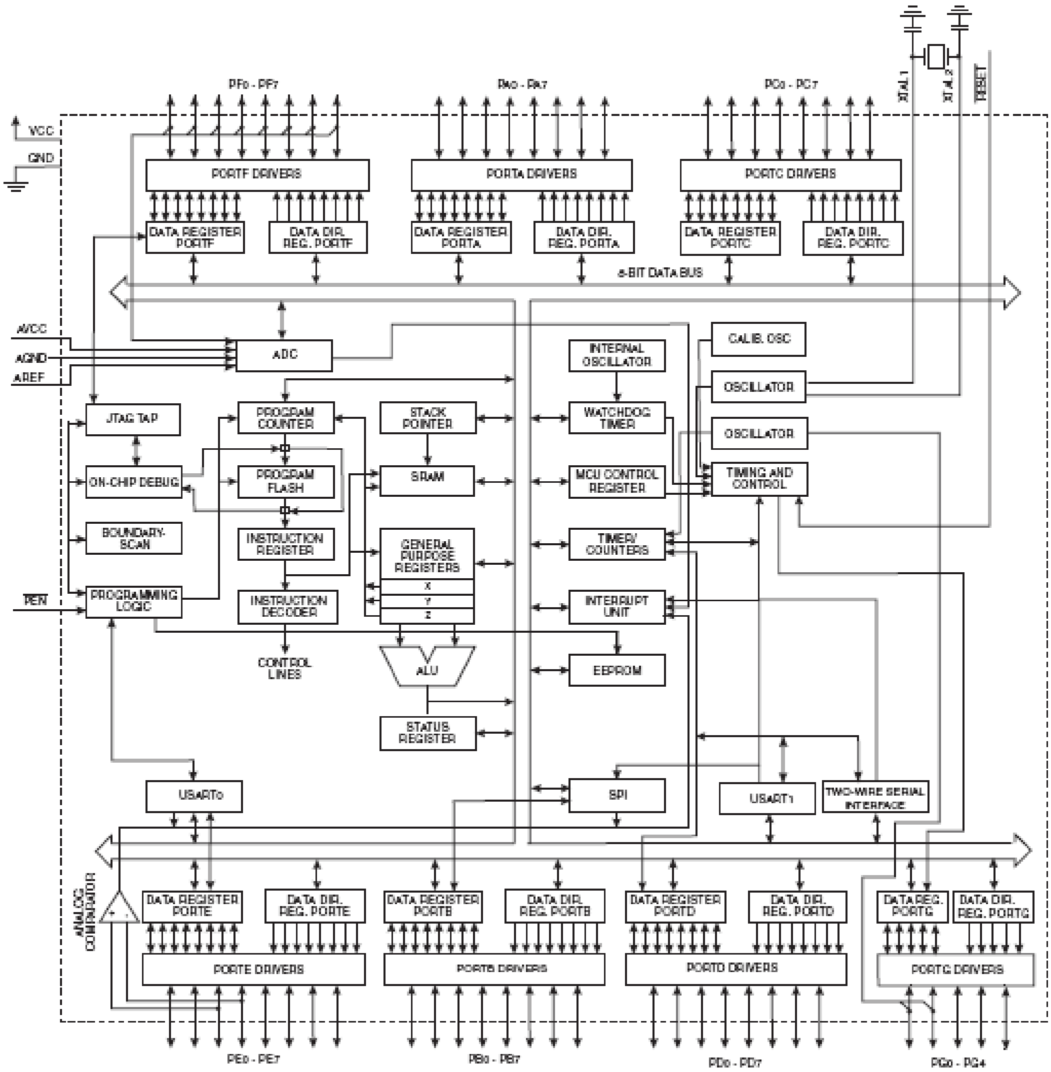


Figure 6.5: Atmel ATmega128L AVR Microcontroller

6.2.2.2 Software Development

Most of the work involved software development using both the embedded microcontroller, written in C programming language, and higher level windows application programming, written in Visual C++ programming language.

Software Development Tools:

- IAR Embedded Workbench 3.10D
  - C Programming Language and Library
  - AVR IAR C/EC++ Compiler

- Microsoft Visual Studio .NET 2003
  - Microsoft Visual C++

6.2.3 Application (Software) Development

6.2.3.1 Embedded Software

The embedded software was written by the author using the EmberNet stack software. This requires writing software that calls standard EmberNet API functions for message delivery etc, and making use of the HAL (hardware abstraction layer) to use make use of specific on board functions. This includes serial port communication, ADC, and other devices mounted on the EmberNet development board (e.g. LEDs, switches etc). Figure 6.6, below, shows the layer functionality of the EmberNet stack.

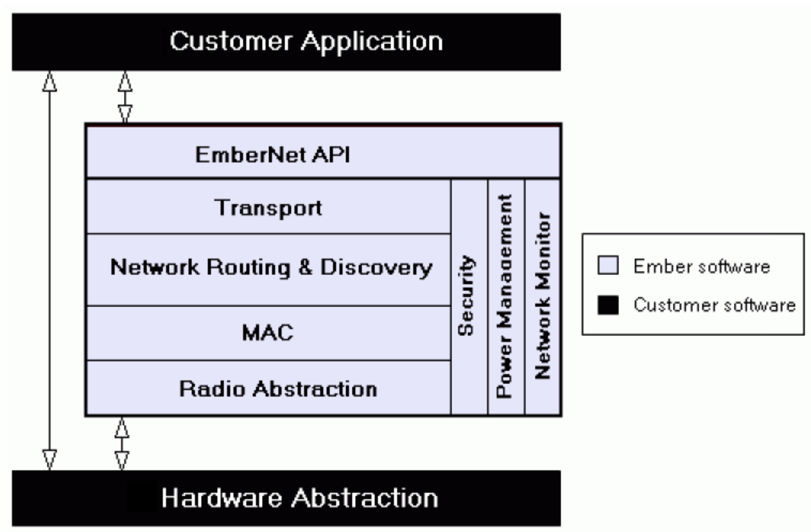


Figure 6.6: EmberNet Stack

EmberNet Addressing and Message Delivery

Addressing:

Every EmberNet has a standard 64-bit extended unique identifier (EUI-64) IEEE EUI-64 address. Messages can either be sent to this 64-bit address or using a common 16-bit Multicast identifier, which is usually assigned to a specific group.

Endpoints and Interfaces:

In addition to the node address, messages are sent to a specific endpoint and interface part, which specifies an additional destination within the target device. This method is analogous to TCP or UDP ports. Each EmberNet device can contain up to 31 different endpoints, where the endpoint is an embedded device connected to the Ember radio e.g. sensor, switch. Endpoints support different interfaces, for example, these may be a control interface, or monitoring interface.

Binding:

Each device maintains a binding table, with a configurable number of entries. These entries are either a multicast binding or unicast binding. The bindings are by directional in that messages can be sent and received. These tables provide the mechanism for virtually joining discrete elements across the mesh network, or common group (multicast).

Message Delivery:

The GRAd routing algorithms, which employ cost tables, ensure efficient message delivery across the network. Messages are either sent as a multicast or unicast.

Multicast – These type of messages are broadcast to the entire network, where they will only be accepted by devices containing the multicast identifier in the binding table.

Unicast – These are sent as either datagram or sequenced messages. Datagrams are sent without any coordination between sender and receiver. Therefore, as they may take different routes message packets may arrive in different orders. In sequenced message delivery, the packets are automatically re-ordered and duplicate packets are deleted.

Smart Sensor Software Development

The embedded software application has two separate types of smart sensor nodes, a ‘sink’ node and a ‘sensor’ node. The sink node acts as a data collection point for the sensors and gateway to external PC or network interface. Upon receipt of a sink ‘advertisement’ sensor nodes will assign themselves to the ‘sink’ and start sending data. Detailed flow charts of the sink node software are shown in Figure 6.7 below, and the sensor node is shown in Figure 6.8 below. Any device running the ‘sink’ or ‘sensor’ node software will take this role in an EmberNet mesh network. The sensor software has been tested with both temperature and barometric pressure sensors. The programs for each differ slightly in setting up the ADC readings etc. The ‘C’ programs for the ‘sink’ ‘temperature sensor’ and ‘barometric pressure’ sensor are given in Appendix A.5. The sample data from the sink node demonstrated successful readings across the EmberNet mesh network.

Sample Serial Port Info from ‘Sink’ Node:

```
INIT: sink app running on node 000D6F0000025BC5 on channel 0x0F, power FF
  reset info (reason): 00
  reset info (PC): 9ACE
EVENT: setting multicast binding, status is 0x00
EVENT: sink automatically advertising to find sensors
TX [sink advertise], status is 0x00
RX [sensor select sink] from: 000D6F0000025BC7; processing message
EVENT: sink set binding 00 to node [000D6F0000025BC7]
TX [sink ready],
RX [sensor select sink] from: 000D6F0000025BD9; processing message
EVENT: sink set binding 01 to node [000D6F0000025BD9]
TX [sink ready], s
RX [Barometric Pressure] from: 000D6F0000025BC7: Data: 967 mbar
RX [Temperature] from: 000D6F0000025BD9: Data: 28 degrees C
RX [Barometric Pressure] from: 000D6F0000025BC7: Data: 967 mbar
RX [Temperature] from: 000D6F0000025BD9: Data: 28 degrees C
EVENT: sink automatically advertising to find sensors
TX [sink advertise], status is 0x00
RX [Barometric Pressure] from: 000D6F0000025BC7: Data: 967 mbar
RX [Temperature] from: 000D6F0000025BD9: Data: 28 degrees C
```

Features of the Smart Sensor Application:

- The sensors are easily scalable. The sink node constantly advertises to look for new sensor devices within range.
- The ‘sink advertisement’ allows the network to constantly check and maintain links. Sensor devices will look for a new sink if the link is lost.
- The sink node acts as a gateway to interface directly to a PC though serial communication, or to a network using TCP/IP.
- The EM2420 nodes contain on board 10-bit ADC inputs, therefore simplifying the hardware requirements for sensor applications only requiring this 10 bit resolution or less.

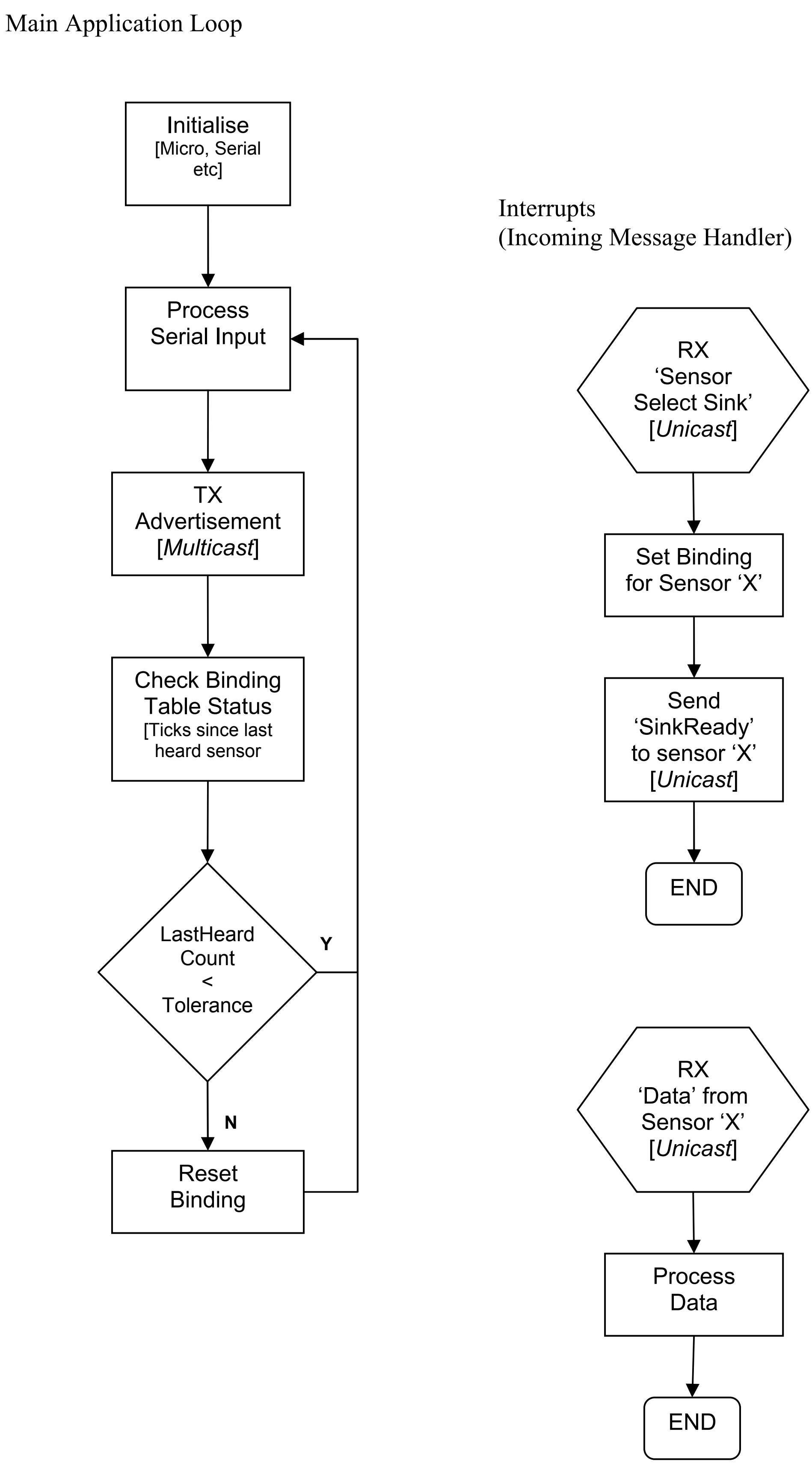


Figure 6.7: Sink Software Flow Chart ['*sink.c*']

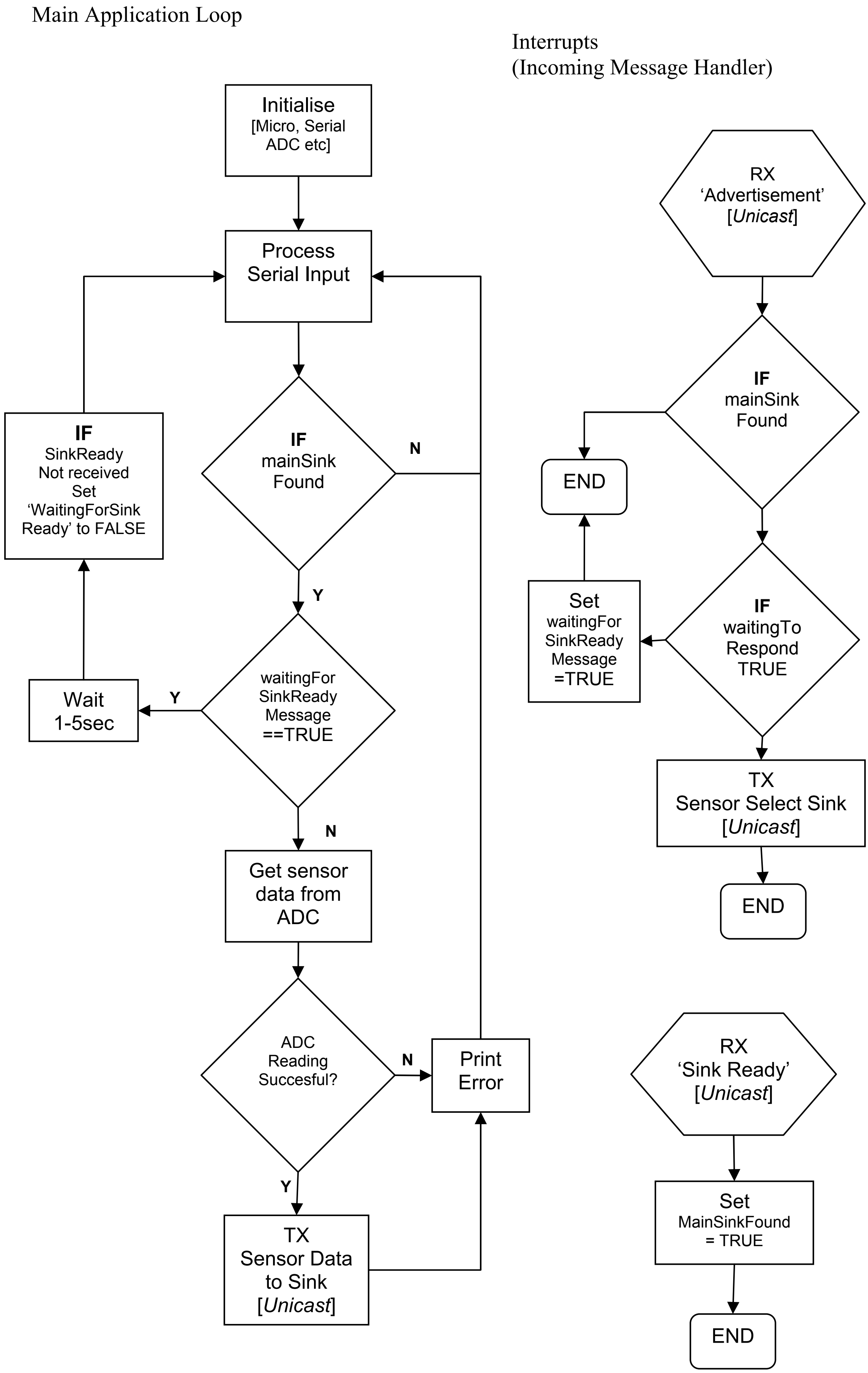


Figure 6.8: Sensor Software Flow Chart ['*xxx-sensor.c*']

6.2.3.2 Windows Interface

The next stage of the smart sensor application was to develop a 'windows interface'. Under the guidance of the author of this thesis, a student developed the windows application for the smart sensors, as part of a final year undergraduate project, at the University of West England. The software was developed using Microsoft Windows Visual C++ (Blundy 2006). The aim of the application was to log and interface the sensory data through a larger network infrastructure. Figure 6.9, below, shows an overview of the software application. The server PC acts collects and stores the sensor data from a 'sink node' to a database, e.g. using SQL. Then a remote PC can log onto the server and access the data from any location, for example through an internal network infrastructure or across the Internet. Figure 6.9 below, shows a flow chart diagram of the widows dada logging software.

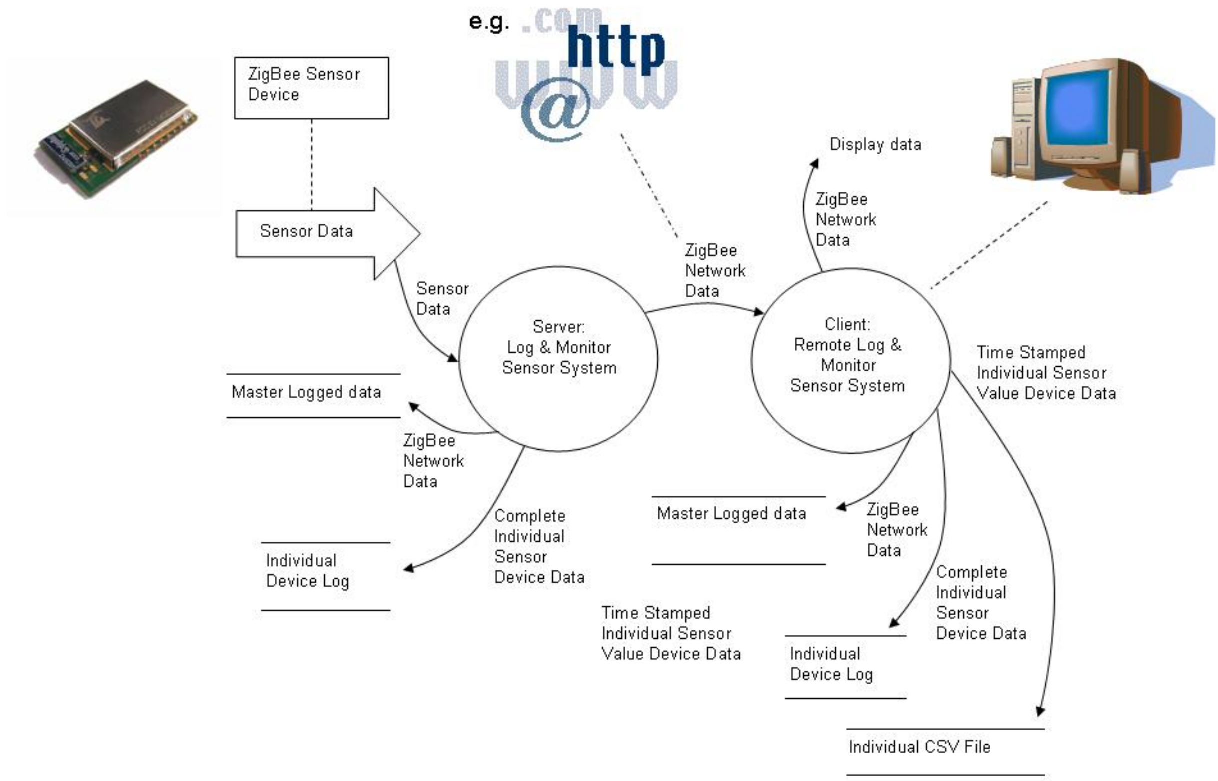


Figure 6.9: Smart Sensor Data Acquisition – Windows Interface

The windows application running on both a server and client PC are shown below in Figure 6.10 and Figure 6.11 respectively. On both the client and server, the data is converted to 'comma separated values' and stored in an SQL database. The intention of having the server at the wireless sensor network side is so that the server can be logged onto remotely, through either Ethernet or Internet to access the data.

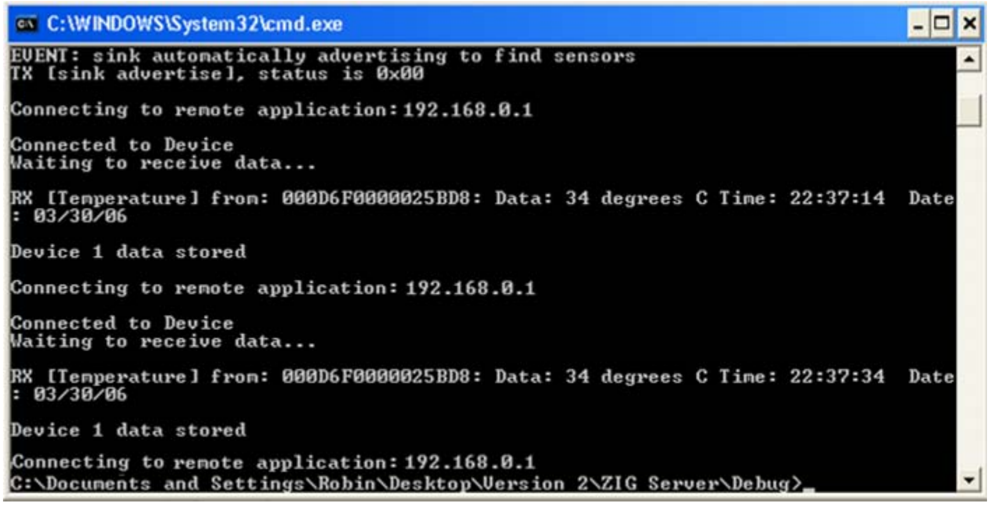


Figure 6.10: Zigbee-PC Server

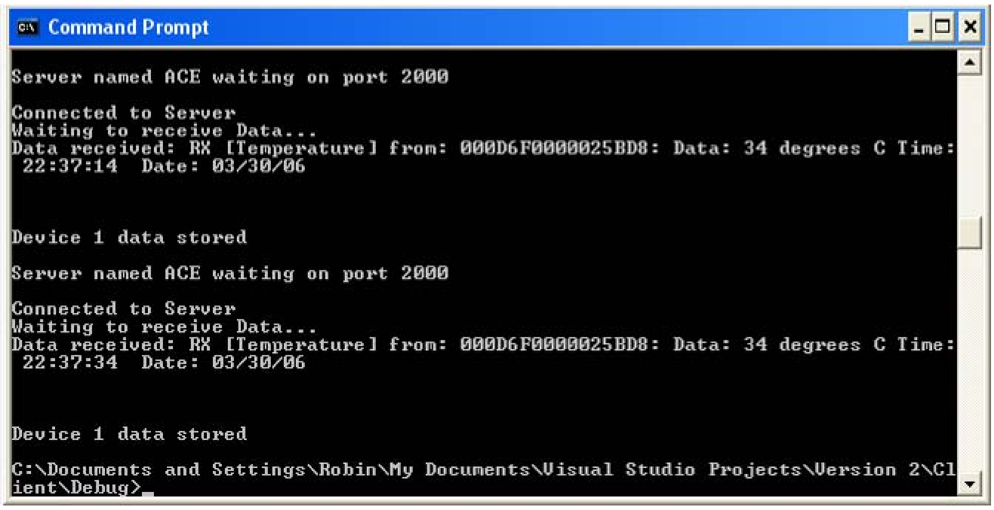


Figure 6.11: Zigbee-PC Client

6.2.4 Further Work Consideration

This application has been successfully taken to proof-of-concept stage. Since the development began, Ember have since released a fully ratified Zigbee stack, called EmberZNet. In addition to this they have migrated to a single chip solution (microcontroller and radio) with enhanced performance, and a likely further development would be to migrate to the new stack and hardware. This smart sensor application also has other related applications e.g. vital signs or other sensory data acquisition including machine diagnostics. Further developments would include tailoring this application towards more specific applications.

6.3 Remote Telemetry (3D Surveying)

6.3.1 Motivation

The characteristics of mesh networks provide the ability to extend transmission range in a RF hostile environment, e.g. confined space or mine. Potentially 'nodes' acting as repeaters can be rapidly deployed to extend RF coverage into non-LOS (line of sight) situations. This has led to joint work between this project and another project at the Camborne School of Mines (Jobling-Purser, 2006), developing an RSV (remote surveying vehicle). The RSV is designed to go into hazardous open stopes in an underground mine and take a 3D profile. The aim of this joint application was to provide remote telemetry with the on-board TPS (or Total Station) using the Zigbee (or in this case EmberNet) wireless mesh network. Using mesh nodes the range could be dramatically increased, keeping the user at a safe operating distance from the hazardous open stope. This type of application is predominantly aimed at hard rock mining, for example, this could be a blockage in an ore pass and the vehicle could be sent in to take the image to calculate the volume of material in the 'hang-up'. Figure 6.12, below, shows the typical setup for this application. The 80m max distance is based on a mesh node transmission power of 0dBm. This could be extended using higher power transmission, but there is a trade off against battery power.

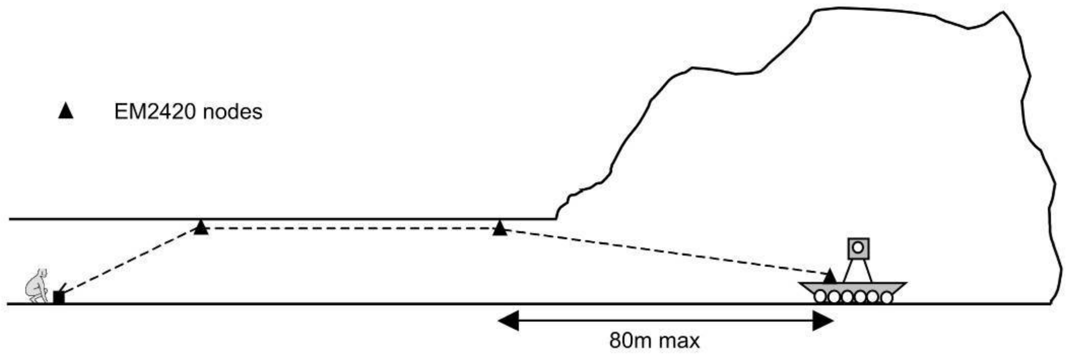


Figure 6.12: Zigbee and RSV Application

The requirement and recognition in progressing automation in the mining industry, from the perspective of improving safety, is certainly growing around the globe. According to a study by Miletic (2003), 30 – 50 percent of all mining industry deaths are caused by or related to rockfall. In developing counties the situation is much worse, according to official data (US Congressional Commission on China, 2004), over 6000 miners died in China during 2003. This highlights the need to improve overall mine safety world wide, and where automation can offer significant advantages. It is also recognised that the introduction of additional equipment into underground environments introduces additional risks directly associated with the equipment. Further research is required to fully appraise the impact and health and safety implications of this.

6.3.2 Hardware and Development Tools

The hardware and software development tools used to develop the 'remote telemetry' application are exactly the same in terms of the EmberNet development kit (for more details refer to Section 6.2.2). The Telegesis ETRX1 modules listed use exactly the same hardware as the Ember EM2420 and are programmed using the EmberNet development kit.

Hardware:

- ❑ Ember EM2420 Development Kit

- ❑ Telegesis ETRX1 Radio Modules
  - o Based on Ember EM2420 Hardware
  - o Runs EmberNet Software Stack

Figure 6.13: ETRX1 Radio Module

- ❑ Leica TCR 705 Total Station, or Terrestrial Positioning System (TPS)

Figure 6.14: Leica TCR 705 Total Station

The surveying instrument used was a reflectorless TPS (terrestrial positioning system), or total station, Leica TCR 705. The instrument is controlled through the serial port using a set of GSI commands. The commands are compatible with TPS 700 and TPS 1100 series instruments.

Software Development Tools:

- IAR Embedded Workbench 3.10D
  - C Programming Language and Library
  - AVR IAR C/EC++ Compiler

- Microsoft Visual Studio .NET 2003
  - Microsoft Visual C++

- GSI (Geo Serial Interface) – Leica Geosystems ASCII Command Reference Set
  - Needed for programming ASCII commands to communicate with TPS

6.3.3 Remote Telemetry Software

6.3.3.1 Embedded Software (Zigbee)

The flow chart in Figure 6.15, below, shows the embedded software that sends ASCII characters across the mesh network between two EmberNet devices. The program is essentially replicates an RS232 port. When a device receives an ASCII character through the assigned COM port (e.g. this could be a serial or TCP/IP port) it stores it in a buffer. When the buffers are either full, or when 'carriage return' is found the message is then sent to another EmberNet node. The messages are sent using a multicast; therefore the packets are broadcast to all devices, but only the device with the multicast binding will accept the data. The EmberNet nodes at each side are identical; therefore each device can transmit and receive the data. There is a slightly modified version of software for a gateway device requiring character echo. The TCR interface (embedded) software is given in Appendix A.5.

6.3.3.2 TCR Telemetry Software (Windows)

The TCR telemetry (or control) software, shown below in Figure 6.16, is a windows based program written by the author to send and receive commands to control a TCR surveying instrument through the serial port. Setting up the serial port communication in windows is based on work by Schneider (2005), using a non-event driven approach. This TCR telemetry software sends all the commands needed to initiate the TCR instrument, move and record laser distance readings at each position. This is based in the user input parameters, selecting sweep length and resolution. The device can either be used to record coordinates or northings, eastings and elevation. The TCR control (windows) software is given in Appendix A.5.

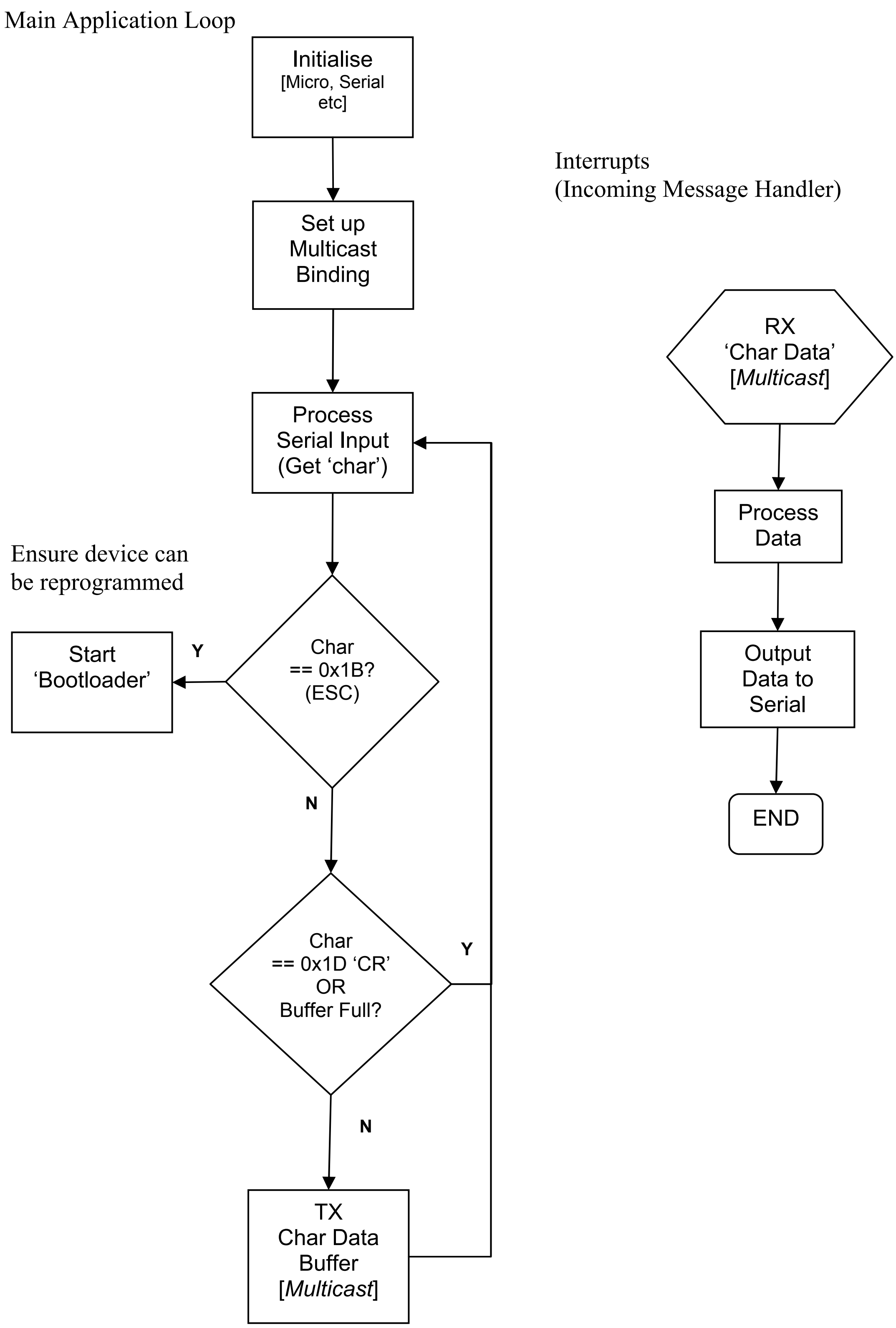


Figure 6.15: Embedded TCR-Zigbee Software Flow Chart ['*theod-control-main.c*']

Main Application Loop

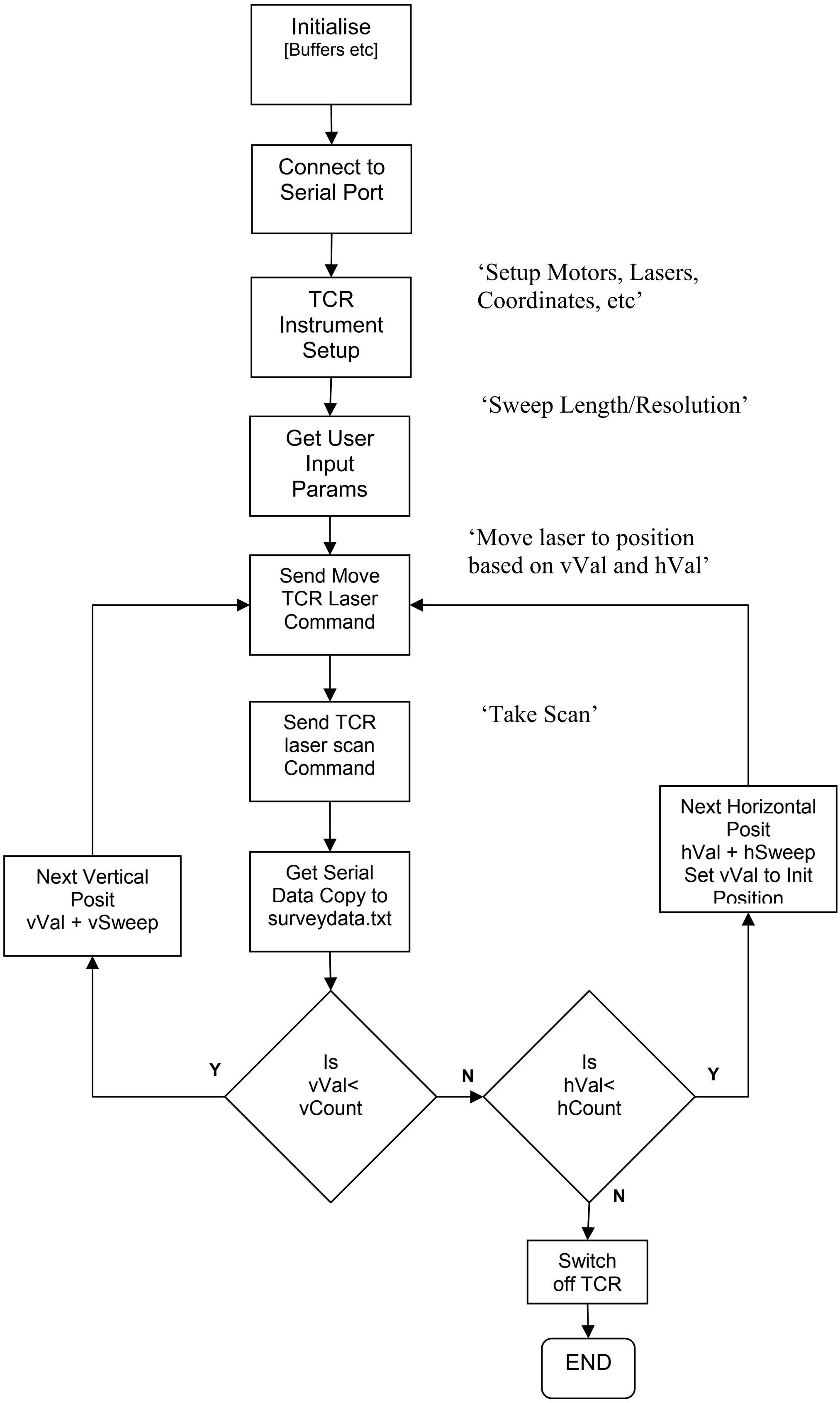
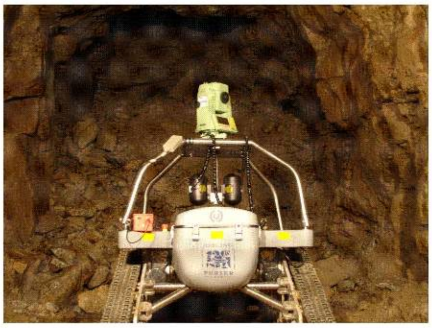


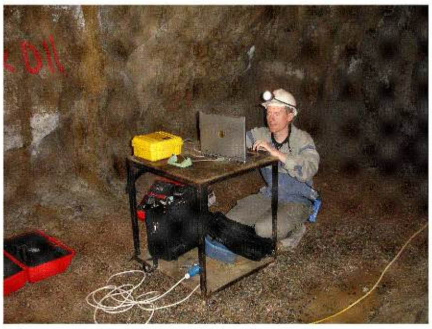
Figure 6.16: Windows TCR-Zigbee Software Flow Chart ['*surlog-tcr.cpp*']

6.3.4 Testing/Evaluation

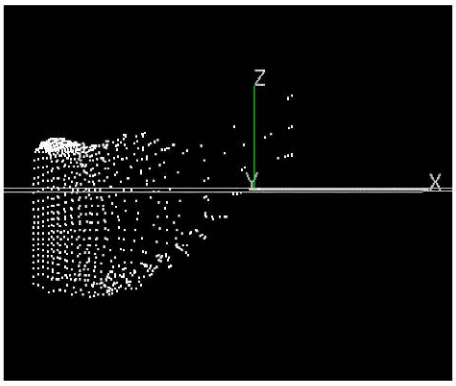
The TCR remote telemetry application using the Zigbee (or closely related EmberNet) mesh network nodes was successfully tested in the CSM Test Mine. The vehicle was driven into a drawpoint and the TCR instrument gathered the 3D profile data across the wireless mesh network. Figure 6.17, below, shows the equipment set up in the Test Mine, along a 3D plot of the data obtained from the draw point. The data was plotted using Datamine software. Text files containing the raw survey data is given in Appendix A.5.



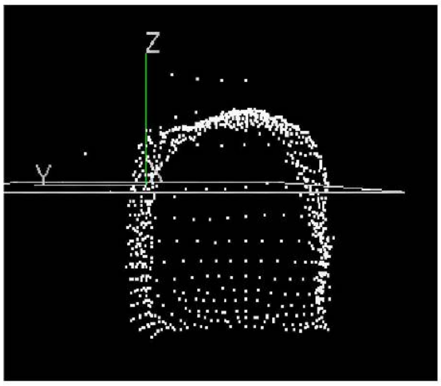
RSV and TCR Instrument
with Zigbee Device



Remote Data Collection
over Zigbee Network



3D Survey Data - Side View

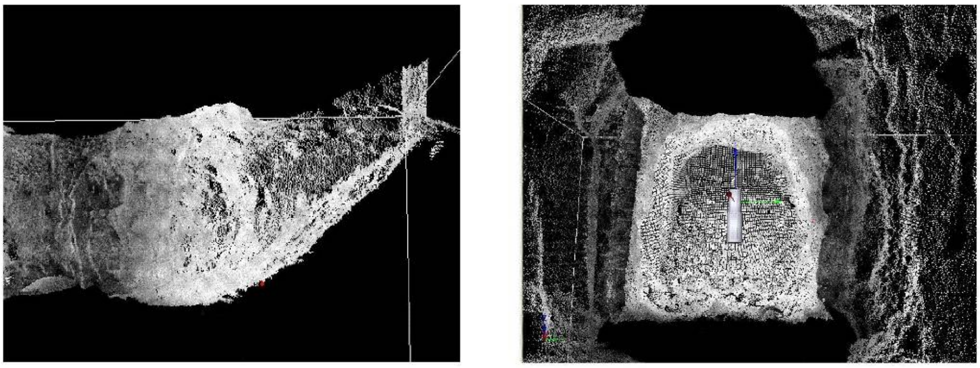


3D Survey Data - Front View

Figure 6.17: Drawpoint Scan using RSV and Remote Telemetry

A 3D profile of the same drawpoint taken using a Riegl Cloud Scanner instrument is shown for comparison in Figure 6.18. Whilst it is clearly evident that the Cloud Scanner is far superior in terms of image quality/resolution, it also takes a fraction of the time to perform a scan. However, the application, described above, using a conventional TCR instrument will give a relatively accurate volumetric calculation of the open stope. The main advantages of this applications are that the system can be reduced in price <£10k, as opposed to circa £100k for a

Cloud Scanner. This is significant when considering the cost versus the high risk of equipment loss in the hazardous environments.



3D Laser Scan Image - Side View

3D Laser Scan Image - Front View

Figure 6.18: 3D Laser Scan of Drawpoint Comparison

6.3.5 Further work consideration

Given that it currently takes around 1 hour to perform a 180 degree sweep at 5 degree resolution steps with the TPS, a key focus on further development would be to improve on the efficiency of operation. There are a number of ways this can be achieved in both the software and hardware. From the hardware perspective the system could sweep faster if the scanner was sweeping, or tracking, whilst constantly, returning coordinate data. There is a tracking function built into the TCR instruments and this needs further investigation. Key improvements can be made in the software by using ‘event’ driven serial communications in the windows software application, and switching the message delivery to ‘unicast’ messages, possibly also using the ‘sequenced’. Eventually, full automation of the RSV could be achieved using a mesh type network, with the vehicle automatically placing nodes to maintain RF communication.

6.4 Summary

Building on the work in previous Chapters, in particular Chapter 4, two key application areas have been developed to a proof-of-concept stage: underground wireless mesh smart sensors and remote telemetry. The potential applications of underground smart sensors include: environmental monitoring, machine diagnostics, distributed temperature sensors and vital signs. The smart sensor software has been tested using temperature and pressure sensors. A remote telemetry application has been developed in conjunction the RSV project at CSM, controlling and gathering data across a mesh network with a TPS surveying instrument. With the aim of fully automating the process of gaining a 3D profile of dangerous open stopes. The application was successfully tested at a typical drawpoint in CSM Test Mine.

Chapter 7: Zonal Location Information

The concept and novel use of low power wireless mesh networking technology for underground tracking is examined in this Chapter, as an alternative to RFID techniques. Conventional RFID tracking techniques versus the use of wireless ad hoc technology is discussed. The Chapter then goes onto propose a method of tracking mobile nodes within a mesh network to provide 'Zonal Locational Tracking'. Considerations are also given to potential further work in being able to achieve more accurate positional tracking techniques.

7.1 RFID and Mining

Tracking in underground mining has commonly been achieved in recent years through the use of active or passive tags. There are a number of systems available in the market ranging from tags that simply record whether personnel have entered the mine, to providing more locational awareness of personnel whereabouts. RFID (radio frequency identification devices, otherwise known as 'Tags', or 'Transponders') are finding use in a whole range of current and future applications. Table 7.1, below, shows the different types of RFID technologies relating to operating frequency, active or passive, and some examples of applications (IET, 2006).

Table 7.1: RFID Technology Characteristics

Band (MHz)	Typical Range		Typical Tag Size		Relative Data Transfer Rate	Typical Applications
	Read Only	Read / Write	Active[2] (cm^3)	Passive[1] (cm^2)		
0.125 – 0.134	> 2m	Few cm	5–10 cm^3	2–5 cm^2	Slow Non-concurrent multiple access	Animal ID Car immobiliser Access and security
13.56	> 1m	> 0.5m	3–5 cm^3	10 cm^2	Medium Multiple concurrent read <50 items	Smart Cards Smart labels Domestic electrical goods Access and security
433	Tens m	Few m		5 cm^2	Active tags	Specialist Animal Tracking
860 – 960	> 5m	> 0.5m	1–2 cm^3	4 cm^2	Fast Multiple concurrent read >100 items	Asset tracking in industrial and consumer distribution
2450	> 10m	> 1m		1 cm^2	Fast	Moving car electronic toll collection

[2] Active tag size given in volumetric dimensions, passive is described in terms of area only as passive tags are generally made virtually flat <1mm in height (IET, 2006)

There are a number of characteristics to consider what type of RFID system to develop or use in an application. Depending on the nature of these, it can lead to complex design issues in the reader or interrogator unit. These are considered individually below:

Passive and Active Devices: An active RFID tag is a device that contains memory (or information) and a power supply to transmit data, a passive RFID tag is able to gain enough power from the reader RF signal to transmit data.

Range: This is the maximum distance over which an interrogator and tag can successfully communicate. This will have a direct impact on power requirements.

Tag Orientation, Speed and Trajectory: This can have a significant effect on the complexity of designing an interrogator reading unit.

Multiple Tags: Multiple tag reading can lead to difficulties if the need arises to read multiple tags in one instance, this can lead to interference between tags.

Frequency: Choice of frequency has a direct impact on speed of reading, bandwidth, active vs. passive, and power.

Advantages of RFID tag based tracking:

- Simplified robust design from the tag (or transponder) perspective.
- Tags require minimal, or no battery power.
- Ease of installation and maintenance – requires minimal user input, and easily scalable, and easily replaced.
- Each tag can be made completely unique

Advantages of RFID tag based tracking:

- The interrogator or reader can lead to a high degree of complexity; particularly if multiple tags are needed, and certain parameters are not constant e.g. tag orientation, speed, range etc. This will ultimately lead to relatively expensive reader units.

An example of a state of the art active RFID tag system developed by Davis Derby for mining is shown below in Figure 7.1. The diagram shows the general requirements of a mine tracking system. This system has similar advantages and disadvantages to those described above.

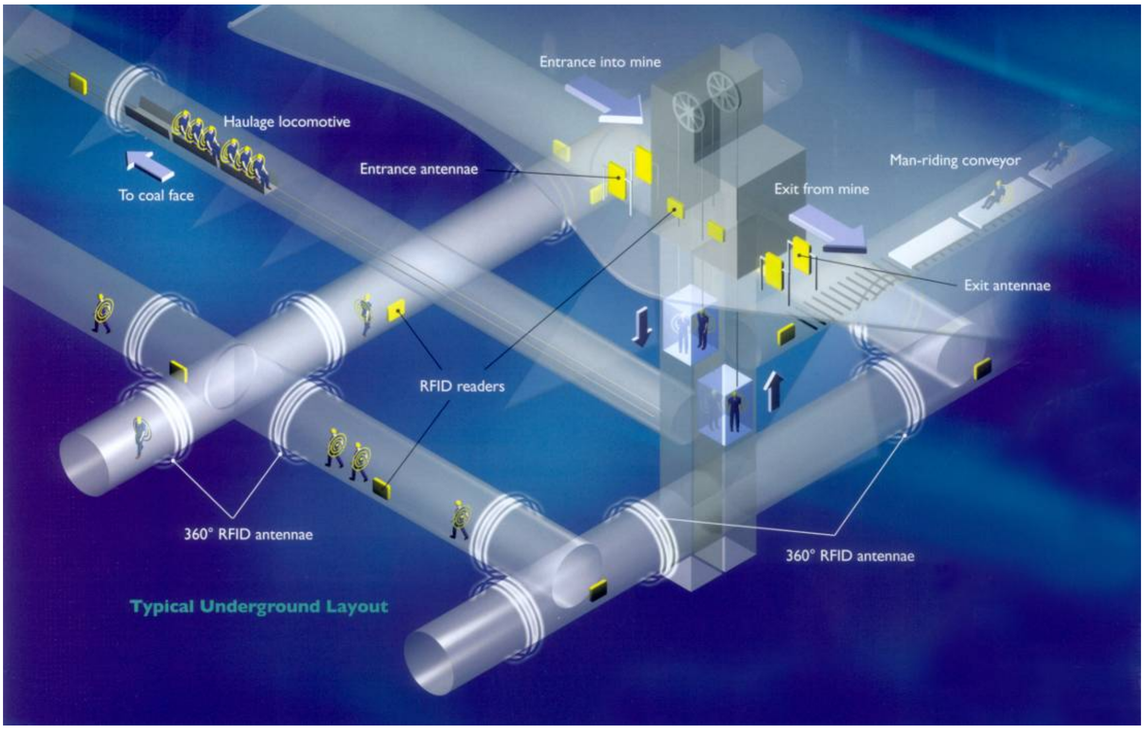


Image courtesy of Davis Derby, UK

Figure 7.1: Mine RFID System and Requirements

7.2 Wireless Location Techniques

RFID / tracking applications using low power wireless mesh networking technology e.g. Zigbee / IEEE 802.15.4 related have been identified as a key aspect of this research. The main advantages of this type of active tracking system, is the simplification of the receiver (or read station) design, and that it can be coupled with other underground wireless sensor applications (e.g. sensory data acquisition). There are of course disadvantages in using a wireless technology for active tracking compared with RFID, such as increased battery power, increased complexity in network infrastructure etc. The feasibility of the use of wireless mesh networking technology to provide RFID / tracking and location information has been investigated within this project. There are essentially two different groups of location techniques, which can be incorporating using wireless technology: 'Zonal Location Tracking', as traditional in RFID schemes where a mobile node is only recorded passing a reader station or point, and 'Positional Location Tracking' where the exact position of a mobile node is either monitored or the node only requires to know its location (e.g. GPS). In underground environments, the 'positional' over 'zonal' tracking would require relatively more complex research and development. A proposed method for 'Zonal location tracking' using Zigbee/EmberNet related mesh wireless networking technology is presented. 'Positional location tracking' techniques are presented and discussed in consideration for potential future work

7.2.1 Zonal Location Tracking

A proposed zonal location tracking application using EmberNet wireless mesh networking devices is shown in Figure 7.2, below. The tracking is achieved by a method of using 'beaconing' to track a mobile device. The full-functional devices (FFD) are set-up in pre-determined locations. The FFDs then periodically transmit beacons. The reduced functionality RFD, or 'leaf-node' (EmberNet specific term) devices, then pair themselves with a particular FFD upon receiving a beacon. The mobile node is then actively 'tracked' both entering and leaving a 'zone'. The disadvantage of incorporating beacons is that they are sent separately to the MAC layer (CDMA/CA), and that careful design is required to ensure efficient use of network resource. However, there are key advantages of this type of system, namely simplified receiver/interrogator design (resulting in reduced cost) and added functionality.

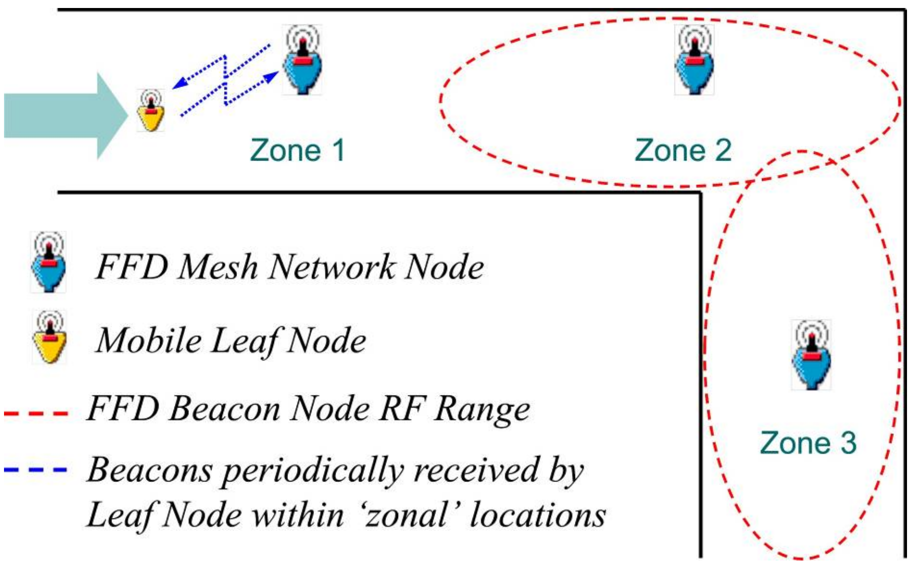


Figure 7.2: Zonal Location Information using EM2420 devices and 'beaconing'.

Features of Proposed Method:

- Zonal locational information of mobile nodes is established through the use of beaconing, where the zones are completely dependant on the location of base stations being known (similar to RFID).
- The mobile nodes can be anything from assets/equipment, vehicles to personnel.
- The system is fed into a back bone infrastructure (e.g. Ethernet), allowing information to be stored at the surface as well as locally, which may be useful in an emergency incident allow rescue personnel to download information.
- Potentially base stations could be relatively installed every 50 – 100m if required, which would in turn define the 'zones' and accuracy of tracking.

- Using wireless networking for tracking introduces added functionality e.g. sensor machine, or personnel vital signs, monitoring.

Another example of related technology is the WiFi based active RFID tracking system for underground mines which Mine Site Technologies and Aeroscout have recently released (Aeroscout, 2006).

7.2.2 Positional Location Tracking

There are a number of established wireless positional location techniques using in modern wireless networking e.g. cellular network. Each of which could potentially improve the accuracy of underground tracking. However, given the relatively close proximity operating range, and significant multipath effects, not all methods would be feasible. This is a topic for further research. A summary of some wireless location techniques is given below:

RSS (Received signal strength): Measuring the received signal strength to estimate distances between nodes is the simplest method of computing distances between nodes. However, the accuracy would not be reliable using RSS alone in a multipath rich environment, such as a tunnel.

AOA (Angle of arrival): This requires multiple antennas to determine the incident angle of arrival between two base stations and a mobile unit. This method requires highly sensitive reception equipment.

TDOA (Time of arrival): A minimum of three base station units measure the difference in time it takes to receive a signal from the same mobile unit. The position is determined by triangulation. It is vital that base stations are synchronised.

TOA (Time difference of arrival): Very similar to TDOA, except the absolute time it takes for the signal to travel from mobile node to base station is used to calculate the distance. Both of these methods would be extremely difficult to implement in relatively close proximity applications i.e. indoor or underground.

E-OTD (Enhanced observed time difference): Similar to TDOA except that the mobile unit logs the observed time of arrival, then reports back to the base station. This method is design to support asynchronous base stations.

A-FLT (Advanced forward link trilateration): Used in CDMA based networks, where the phase delay sent between signals sent to base stations, is compared to determine the position.

GPS & Pseudolites: Pseudolites are ground based transmitters that generate GPS signals for extending coverage into buildings and areas where GPS cannot reach. GPS alone only lets the mobile device pin points its position. Separate transmission is required for tracking.

RF Fingerprinting: RF fingerprinting is a method being used for position estimation, where an RF map, or multipath fingerprint, is stored in a database. This is specific to exact locations for each base station. Nerguizian *et al.* (2006) contains details of a novel impulse response fingerprinting and neural networks technique specific for underground mine geolocation. This is perhaps the only technique to date considered in achieving underground mine tracking. The main weakness of this type of system is that the mine needs to have an RF survey conducted prior to installation, and there is a large requirement on computational power. However, this may not be an issue in certain applications.

Indoor Specific Techniques:

H-LES (Hybrid location estimation scheme): Technique being developed by Mitsubishi Electric Research Laboratory (Sahinoglu and Catovic, 2004) that uses a combination of RSS and TDOA for close range and partially synchronised wireless sensor networks.

Cricket Indoor Location System: A team of researchers at MIT (Priyantha *et al.* 2000) have developing an indoor location tracking system specifically aimed at wireless devices. The crickets rely on a combination of both RF and ultrasonic transmission. The TDOA of the ultrasonic and RF beacon signals to determine the distance between a cricket 'beacon' and 'listener'. The combination of ultrasonic and RF travelling at different velocities helps mitigate the problem of multipath in an indoor environment. However, how effective this type of system would be in a multipath rich underground environment would certainly require further investigation.

7.3 Summary

The concept of using wireless mesh technology for active tracking of personnel, vehicles and equipment has been considered in this Chapter. Consideration has been given to more conventional RFID techniques, discussing the advantages and disadvantages of both. A method of achieving 'zonal location tracking' in mesh networks has been proposed using a method of beaconing. 'Positional location tracking' techniques have also been examined, discussing potential directions for further research in this field.

Chapter 8: Enhancing Underground Wireless Networks

Consideration to enhancing underground wireless networking performance is examined in this Chapter. Focusing on the modulation characteristics, antenna design and routing, discussing how wireless mesh networking technology could be optimised for underground and critical safety applications and identifying areas for potential further work.

8.1 Routing Considerations

8.1.1 IEEE 802.15.4, Zigbee Standards and Proprietary Solutions

As part of design considerations for various applications, major consideration has been given to the standards associated with IEEE 802.15.4, Zigbee and Ember proprietary solutions. The key advantage in the underground applications identified for ad-hoc wireless networks is the ability of systems to detect and react to unannounced system changes and possibly system disruption. This could, for example, include situations where LR-PAN devices are being used for RFID applications, or to establish a mesh network between firefighters or mineworkers, who may individually be mobile and unconstrained. These dynamic operational requirements pose major design challenges. Dynamic network behaviour is not well supported by the current Zigbee 1.0 standard (ratified December 2004). Anecdotal evidence suggests Zigbee networks with 6 hops have a 'cold start up' requirement of around ~1 minute.

However, there is a distinct advantage in employing a standards based solution (e.g. Zigbee), in that it offers product interoperability and vendor independence. Product innovation is likely to continue as a consequence of industry standardisation. Proprietary solutions also have other issues concerning commercial 'lock-in' and long-term maintenance.

There are inherent trade-offs between static and dynamic (convergence) performance and device complexity (and thus device stack size). One of the research outcomes is that there is significant merit in considering the proprietary EmberNet stack over Zigbee. The EmberNet stack employs a GRAdient routing mechanism, which updates binding/routing information quickly in dynamic and mobile mesh networks. The Zigbee standard operates efficiently with static mesh networks using a 'Cluster Tree' topology, but slows significantly if the network becomes mobile and binding information has to be regularly updated. A transport layer has also been built into the

EmberNet stack, which provides end-to-end acknowledgements with retries and time-outs. Zigbee provides acknowledgements but this is not directly related to individual messages. Therefore, the transport layer enhances the overall message delivery robustness. Ember are a key promoter of Zigbee and have developed their own version of the stack (Figure 8.1, below), EmberZNet with features including a transport layer. Mobility is anticipated to be one of the points to be addressed in subsequent versions of the Zigbee standard.

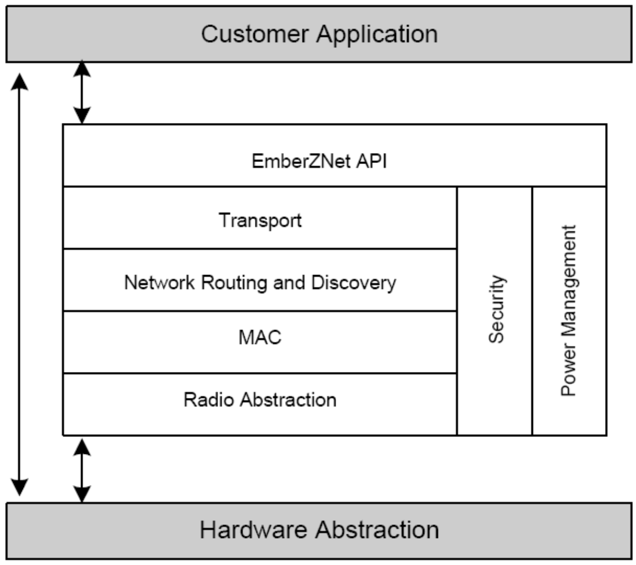


Figure 8.1: EmberZNet Stack

Data throughput in a Zigbee network depends on network density, number of hops, frequency of messages, packet sizes, whether security is incorporated etc. At 2.4GHz the raw data rate is typically around 250kbps. However, after network overhead the maximum throughput is typically 20 to 40kbps. In large complex networks, especially dynamically changing networks, Zigbee network throughput can be reduced significantly. The EmberZNet stack will achieve 45kbps throughput over 1-hop, and will maintain a throughput >25kbps over 5 hops (Egan, 2006).

Despite the relative benefits of EmberNet for dynamically varying network configurations, there remains much work to provide effective routing schemes where very low power consumption is sought. Beacons add considerable functionality to a network, where client devices can in principle wake up only when a beacon is to be broadcast, listen for their address, and if not heard, return to a sleep mode. Beacons are important for mesh and cluster tree networks to keep all of the nodes synchronised without requiring nodes to consume battery energy listening for long periods of time. However, if a very short beaconing period is selected (to improve overall network convergence and response time), then power consumption may still be excessive. Routing in large, battery-powered, non-synchronised networks remains challenging.

8.1.2 Further Discussion on Mesh Wireless Network Routing

Traditional routing protocols are built on the assumption that dedicated routers exist in a network consisting of stationary nodes, so that routes may be established in advance and designated routers may be able to maintain relatively static routing tables. The assumption in many networks is still that the great majority of the nodes are stationary and specifically that the paths between routers are static. Furthermore, it is assumed that both connectivity and bandwidth between routers are high. A mobile ad hoc network is an autonomous system of mobile nodes, which may operate in isolation, or may have gateways to and interfaces with a fixed network. In mobile ad hoc networks the nodes themselves form and undertake the network routing infrastructure.

A defining characteristic of mobile ad hoc networks is that of dynamic topologies. This will often result in link breaks and invalidation of routes. Since the nodes may rely on batteries, consequently energy conservation is of great importance. Finally, scalability is important in order to accommodate large networks. Packet overheads also need to be taken into account since this may seriously affect the network load and available useful bandwidth. Whilst taking all these issues into consideration, effective routing protocols must be provided.

Since mobile nodes are generally free to move, they may or may not be in transmission range of each other, and a previously discovered route may or may not still be valid at a certain point of time. Another source of limited connectivity may be the presence of unidirectional links. Some routing protocols require bidirectional links, whilst others support or even exploit the presence of unidirectional links. A node may periodically switch off its transceiver for battery conservation. In summary, due to the characteristics of mobile nodes not necessarily being within transmission range of each other, traditional routing protocols are not particularly suitable for routing in such environments. Brose *et al.* (2003) note the following to be important in devising protocol structures for ad-hoc wireless networks.

Distributed operation – Essential property.

Loop-freedom – Desirable to avoid phenomena such as packets circulating around the network for arbitrary periods of time, and, though TTL (time-to-live) values can be used, a more structured approach is desirable, which considers overall performance.

Reactive operation – It may be desirable to let the routing protocol adapt to the traffic pattern, and in this way utilise network energy and bandwidth resources more efficiently, at the cost of increased route discovery delay.

Proactive operation – The additional latency incurred by reactive operation may in certain contexts be unacceptable, so if bandwidth and energy resources permit, proactive operation would be desirable.

Security – Routing protocols can be vulnerable to attacks such as eavesdropping and replay transmissions, hence sufficient protection to prohibit disruption and modification of protocol operation is desirable.

'Sleep' period operation – It is desirable for a routing protocol to accommodate 'sleep' periods, because nodes may need to enter this mode for long periods, e.g. for energy conservation reasons.

Unidirectional link support – Unidirectional links occur in wireless networks, and it may be valuable to be able to make use of them.

A detailed taxonomy of routing protocols is proposed by Feeney (1999), which extends the coarser reactive/proactive routing protocol classification. Brose *et al.* (2003) have examined a sub-set of protocols for mobile ad-hoc network application. These included destination-based Dynamic Source Routing (DSR), Ad-hoc On-demand Distance Vector (AODV) protocols, and two non-uniform protocols, one that uses neighbour selection, Zone Routing Protocol (ZRP), and one that uses partitioning, Cluster Based Routing Protocol (CBRP).

The main goal of the Dynamic Source Routing protocol (DSR) is to be able to quickly react to changes in the network, providing highly reactive service to help ensure successful delivery of data packets in spite of node movement or other changes in the network at low overhead. The main goal of the Ad-hoc On-demand Distance Vector protocol (AODV) is to reduce the need for system wide broadcasts. This is achieved by avoiding broadcasts when local changes occur, that will not have an effect on ongoing communication or maintenance of multicast trees. Careful record-keeping is undertaken to identify nodes that have been using a broken link, so that these only need to be notified of the change in status. The main purpose behind Cluster Based Routing Protocol (CBRP) is to efficiently minimise the flooding traffic during route discovery and also to speed this process up, through clustering nodes together in groups. ZRP is a hybrid protocol which consists of one part which is proactive, the Intrazone Routing Protocol (IARP), whose scope is the node's local neighbourhood and another which is reactive, the Interzone Routing Protocol (IERP), which is responsible for discovering routes beyond the routing zone. Brose *et al* (2003) provide a discussion on properties, route discovery and route maintenance methodology for each of these protocols.

8.1.3 Optimal Mesh Routing Characteristics Underground

The routing characteristics required in a high integrity underground or confined space mesh wireless network perhaps have different priorities to that of a conventional system. The following important points are considered in a high-integrity underground mesh (or ad hoc) network:

Data integrity vs. Throughput: In the types of applications considered during this research, data integrity is actually more important than throughput. In that the need for data to arrive, takes priority over how quick, how fast it actually gets there. End-to-end message delivery acknowledgements are essential.

Dynamic and mobility nodes: It is essential that these underground mesh networks provide dynamic routing capabilities, where the network efficiently updates routing tables with mobile nodes travelling around.

Redundancy: Network redundancy is a key requirement, where in order to ensure survivability and robustness it is essential mesh networks are in fact 'over-designed'. It could also be possible to make use of the multiple paths to improve the efficiency of packet delivery, and compensate somewhat for the loss in throughput vs. data integrity.

Power: Battery power is a key factor in underground safety applications, specifically the mobile nodes. Therefore the routing algorithms need to ensure that network traffic is mostly sent through 'base station' type nodes as opposed to battery power mobile nodes, wherever possible.

Emergency Priority: In an emergency event there should be a mechanism built into the mesh network to provide a priority communications route (or channel) to key functions and/or nodes. Ensuring only the vital information gets through. Potentially this could also be used as a back up communications override.

8.2 Robust Underground Antenna Consideration

8.2.1 Overview

Antenna development has been very much driven by the modern telecommunications industry. Practical mobile systems require antenna elements that are small, low profile, offer a predictable behaviour and are relatively inexpensive to manufacture. Following market developments both in the business and consumer mobile telecommunications sectors, designers must produce aesthetically pleasing devices, often with the antenna mounted internally within the chassis of the device. This has stimulated a range of advanced developments in efficient low-profile antenna technology.

From an engineering perspective, integrating a low-profile or internal antenna into the overall design offers advantages. Systems with planar, low profile radiating elements, or internal antennas offer a significant increase in mechanical protection. This increases the overall ruggedness and durability, prolongs operational lifetime and reduces warranty returns. The aerospace industry is equally familiar with this technique of protectively housing antennas, an example being 'radomes' built into the nose of aircraft.

To facilitate the above designs, advanced software design tools have become available which allow designers to predict the overall performance (radiation, bandwidth etc) of the antenna technology and operating device as a complete system to gain the optimal performance from their designs. This optimisation may be contrasted with producing a 'one size fits all' compromise antenna design, which may be subject to various detuning effects e.g. location metal work, batteries, and proximity to the human body.

Robust antenna technologies suitable for Zigbee, Bluetooth and other 2.4GHz ISM band technologies operating within an underground mining environment are investigated in the rest of this section. Traditional monopole (whip) and helical antennas are fundamentally susceptible to damage within confined space industrial environments, in particular mining. First of all, conventional antenna excitation techniques are before conducting a review of compact and planar antennas discussing the performance in comparison to such conventional techniques. Details of practical tests are also given investigating the performance of a planar antenna operating in close proximity to large metallic objects in an underground mine.

8.2.2 Antenna Technology

The simplest form of wire antenna used in wireless systems is the dipole. The dipole antenna is $\frac{1}{2}\lambda$ (wavelength, λ) in length with a coaxial (or two-wire transmission line) feed at the centre. A $\frac{1}{4}\lambda$ line extends upwards from the feed point and a $\frac{1}{4}\lambda$ line is attached to the coaxial sleeve (negative transmission line). For vertical orientation, the dipole radiates in the horizontal direction. Figure 8.2 below shows a computer generated model of a ½ wave dipole tuned to 2.4 GHz along with the expected radiation pattern.

Note: The following computer models were generated using SuperNEC Version 2.9, which is based on MOM-UTP hybrid code. For more information refer to www.supernec.com.

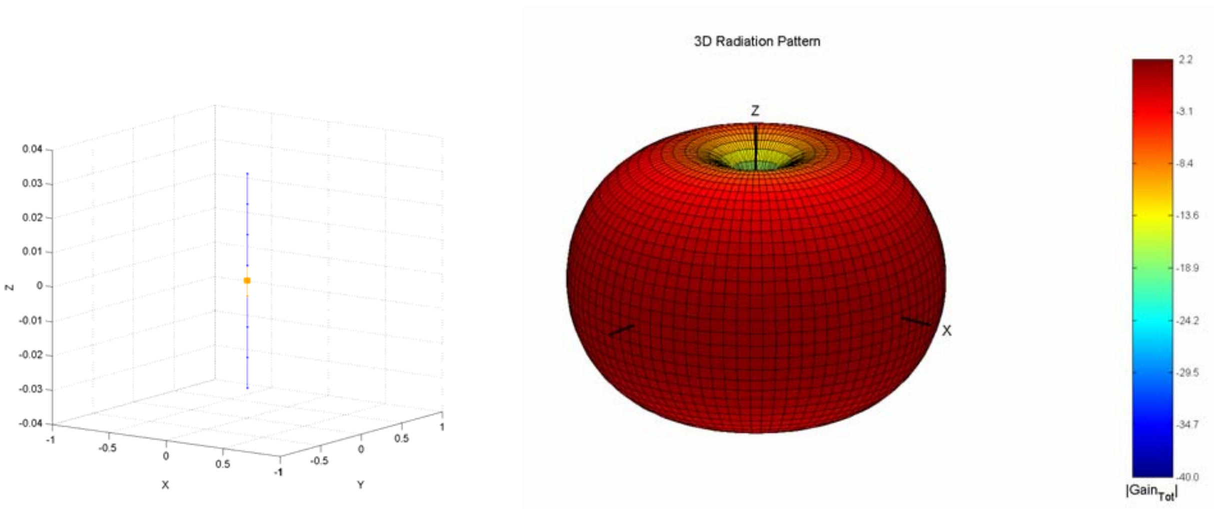


Figure 8.2: Dipole Antenna and 2.4GHz Radiation Pattern

By far the most common antenna used in many applications is the quarter-wave monopole (or Whip). The ¼λ (wavelength) monopoles are ground dependant, where an electrical image of the ¼λ whip antenna is replicated in the ground plane. When the ground is infinitely large the ¼λ behaves identical to the equivalent ½λ dipole, except that radiation only occurs above the ground plane. The input impedance is typically half that of a ½λ dipole. Theoretically, the directivity is 3dB larger because the radiation power is radiated only to the upper half space of the ground. In practice, the effective gain of the antenna is usually lower than that of the dipole. The monopole is a versatile across a broad range of applications and is particularly useful above large chassis, metal plate ground planes e.g. vehicle-mount, for a relatively modest gain.

Figure 8.3 below shows the theoretical radiation pattern for a 2.4 GHz ¼λ monopole. The model was simulated using a perfect conductive ground plane of finite size 1m^2.

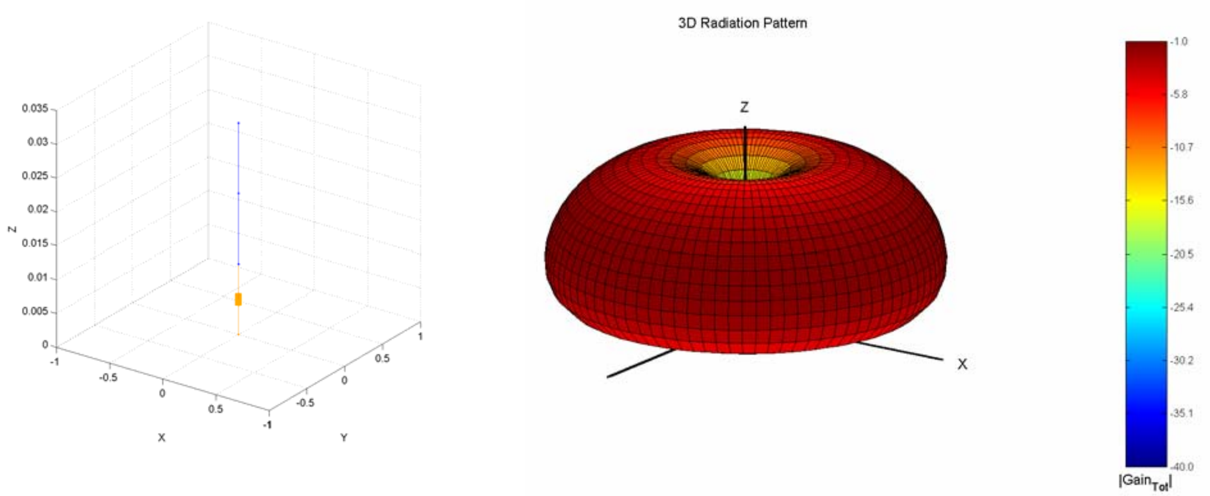


Figure 8.3: Monopole Antenna and 2.4 GHz Radiation Pattern

The helix (or helical stubby) antenna is commonly used in portable radio devices. The helix is a coiled ¼λ wire antenna, again operating above a ground plane. It has a radiation pattern that more closely approximates the radiation characteristics of an isotropic source, providing an optimum condition for portable devices. Figure 8.4, below shows a typical helix antenna along with a modelled radiation pattern at 2.4 GHz.

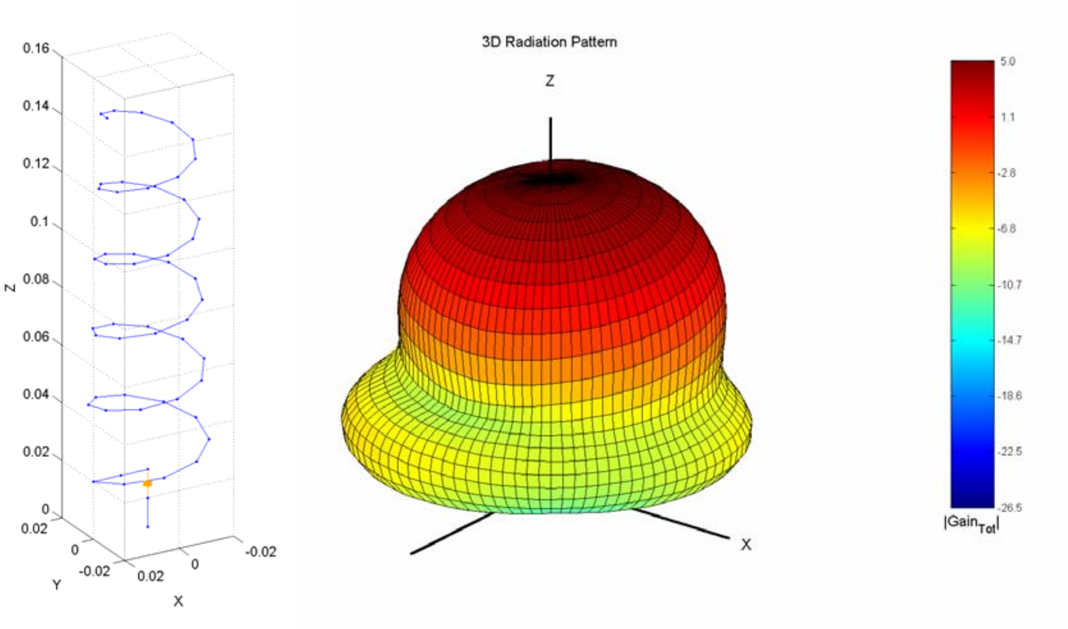


Figure 8.4: Helix Antenna and 2.4 GHz Radiation Pattern

Other common types of wire antennas include the loop with a radiation pattern similar to that of a dipole. Horn antennas are used at microwave frequencies; these are excited by waveguide structures and are used to achieve high directional gain. Another method of achieving high gain and directionality is to construct an antenna element array. A familiar design is the Yagi-Uda (Figure 8.5), which is commonly used in television reception. The Yagi-Uda is also used in WLAN applications, mainly for bridging networks across a peer-to-peer long range link. This type of antenna is not suitable for low profile applications.

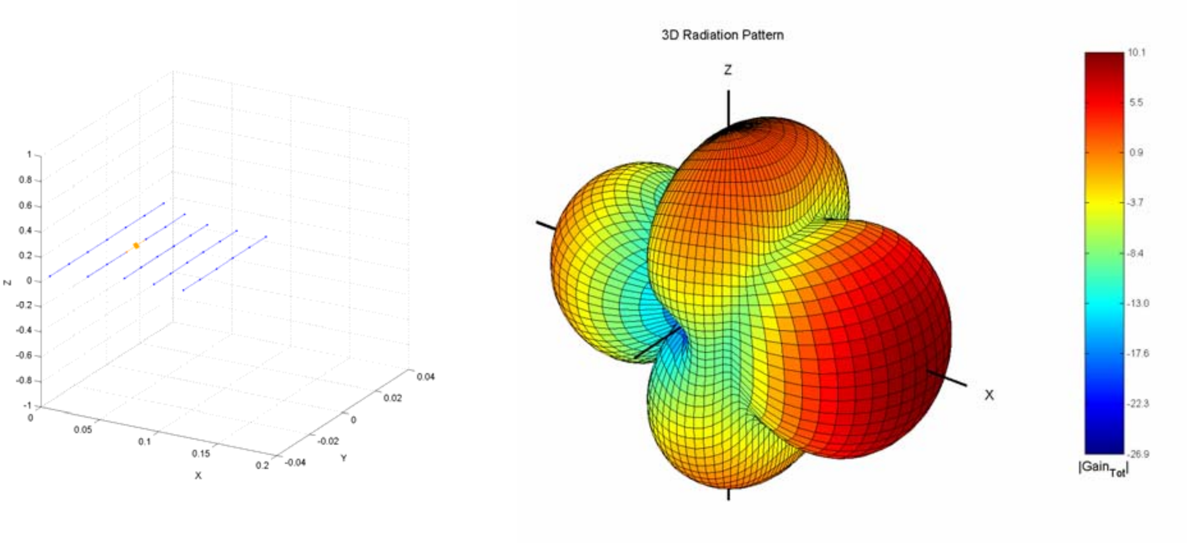


Figure 8.5: Yagi-Uda Directional Antenna and Radiation Pattern

A printed meander line antenna is a type of printed antenna that achieves miniaturisation in size of a conventional antenna e.g. monopole, dipole, and bow-tie. The meandered line antenna structure is an embedded wire, or planar strip line (or combination of both) on a dielectric substrate. Benefits include configuration simplicity, compactness, ease of integration, and being inexpensive to manufacture. A bow-tie antenna is modelled below in Figure 8.6. The radiation pattern is similar to that of a vertically polarised dipole, with lower gain. The simplistic planar design is suitable for simple, inexpensive, low gain applications. This would not be the design choice for more critical solutions, particularly is horizontal polarisation is required where the planar antenna would have to be vertically mounted. A monopole or helical stub would be the better choice under this circumstance.

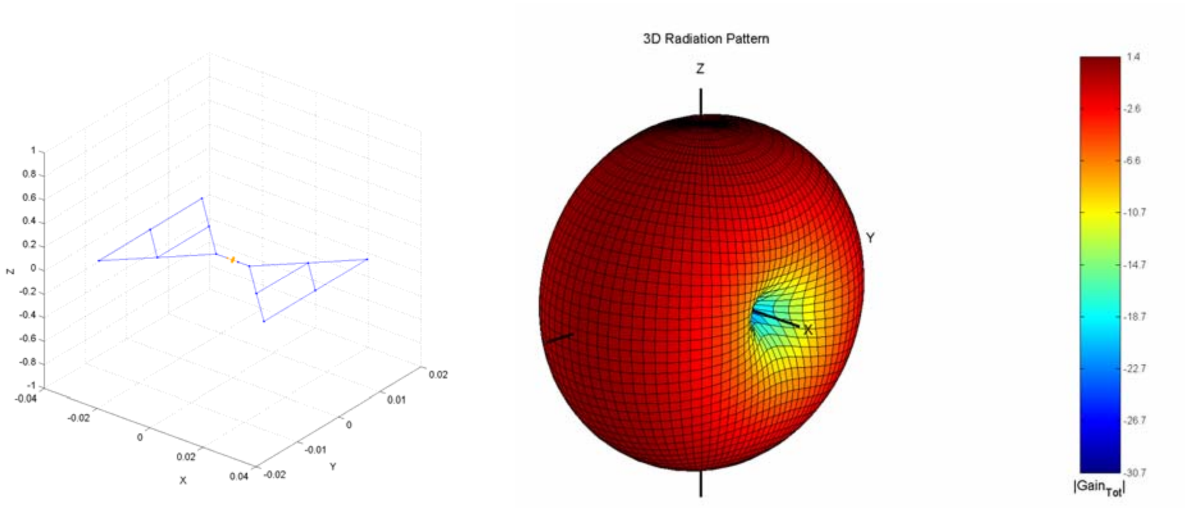


Figure 8.6: Bow-Tie Antenna and Radiation Pattern

The microstrip patch antenna has been available for the last three decades (Waterhouse, 2003) and has seen many significant developments towards meeting demands for highly efficient, small, low-profile radiators. The microstrip antenna in its basic form is a rectangular strip above an air substrate and ground plane, and is modelled at 2.4 GHz in Figure 8.7 below.

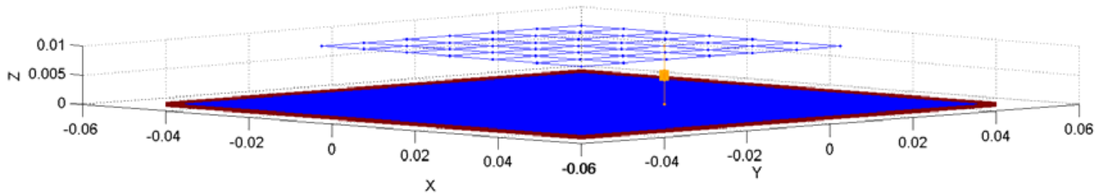


Figure 8.7: Rectangular Microstrip Patch above Air Substrate.

The 3D radiation pattern (Figure 8.8) demonstrates a relatively high gain in all directions above the ground plane. The 2D polar plots in Figure 8.9 give a clearer representation of the gain in both the azimuth and elevation planes.

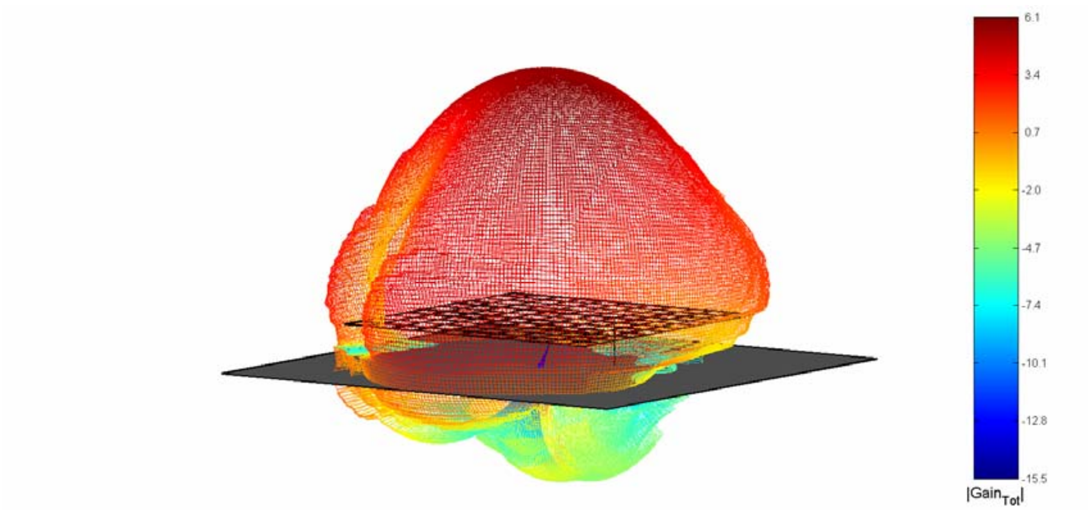


Figure 8.8: Microstrip Patch 3D Radiation Pattern

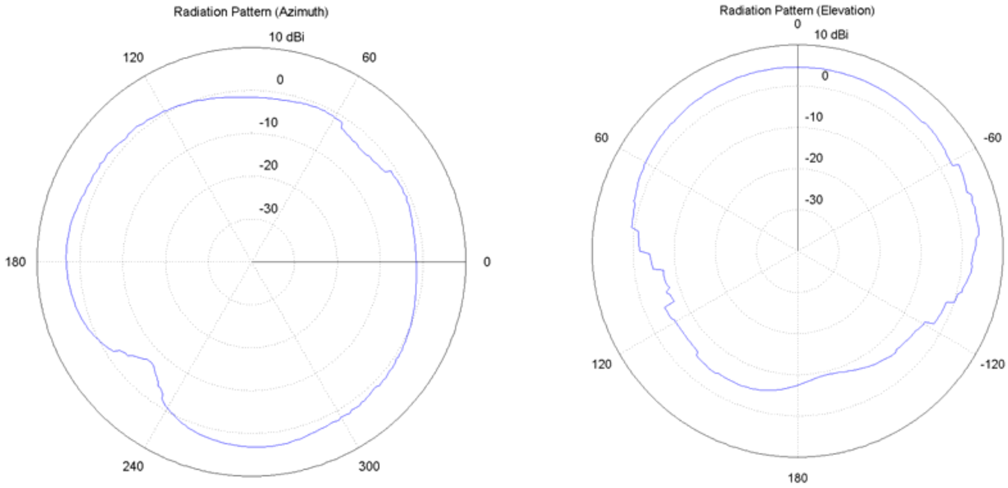


Figure 8.9: (a) Azimuth radiation pattern (b) Elevation radiation pattern

Variations in design, types of material, substrate and excitation method significantly alter the characteristics of the patch antenna. This will be discussed in further detail in the next section.

It is noted that the SuperNEC Academic Lite version of the software used is limited to 300 segments and will not allow for more complicated microstrip structures. At present the MOM-UTB software is not suitable for modelling a patch antenna above a dielectric substrate. Further modelling work will require specialised software design tools and was beyond the time scales and scope of this work. The rest of this review will examine various planar and compact microstrip antenna designs and their characteristics and feasibility of operating around generalised underground mine plant and machinery.

8.2.3 Compact and Microstrip Antenna Technology

8.2.3.1 The microstrip patch antenna

Microstrip patch antennas are used in numerous wireless communication applications. In its early form, microstrip antennas were used in military narrowband radar detection, collision avoidance telemetry and missile telemetry systems. More modern microstrip patch arrays are being used in commercial aircraft, although by far the most common application is mobile communication base station use. More recently, novel design techniques have permitted a reduction in size for lower GHz frequency microstrip patch antennas, resulting in widescale use in small mobile communication handsets and devices.

Advantages

- *Size and Profile*: The microstrip patch is small relative to other radiators. Single layer solutions typically use substrates less than $0.05\lambda_0$ (where λ_0 is the free space wavelength). Therefore, it has a very low profile above a ground plane.

- *Mechanically Robust*: The low profile antenna can be made conformal to its host, and therefore mechanically robust when mounted on rigid surfaces.

- *Low Fabrication Cost*: The microstrip can be readily manufactured using printed circuit etching techniques. In general, standard PCB material e.g. FR4 can be used if the operating frequency is less than 1 GHz. However for frequencies >1GHz, dielectric losses can become excessive, therefore materials with lower dielectric constant are required (typically $\varepsilon_r \approx 2.55$).

- *Ease of Forming Arrays*: Microstrip antennas are generally considered as medium gain radiators. For applications requiring high gain designs, array formations are relatively straight forward to manufacture. Patches are designed as 2-dimensional antennas (ignoring the height) therefore an array network is designed across a single plane.

- *Linear and Circular Polarisation*: Linear, dual polarisation (used in WLAN) and circular polarisation (CP) can be achieved using microstrip patch antennas. CP provides a robust alternative to ensure common polarisation between transmit and receive antennas regardless of orientation and is commonly used in satellite communications and WLAN applications.

- *Efficient*: Microstrip patch antennas are essentially efficient radiators attributed to the fact they are resonant-style radiators. There are three loss factors associated that need to be addressed; conductor loss, dielectric loss and surface wave loss. Therefore careful design and selection of materials is essential to ensure high efficiency.

Disadvantages

- *Impedance Bandwidth*: The basic microstrip antenna has a very narrow bandwidth, typically 2-3% of the operating frequency. Therefore conventional microstrip patches may not be suitable for a variety of applications, e.g. WLAN. Zigbee requires a bandwidth of at least 5% due to the direct sequence spread spectrum (DSSS) used and potential to operate across 16 channels. The bandwidth could be reduced by restricting the number of channels.

- *Excitation of Surface Waves*: The presence of the dielectric substrate within standard microstrip antenna designs will always excite a TM_0 surface wave (unless it is an air substrate). Depending on the type of material used this excitation can lead to significant degradation of the antenna efficiency. There are a number of solutions to mitigate this effect; some of these are discussed later.

- *Size (lower GHz range)*: When we start considering the lower end of the GHz frequencies, say 0.9 - 2GHz for handheld and small device communication applications, the conventional microstrip patch antenna can be too large. There are various techniques that permit a reduction in the overall size, some of which are discussed later.

- *Extraneous Radiation from Feeds and Junctions*: Care is need both at the design and fabrication (drilling, soldering) stages to ensure that excess radiation is not lost through the feed or junction. The different types of excitation, the edge-fed and probe-fed, along with others offer comparative advantages and disadvantages. These are discussed later.

Important qualities of the dielectric substrate material:

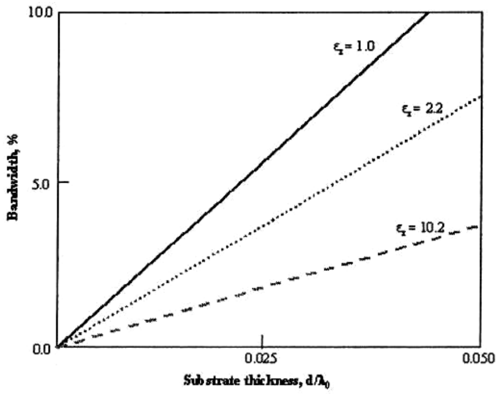
A number of parameters are important in the selection of dielectric substrate materials (Jefferies, 2005), including:

- Microwave dielectric constant.
- Frequency dependence of this dielectric constant which gives rise to "material dispersion" in which the wave velocity is frequency-dependent.
- Surface finish and flatness.
- Dielectric loss tangent, or imaginary part of the dielectric constant, which sets the dielectric loss.
- Cost.
- Thermal expansion and conductivity.
- Dimensional stability with time.
- Surface adhesion properties for the conductor coatings.
- Manufacturability (ease of cutting, shaping, and drilling).

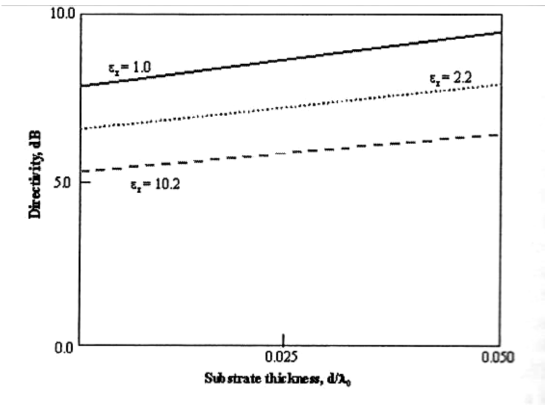
There are a number of reasons for choosing an 'air filled' dielectric substrate, namely cost and ease due of manufacturing as highlighted above. Commonly used dielectric materials include; plastics - fast substrate (ε_r = 2.55) and slow substrate (ε_r = 10.2), ceramics, and single crystal Gallium Arsenide (GaAs) and Silicon (Si), both of which are used for monolithic microwave integrated circuits (MMICs). Ceramics and single crystals have a relatively higher dielectric constant ($\varepsilon_r \approx 10$), but far exceed the strength of plastics and tend to be used in high power applications (Jefferies, 2005).

Impedance and Radiation Performance

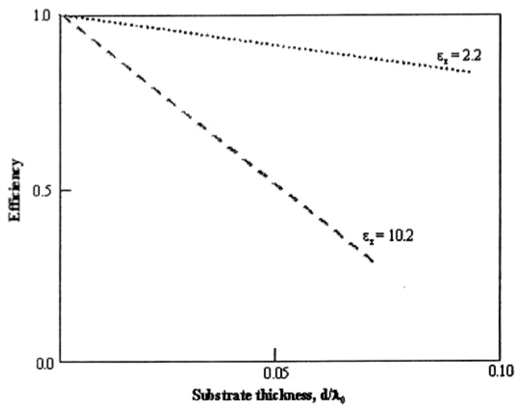
Important performance trends in a typical rectangular single layer patch antenna are shown in Figure 8.10 below (Waterhouse, 2003). Directivity (a) and impedance bandwidth (b) increases with the thickness of the dielectric substrate. Figure 8.10 (c) shows that as the substrate thickness increases, along with the dielectric constant, efficiency is lost due to increase in excitation of the TM_0 surface wave. Note that no surface waves are excited for the case $\varepsilon_r = 1.0$. Therefore, there is a trade-off between achieving the required impedance bandwidth and radiation efficiency.



(a)



(b)



(c)

Figure 8.10: Performance trends of single layered antennas: (a) impedance bandwidth (b) directivity (c) surface wave efficiency

[*Source:* Waterhouse (2003)]

Conductor Shapes

The most common types of patch antennas are rectangular and square. Square patch shapes can also be used in generating circular polarisation. Figure 8.11, below, shows typical shapes used in microstrip patch design. Certain shapes are better suited than others to specific application e.g. dual and circular polarisation. In general, standard geometrical shapes are used to keep manufacturing costs at a minimum.

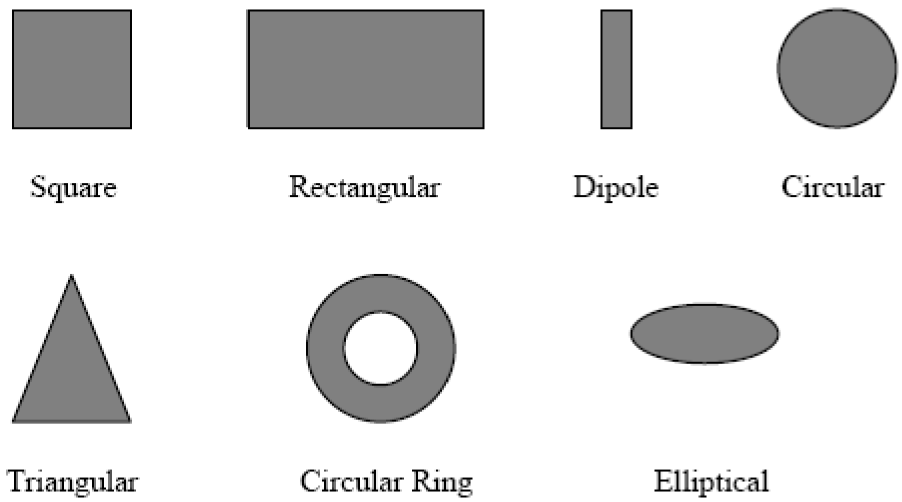


Figure 8.11: Examples of Conductor Shapes for Microstrip Patches

Excitation Methods of Microstrip Patches

A simple method of exciting the microstrip antenna is the edge-fed arrangement (Figure 8.12). The main advantage of this type of method is ease of fabrication. The input impedance of an edge-patch can also be controlled by inserting the feed into the patch. It can be adjusted from around 150-250 Ω on the edge to 0 Ω at the centre. The 50 Ω impedance match point is located just off the geometric centre.

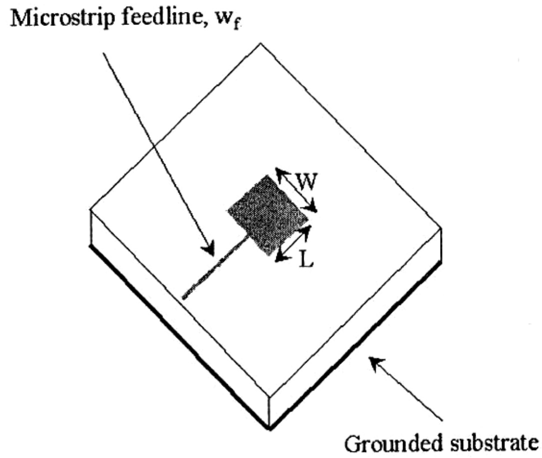


Figure 8.12: Edge-fed Microstrip Antenna
[*Source*: Waterhouse (2003)]

$$L = \frac{\lambda_e}{2} \tag{8.1}$$

Where L is the length and λ_e is the effective wavelength given by:

$$\lambda_e = \frac{\lambda_0}{\varepsilon_e} \tag{8.2}$$

Where an approximation of the permittivity ε_e is given by

$$\varepsilon_e = (\varepsilon_r + 1)/2 \tag{8.3}$$

Where ε_r is the relative permittivity.

Another method of excitation is the probe-fed method (Figure 8.13). The advantage of using a direct probe in contact with the patch is the elimination of spurious radiation, making it highly efficient. The 50 Ω impedance point can be readily determined as in the edge-fed method.

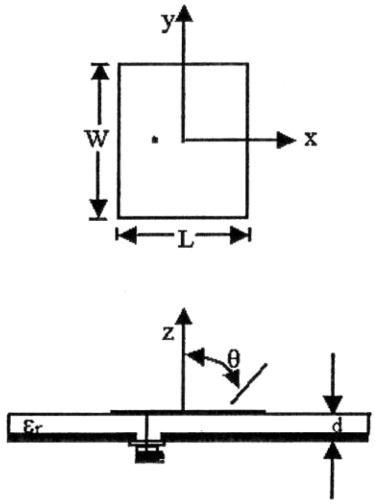


Figure 8.13: Probe-fed Microstrip Antenna
[*Source*: Waterhouse (2003)]

An alternative form of exciting patch antennas is the non-contact fed patch, such as the proximity fed patch shown below in Figure 8.14. The microstrip feed line and patch antenna are separated by an additional dielectric laminate. The power from the feed is electromagnetically coupled to the patch antenna above, as opposed to direct contact. The key attribute of this type of antenna is that the coupling is capacitive in nature, in contrast to inductively coupled direct contact patches. This allows for a greater attainable impedance bandwidth as it allows for larger thicknesses of material to be used. The drawback is that it is not as efficient as the direct contact counterparts and is heavily dependent upon correct alignment and material fabrication.

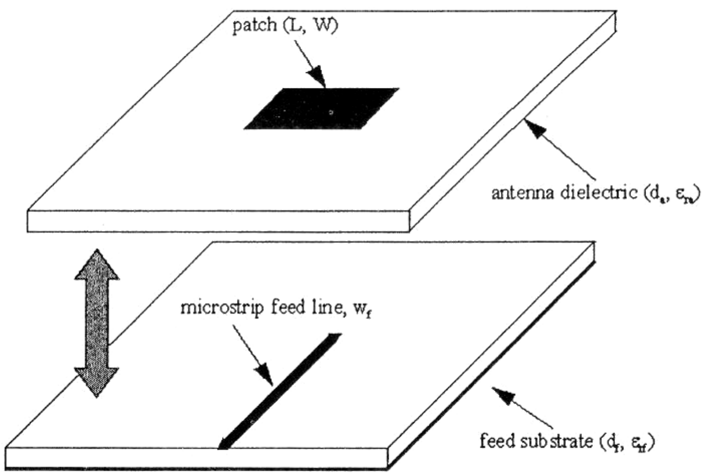


Figure 8.14: Proximity-coupled Microstrip Antenna
[*Source*: Waterhouse (2003)]

Aperture-coupling (Figure 8.15) is another non-contact feed mechanism, very similar to proximity fed except that the laminates are actually separated by the ground plane and coupling is achieved via a small slot, or 'aperture', in the ground plane. The feed-line is terminated either with an open circuit or a short circuit stub. There are several key advantages to this mechanism, including independent optimisation of the feed and antenna substrates, making it very suitable for integration into active devices. Again, the non-contact coupling involves a relatively simple fabrication process and larger bandwidths are attainable. Aperture-coupled microstrip antennas are probably the most utilised feed mechanism in the current global telecommunications market (Waterhouse, 2003).

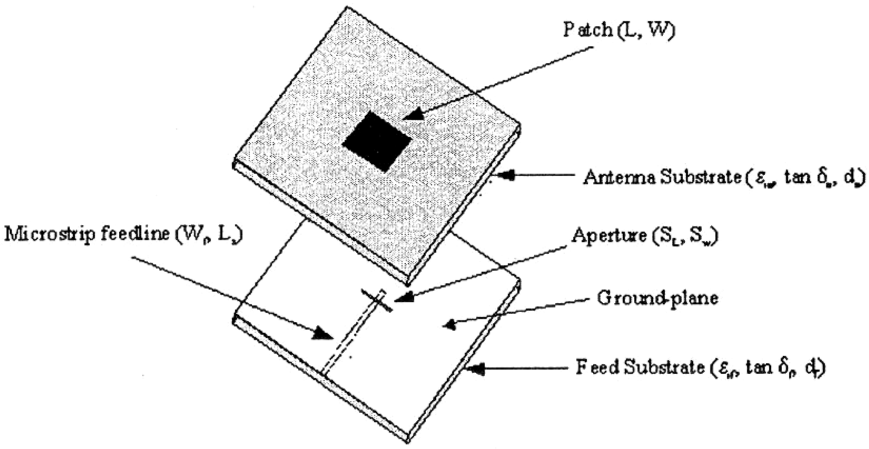


Figure 8.15: Aperture-coupled Microstrip Antenna
[*Source*: Waterhouse (2003)]

8.2.3.2 Advanced Microstrip Patch Antennas

Circular Polarisation

Circular polarisation generation is another key advantage of microstrip antennas. Circular polarisation (CP) is achieved by exciting two orthogonal modes. There are three methods for achieving CP; single line feed, a dual excitation, or a synchronous subarray approach. The single line feed method is shown below in Figure 8.16, making one resonant length slightly longer than the other to achieve the 90^{O} phase difference.

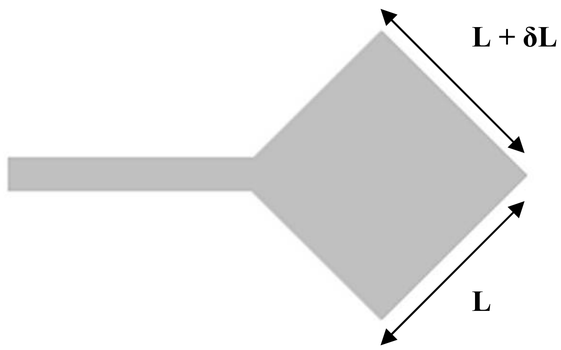


Figure 8.16: Single feed CP edge fed microstrip antenna

The main advantage of CP is that regardless of receiver orientation some component of the signal will be received, which explains why microstrip patch antennas have become popular in satellite applications. CP microstrip patch antennas are being more widely considered in WLAN and other ISM band applications. A wideband CP microstrip patch antenna for WLAN applications is described in Yang and Dougal (2005). The feasibility of using a novel technique employing a dual CP antenna system to provide a polarisation-sense antenna diversity enabling cancellation of reflected multipath components in RF transmission for indoor wireless communications is described in Neelakanta *et al.* (2004), . The robust transmission scheme proposes the use of dual RHCP and LHCP antennas for ISM band wireless systems e.g. Zigbee, Bluetooth and WLAN.

Shorted microstrip patches

Microstrip patches operating at the lower GHz frequencies can still be relatively large in size. A method of reducing the size whilst maintaining performance is the 'shorted microstrip patch antenna' (or SPA). The SPA configuration, as shown below in Figure 8.17 for both rectangular and circular, contains one or more 'shorting pins' adjacent to the feed pin. When the shorting pin is located near the feed pin a strong capacitive coupling between the pins occurs. The capacitive effect counters the usual inductive nature of the patch below resonance, therefore allowing the patch to be dramatically reduced in size, depending on the strength of capacitive coupling.

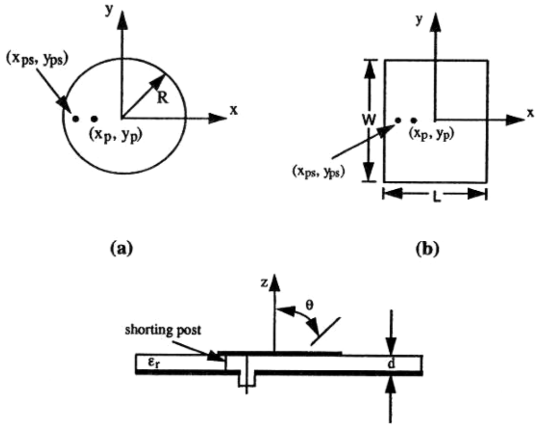


Figure 8.17: Shorted Microstrip Patch Antennas (a) Circular (b) Rectangular

[*Source*: Waterhouse (2003)]

Further enhancements to this technique include further size reduction techniques; cutting notches near the shorting pin, and the winged shorted patch. The shorted spiral patch significantly reduces the resonant frequency.

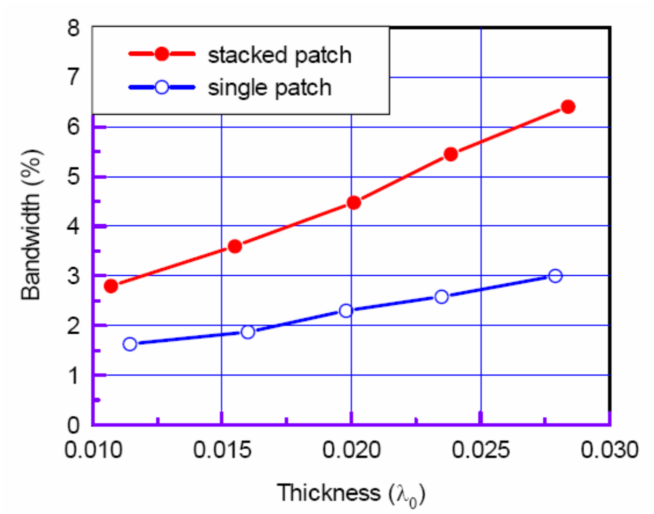


Figure 8.18: Impedance bandwidth versus total thickness for single and stacked patch

[*Source*: DeJean (2005)]

Another enhancement is the stacked (or folded) shorted patch, which is a technique used to enhance the bandwidth of a printed antenna. The significant advantage of stacking patches to meet higher bandwidth requirements is that surface area is not dramatically increased. Figure 8.18 above shows attainable bandwidths using the stacked patch method. A prototype folded (or stacked) shorted patch antenna is shown in Figure 8.19 below.

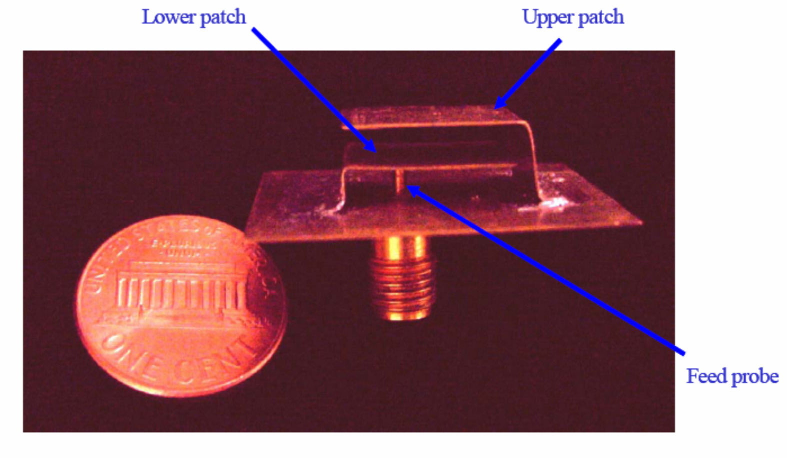


Figure 8.19: Prototype of a Folded SPA at 2.4 GHz

[*Source:* DeJean (2004)]

Microstrip Array

A key attribute of the microstrip patch is the ease of forming antenna arrays. The single patch antenna is generally classified as a low to moderate gain antenna in the order of 5 -8 dBi. High-gain and directional linear antenna array configurations can be readily designed. This technique is very widely used for mobile and wireless base station antennas. Again, arrays can be designed to generate linear, dual and CP, hence CP patch antenna arrays are used in satellite communications. Arrays are also used to achieve omni-directional radiation patterns, e.g. wraparound microstrip patches used in missile telemetry.

8.2.3.3 Planar Inverted-F Antenna (PIFA)

The planar inverted-F antenna (PIFA), derived from the folded monopole, is achieved by short-circuiting its radiating patch or wire to the antenna's ground plane with a shorting pin. It is similar to the shorted patch in that it can resonate at a much smaller size for a fixed operating frequency. Generally, the PIFA comprises a rectangular planar element located above a ground plane, or is printed directly onto the substrate board. Figure 8.20 below shows typical geometries for a mobile phone handset.

The PIFA has interesting characteristics in that, on the one hand, it can be considered as a type of linear inverted F antenna with the wire radiator element replaced by a plate to expand the bandwidth. One the other hand it shares some of the same properties as shorted microstrip patch antenna (Centurion, 2005). The PIFA antenna can be optimised to achieve a relatively moderate bandwidth and omni-directional radiation patterns. The key advantage of the PIFA radiator is that it is capable of dual-band and tri-band frequency tuning, making it a popular choice in the mobile telecommunications industry. The PIFA is a suitable choice for multi-band applications associated with severe equipment size restrictions.

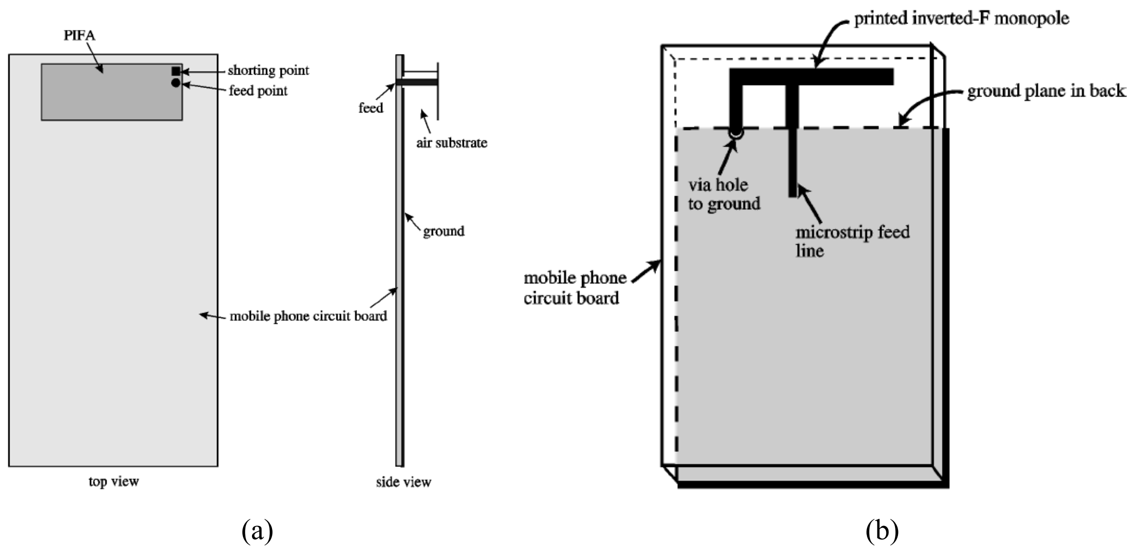


Figure 8.20: PIFA Geometries (a) mounted on PCB (b) printed on PCB

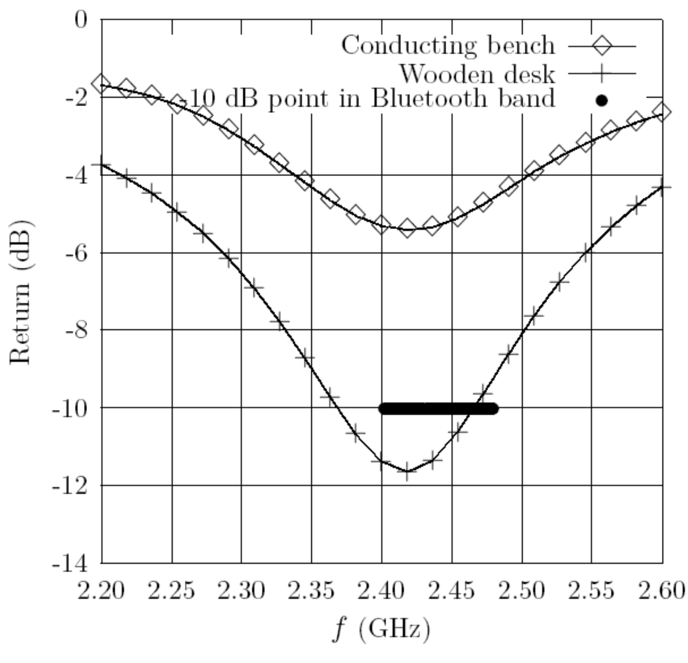


Figure 8.21: Return loss for printed IFA above metal and wooden surfaces
[*Source*: Flint and Vardaxoglou (2003)]

A significant disadvantage of these types of planar antenna is their operation when in close proximity to large metallic objects. Following experimental work conducted in Flint and Vardaxoglou (2003), Figure 8.21, above, shows the return loss of a IFA antenna placed in close proximity to a conducting metal surface. Other experimental work demonstrated considerable loss for a printed IFA antenna when situated within 15cm of a low-loss semi infinite ground plane.

A low-cost tri-band planar PIFA antenna is proposed in Leelarante and Langley (2005) for mobile and emergency call communications in vehicles. Three mount positions were investigated; roof, windscreen and rear bumper. The vertical roof mount position was deemed to be the optimal position, and the ground plane could be eliminated, further reducing the overall size. The front windscreen and bumper also produced adequate results, with the main advantage of these mounts being the mechanical protection afforded. Installation of an antenna on the bumper is common for emergency call systems where statistical surveys have shown that either a high mounted antenna or a bumper antenna will survive intact after an accident.

8.2.3.4 Electromagnetic Bandgap

Electromagnetic Bandgaps (EBG), also called Photonic Bandgap (PBG) structures, have been investigated recently as a means of improving the performance and efficiency of patch antennas (Waterhouse 2003, Karmakar and Nollah 2005). EBGs are artificially engineered structures that forbid the propagation of electromagnetic waves within a designated frequency, hence referred to as 'bandgap'. Initially designed for the control of optical properties in materials (emission/propagation), EBGs have been found to be scalable with frequency. At microwave frequencies, EBG structures have unique characteristics including; antenna gain enhancement and radiation pattern shaping properties (beam steering), high Q filtering, directivity improvement and bandwidth improvement.

Figure 8.22, below, shows a typical EBG structure, the lattice of metal plates connected to ground with vias creates a high impedance surface. The high impedance surface creates a stopband in the microwave region. This property allows an EBG ground plane to suppress TM_0 surface waves generated by a microstrip patch antenna, dramatically increasing the antenna efficiency.

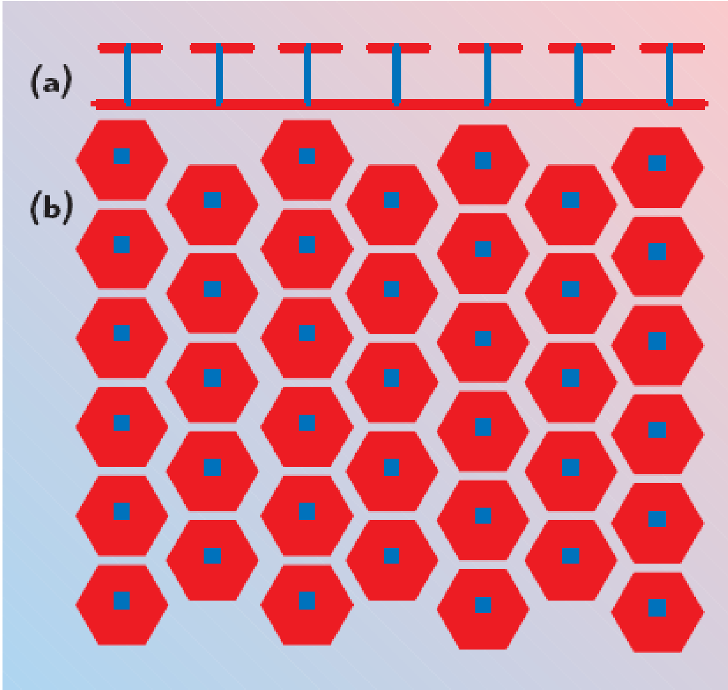


Figure 8.22: EBG Surface (a) cross-section (b) top view

[*Source*: Karmakar and Nollah (2005)]

8.2.4 Underground 'Base Station' Antenna Consideration

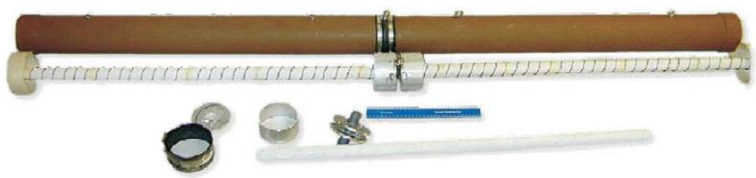
Another aspect in a robust underground mine antenna solution is the base station antenna. Efficient use of a higher powered base station unit could alleviate the design requirements on the 'mobile' antenna, say mounted on personnel or machinery. During the underground wireless propagation investigation in this research (Chapter 3), it was shown that omni-directional antennas had significant improvement over more a conventional antenna assembly. An interesting area for further research would be to take this further and develop specific mine, or tunnel, antennas that achieve efficient propagation within this type of environment. The following characteristics and requirements are noted.

Tunnel antenna requirements

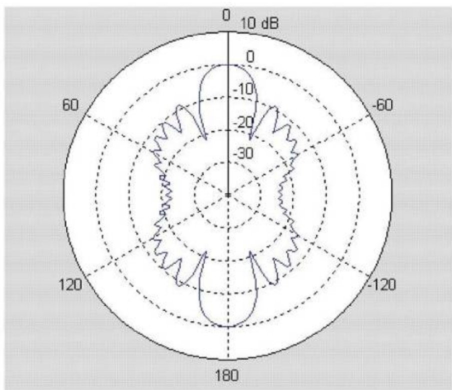
- Efficient coupling to the lowest order waveguide propagation mode – high directionality.
- Multiple beam direction formation – Junctions, bends, or simply in both directions along tunnel.
    - This could be achieved through a fixed shape design or through adaptive beam forming – MIMO antenna technology would be worth further investigation.

- Circular polarisation (CP) – A constantly changing ‘circular’ polarised Electric field transverse the direction of propagation can offer increased immunity to multipath, and potentially couple efficiently to the lowest order waveguide propagation mode.
    - o A drawback is that CP would increase the complexity, and hence, expense of the remote mobile node. However CP is certainly worth further investigation.

Figure 8.23, below, shows an example of a specifically design tunnel antenna, which is probably the only antenna available of its kind in the market. MinePoynt is developed by a South African company Poynting Antennas (Pty.) Ltd, part of the group who developed SuperNEC EM modelling software. The antenna is available in two varieties, bi-directional (shown below) and uni-directional (Poynting, 2004). This antenna uses horizontal helical antenna, using left-hand circular polarisation (LHCP). The polar plot is shown in the diagram below is a good indicator to the types of efficient performance required for a tunnel antenna. MinePoynt is a good solution for straight line of sight tunnel environments. However, there is still further work to be down in achieving the optimal ‘base station’ antenna, when you consider the small mobile device requirements and achieving optimal performance at tunnel junctions/intersections. This could be where MIMO antenna array technology may be candidate technology.



MinePoynt Helical 2.4-2.5GHz Antenna



Bi-diectional Antenna Radiation Pattern

Figure 8.23: MinePoynt Tunnel Antenna

[*Source*: Poynting (2004)]

8.2.5 Underground Antenna Review Summary

Compact antenna consideration for mobile/remote devices:

Robust underground antenna technology options have been reviewed, which might be suitable as the basis of a compact, low profile antenna system suitable for mounting on machines and in other mechanically vulnerable locations underground. This is in response to recognition that helical or monopole antennas are fundamentally susceptible to damage in an underground or confined space environment. The following points can be made:

1. Compact planar antennas offer a range of potential advantages including; compactness, low-profile, ease of fabrication, array formation, efficiency and mechanical robustness.
2. Important characteristics of planar microstrip antennas have been reviewed. This has highlighted potential weaknesses, along with various microstrip antenna design enhancements which may be used to overcome the issues raised.
3. Potential candidate antenna technologies include; shorted patch antenna, folded SPA, PIFA and EBG structures.
4. Mounting of antennas in close proximity to large metallic substrates may pose significant limitations on antenna performance. Further work is required to characterise this.
5. Of the candidate antenna technologies identified, the PIFA and EBG solutions are proposed for further investigation.

Base station antenna consideration:

In addition to generalised considerations of antenna performance, further specific investigation is required to establish the exact performance requirements of a wireless network, including Zigbee and Bluetooth operating in an underground environment. For example, in a smart sensor application, the requirements for both the base station units along with network client units should be considered within a complete system appraisal. It may be that the base station unit's gain and performance requirements are somewhat higher than that those of the network client units. Therefore a high gain patch array might be used to provide a networked structure of base stations, thus simplifying the requirements for remote client units. However, for high-integrity communications, there may be a high demand on the antenna efficiency on both base station and remote hosts, therefore careful consideration may be needed throughout the system. The requirements for an efficient tunnel antenna have been discussed, following on from the wireless propagation tests in Chapter 3, as consideration for potential further work.

Note on software tools:

Planar and microstrip patch antenna technology modelling and design requires specialised software tools. One software tool, SuperNEC was used as part of these investigations. It is noted that this package is limited when it comes to modelling dielectric substrates (although a future revision is being planned). Suitable alternative commercial software tools include IE3D and CST Microwave Studio.

8.2.6 Planar Antenna Tests in Proximity to Metallic Equipment

The review of robust antenna technology options is dependent on the actual performance we can expect to achieve with a planar antenna operating in close proximity to large metallic objects. As part of this investigation, further tests were carried out using a Netgear 2.4GHz 5dBi planar patch antenna, and 2.3GHz GHz continuous wave (CW) transmission equipment, as used in the wireless tunnel propagation tests (see Chapter 3). Two scenarios have investigated the transmitting antenna mounted in various positions on (a) a typical mine vehicle (dump truck) and (b) a belt conveyor drive. A Willtek 9102 hand held spectrum analyser was used for signal strength measurements.

Figure 8.24, below, shows the positions of the TX antenna mounted on the roof canopy of the mine dump truck. The values indicate received signal for each position. The spectrum analyser (RX equipment) was located 6m behind the vehicle. A measure of -22dBm, was recorded at the 6m distance, with the TX antenna held directly behind the vehicle. This provided a benchmark signal with no screening. Refer to Chapter 3, for actual vehicle screening tests that were conducted. The dump truck proximity tests were conducted at CSM Test Mine.

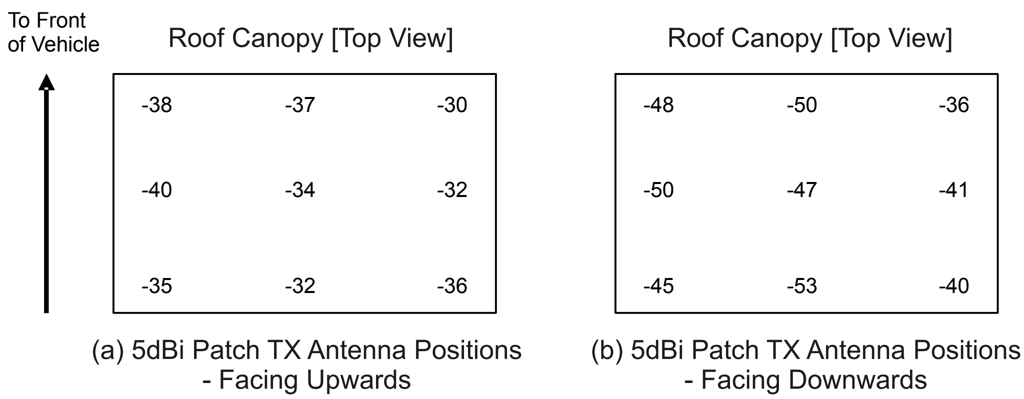


Figure 8.24: Dumper 5dBi Patch Antenna Proximity Test – Roof Canopy, TX Position versus RX signal (dBm)

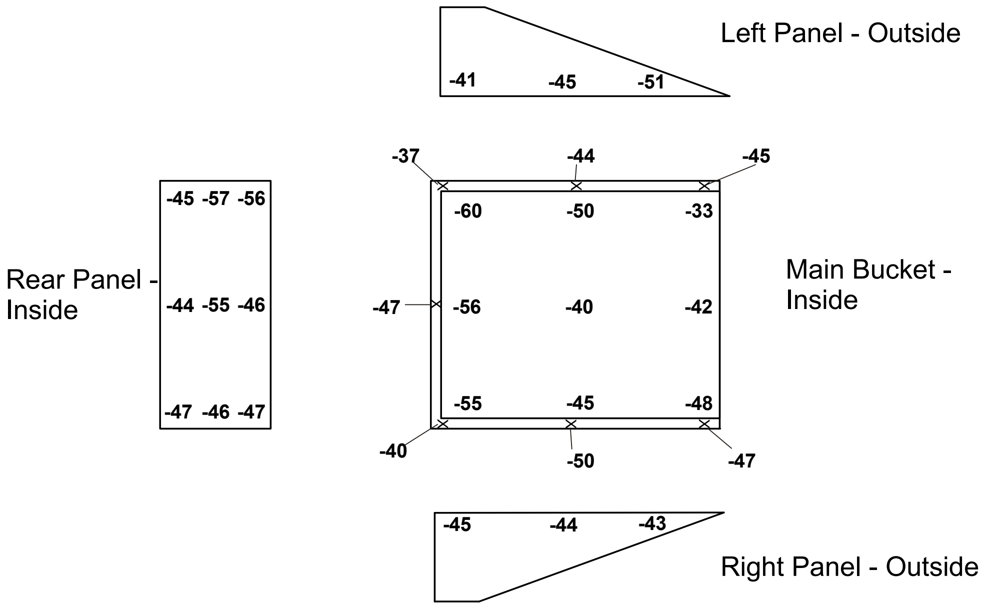


Figure 8.25: Dumper 5dBi Patch Antenna Proximity Test – Bucket, TX Position versus RX signal (dBm)

Similar recordings were made mounting the TX antenna in various positions in and around the actual bucket of the dump truck vehicle, as shown in Figure 8.25, above. In summary, the general observation was that the absolute 'worst case' received signal was approximately -60dBm. The received signal directly behind the vehicle (i.e. no screening between TX and RX antenna) was -22dBm, therefore the maximum observed signal loss was approximately 40dB.

Further antenna proximity to metallic equipment tests were carried out at MÜZ using a belt conveyor drive. The TX antenna was placed at several locations along the belt conveyor, again recording received signal for each location. The detailed antenna proximity positions and results are given in Figure 8.26, below. The receive equipment was permanently fixed at the start position 'X' as indicated. The total distance of the gateroad (from position 'X' to '8') is approximately 60 metres. Approximate distance between each measurement and the RX equipment is also noted. In summary, the 'worst case' received signal was -75 to -80dBm. Comparing this with typical straight tunnel propagation results obtained at MÜZ over 60m (from Chapter 3), this actually equates additional signal loss of around 40 dB.

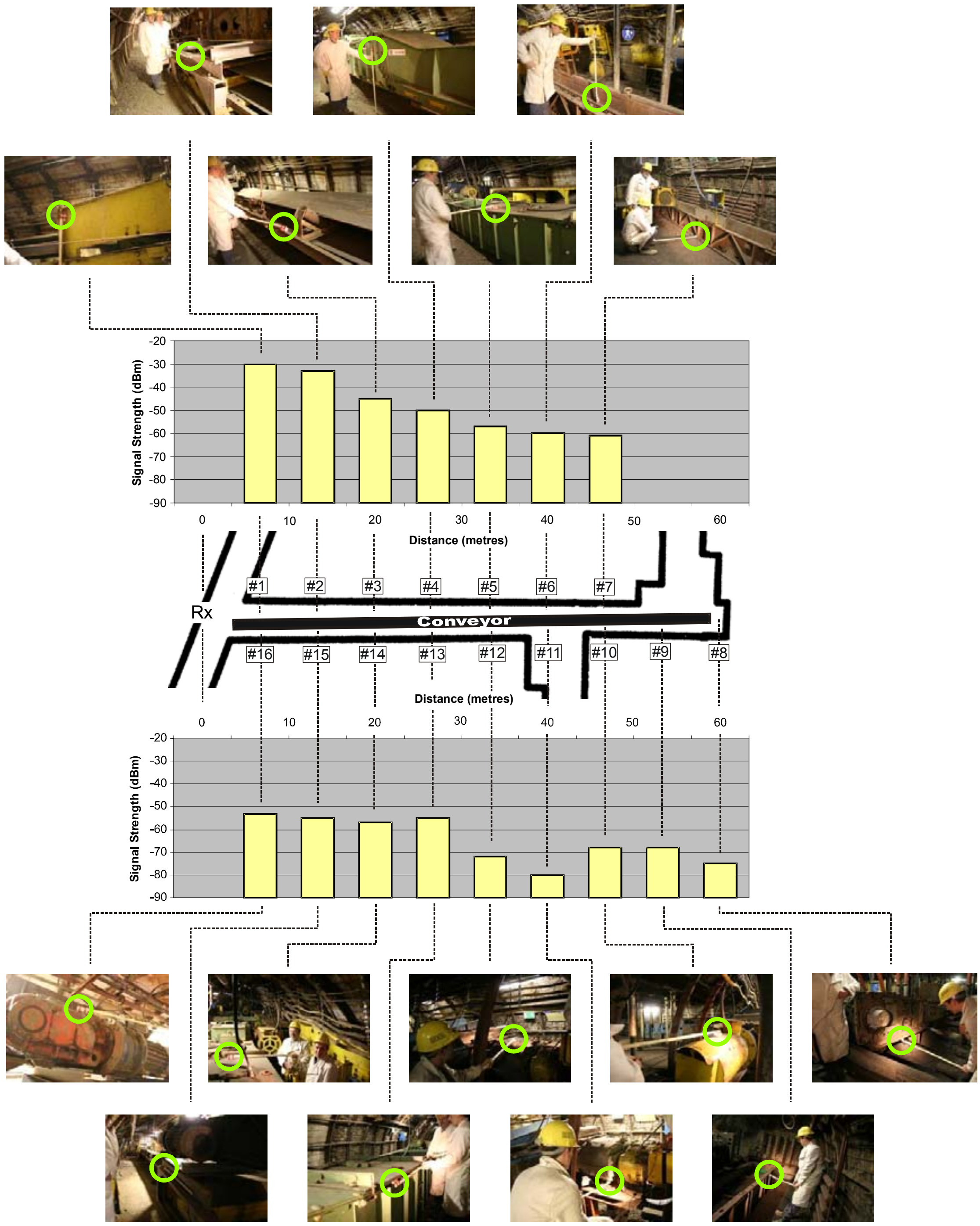


Figure 8.26: Belt Conveyor 5dBi Antenna Proximity Test

These results have shown that within this type of application, where devices will be operating within relatively close proximity to one another, it is quite feasible to use low-profile planar antennas mounted directly on machinery. This would suit a wireless sensor mesh network with a relatively high density of distributed sensors. However, for operation range critical applications there is clearly a need to investigate improving the performance using some of the techniques noted earlier in the review of robust antenna technology. Compact patch antennas, planar PIFA antennas, or EBG structures have the potential to achieve mechanical robustness and optimised performance.

8.3 Hybrid Mine Zigbee

The findings of the research have provided the potential 'ingredients' to develop a hybrid Zigbee device optimised for underground use. However, the feasibility and cost of each does significantly vary. Figure 8.27, below, shows the potential areas of improvement to develop a hybrid mine Zigbee with respect to the various layers. For example, the most expensive, without large corporate backing, would be optimising routing algorithms as these are locked away in the network software stack. An interesting area for optimising Zigbee type technology is in improving the PHY (physical layer). During this research it was found that there is significant merit in choosing a frequency diversity technique, e.g. FHSS or OFDM. This could be achieved by investigating alternative PHY platforms, where the software stack and applications could migrate across. Although a point to note, DSSS was carefully selected in IEEE 802.15.4 wireless sensor applications as it offers by far more optimal data latency, compared with FHSS (Gutierrez *et al.*, 2004). Therefore an optimal solution may be a type of hybrid frequency diverse, or adaptively selective, direct sequence spread spectrum. Potentially this could also be achieved in the application layer, keeping development costs down.

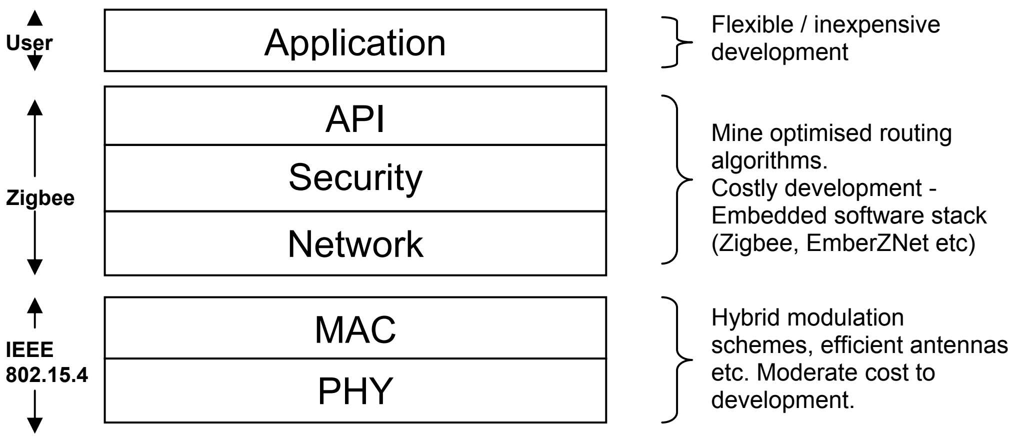


Figure 8.27: Hybrid Mine Zigbee Consideration

8.4 True Wireless

The introduction of wireless systems into underground mine environments brings an additional issue of providing a means of powering the devices. If the power requirements are high, thus requiring an external supply from mains electricity, then many of the advantages of a system being 'wireless' transmission are lost through the need to provide an external power supply. Therefore it is essential that mobile wireless devices (e.g. sensors, actuators, transponders) either have enough internal battery supply for a given operational life requirement, or have an in-built means of 'scavenging' power through other sources. There have been interesting recent developments in new emerging technologies called 'energy harvesters' or 'microgenerators'.

These microgenerators convert vibration energy into electric power and are specifically aimed at low power wireless sensor technology. Figure 8.28 below is an example of a microgenerator (PM07) developed by Perpetuum in the UK. Ferro Solutions (2004) have also developed a similar device, which generates, typically, 2.4mW at 50mg of vibration. Perpetuum are currently working on the next phase PM17, which can generate 100 µW from 16mg, at standard frequencies between 50 – 60 Hz (ThomasNet, 2006). Future developments in this field are likely to also produce very small microgenerator devices, for example, Beeby *et al*. (2004) are developing a micromachined silicon generator for energy harvesting applications.

Figure 8.28: Energy Scavenging Microgenerator
[*Source*: www.perpetuum.co.uk]

There are potentially other forms of energy scavenging techniques, or forms of energy to tap into in an underground mine e.g. moving water/air, or as mentioned, machine vibration. Ultimately, many of the applications considered in this thesis require 'true' wireless networking, whereby energy harvesting/scavenging is worth further investigation as a potential means of extending or even replacing batteries.

8.5 Summary

Specific potential areas of enhancing underground wireless networking have been considered; routing considerations, robust antenna options, a hybrid/enhanced mine Zigbee, and energy scavenging. The potential use of Zigbee related low power wireless networking technology has been shown to have significant potential in underground and confined space applications, specifically relating to safety. Whilst the key advantages of wireless mesh technology underground, such as robustness and survivability has been clearly shown in earlier Chapters, the aim of this Chapter was to identify weaknesses and areas for potential further research.

Chapter 9: Conclusions

9.1 Introduction

The emergence of low power wireless mesh networking technology relating to IEEE 802.15.4 and Zigbee standards offer exciting opportunities in the mining industry and other underground and confined space environments. For example, distributed smart sensor networks could used for monitoring the environment, machine diagnostics or even personnel's vital signs, and could also be used to provide active tracking of vehicle, plant, or more importantly, people. Tracking information is not only valuable from a logistical perspective, it could be of vital importance for both precautionary safety measures and in post emergency incidents. The underground environment is a particularly harsh environment, in that electrical/mechanical equipment has to be extremely robust, there is the presence of water and dust, and in many cases the atmosphere is potentially explosive. Data transmission systems operating underground have to be robust, of high integrity, and ideally survivable. Maintaining data communications links following an emergency incident, such as an explosion or roof-rock fall, would provide invaluable assistance in a rescue operation. For example, knowing the last location of trapped miners (or at least being able to access their last stored location), their 'vital signs' status, and possible even establish a basic form of two-way communications. Since this project commenced, there has been an ever growing demand for robust underground communication in both mining and public sectors. Following mine incidents such as the Sago disaster, the US Mining Health and Safety Administration (MSHA), issued an international call-out for improved underground communication and tracking systems (MSHA, 2006). Here in the UK, a report following the July 7 bombings (Greater London Authority, 2006), highlighted that the emergency services radio systems were simply inadequate underground.

The work in this thesis has examined the feasibility of underground wireless mesh technology, including subsurface propagation characteristics and high integrity performance. Potential safety applications using low power wireless mesh networking technology in underground mining have been investigated. The work has been broadly encompassed through the following areas:

- Review and initial feasibility study
- Subsurface UHF and microwave propagation characteristics in tunnels
- Examining the potential and feasibility of mesh wireless technology
- Underground safety application concepts and development

9.2 Feasibility and Review

The initial feasibility study and literature review was carried out under an original theme 'enhancing underground data transmission technology, particularly towards improving mine safety systems'. The study evaluated the status, including general trends and needs, of underground telecommunication technology. The ever-increasing demands on the global mining industry to improve underground safety, whilst maintaining an improvement in operational efficiency are increasingly making telecommunications a vital part of modern underground operations, such as mining and tunnelling. Telecommunication systems can be used to transmit valuable data to/from remote locations for monitoring and control purposes, or provide a valuable communications link between personnel. Radio propagation has many desirable attributes as a medium for transferring information underground. Radio systems are mobile and flexible, thus also reducing installation time and costs in regard to metallic and fibre optic media. Wireless networking technology operating in the UHF and microwave spectrums could prove very advantageous, and are rapidly gaining momentum within the mining industry.

Following the review it has been found that emerging technology, being termed as LR-WPAN (low-rate wireless personal area network) standards and specifically aimed at sensor type applications, have significant potential in underground mining and confined space environments. More specifically, the IEEE 802.15.4 and Zigbee standards were identified as key core-enabling technologies given the low power, low data rate, and mesh network characteristics. Standardised technology, as opposed to proprietary systems, also unlocks the potential for 'open' and interoperable data transmission. Open, being that the technology can be developed by multiple manufactures, thus reducing cost and improving the overall availability. Interoperability, such as TCP/IP networking, allows Zigbee, or other related technology to be coupled into a higher level network infrastructure. This is very much in line with what the mining industry is working towards at present. For example, UK Coal are currently in the process of upgrading their deep coal mines to a fibre optic Ethernet based SCADA system. Whilst this work is not directly related to this thesis, the two parties have remained in contact and it is mentioned for further justification of work presented here. A short summary of UK Coal's SCADA project is given in Appendix A.3.

9.3 Mesh Networking

Mesh networking technology offers many significant advantages in underground safety applications. The self-organising, self-healing, and multiple pathway redundancy characteristics of a mesh network significantly increase network robustness and survivability. Information is simply sent as packets and delivered from address A to address B. The network does not rely on pre-determined infrastructure, and will reorganise itself in the event of failure. For example, in the event of a roof-rock fall completely blocking a passageway, hence obstructing the RF link, the data will re-route through another path. Even in a mine, there is rarely a single route to a particular location, given the need for 'intake' and 'return' gateroads for ventilation. Mesh networks are also scalable up to hundreds of nodes in any one particular network. The feasibility of LR-WPAN mesh technology has been examined, with particular respect to underground environments, and a range of exciting novel safety oriented applications have been proposed.

The characteristics of mesh network routing have also been examined with respect to optimising the mesh data routing in underground safety applications. For safety an emergency applications, data integrity takes precedence over throughput and measures need to be included in the routing algorithms to ensure data integrity. Also in terms of static versus dynamic networks, it was found that certain mesh routing algorithms are better suited to dynamically changing networks than others. For this reason, the EmberNet mesh network stack was selected for development work over ratified Zigbee 1.0 standards based systems. EmberNet, developed by Ember Corporation, was optimised in terms of mobility and dynamic networks over Zigbee 1.0. However, Ember one of the main driving forces behind the Zigbee standard, and it is anticipated the new Zigbee standard will address the issue of mobility. Ember have also since released their own fully ratified Zigbee stack called EmberZNet, which has an additional built in transport layer, providing end-to-end acknowledgements and number of retransmissions, which have been carried forward from EmberNet. Therefore, it is anticipated that EmberZNet provides both fully standards based networking, making it open and interoperable, and is better suited to mobile dynamic networks.

Various tests have been carried out with EmberNet wireless networking technology in an underground mine environment, using 868 MHz (EM1020) and 2.4 GHz (EM2420) technology. The main finding from these tests were that the 2.4GHz system far outperformed the lower 868 MHz system, in terms of robust transmission. This was partially due to the fact the 2.4 GHz transmission system employs DSSS, which does provide mitigation against multipath effects. This was a particularly interesting find as earlier research e.g. (Emslie *et al*., 1975) had assumed performance would deteriorate at frequencies increasing above 1GHz. Waveguide behaviour was also observed with weak non line-of-sight signals present, particularly using the 2.4GHz system. This was enhanced using higher gain omni-directional antennas.

9.4 Wireless Tunnel Propagation

In an underground environment the most vital factor is whether RF communication at the UHF and SHF (microwave) frequencies can feasibly be achieved. In general, modern wireless networking technologies operate in the ISM licence exempt frequency bands. The majority operate at 2.4GHz, with some operating at lower UHF frequencies (e.g. Zigbee operates at 868MHz or 2.4GHz in Europe), and some wireless technologies operate at 5GHz and beyond. Building on previous research of subsurface electromagnetic propagation, a study of underground wireless propagation at UHF and microwave frequencies has been carried out. At these higher frequencies tunnels essentially behave as a lossy waveguide. Waveguide theory has been examined; in particular, the lossy dielectric tunnel waveguide model has been studied and compared with practical tests. A range of underground tests have been carried out using CW microwave transmission, and various wireless technologies including: WiFi (IEEE 802.11b, -g, -super-g, -pre-n, and draft-n) and Bluetooth.

The tests have fully supported the theoretical hypothesis that tunnels behave as a lossy waveguide. This was particularly observed in line of sight tunnels, where in some instances the transmission range was enhanced. Practically all CW tests demonstrated an initial higher attenuation rate usually up to around 10m and beyond this relatively low attenuation rates were observed. Antennas do not efficiently couple to waveguides, and in fact, it is impossible not to excite multiple higher order modes. Given that the different modes have different phase constants and travel at different velocities, the presence of standing waves is inevitable. This causes both constructive and destructive interference in various places along the tunnel. The lowest order waveguide, which is the dominant mode, has the lowest attenuation rate, and the higher order modes usually have a very large attenuation rate, and diminish within the first 10m. Therefore, there will be far more severe inter-mode interference up until this point. This has been shown through both theory and practical testing.

Further observations made during the CW tests were that high gain directional antennas (patch antennas) had increases efficiency. For example, a 5dBi patch antenna had better performance than a 9dBi omni directional antenna. It was assumed that directional antennas couple more efficiently to the lower order waveguide propagation modes. Tests were also carried out using 5.8 GHz CW transmission. The results displayed similar performance to the observations made during the 2.4GHz tests. Therefore, it can be expected that 5GHz technology, and higher frequencies, becoming more widely available on the market could be expected to have similar performance in tunnels.

Whilst there has been research work into UHF and higher transmission in underground mines and tunnels, there has been relatively limited work regarding modern digital transmission techniques. The wireless technology tests have provided some interesting results. It was clearly shown that diversity techniques, such has DSSS, and in particular the frequency diversity techniques FHSS and OFDM, offer significant improvement in tunnels. Technologies such as Bluetooth, employing frequency hopping spread spectrum (FHSS), degrade gracefully in both line-of-sight (LOS) and non-LOS situations. Considering standing waves causing interference, these are present at particular places at particular frequencies. Frequency diversity, or frequency hopping mitigates this effect by simply hoping to another channel, albeit unintentionally. In summary all the 2.4 GHz wireless technologies tested had a satisfactory performance in the environments tested. Comparisons were made between the throughputs of select technologies in tunnels versus the throughputs that can be achieved in an office and outdoor environment. It was found that the operational range was clearly enhanced in a tunnel environment, which fully supports the assumption that tunnels behave as waveguides.

9.5 Novel Underground Safety Applications

A potential range of novel underground wireless mesh network safety applications have been examined. The LR-WPAN technology discussed, specifically geared towards sensors networks, could be used to provide a distributed smart sensor network e.g. environmental monitoring, machinery diagnostics and remote telemetry. Details of a proof-of-concept distributed smart sensor application have been presented in this thesis. Another proof-of-concept remote telemetry application has also been described, which gathers remote 3D surveying data from a robotic vehicle. This was carried out in conjunction with a separate ‘remote surveying vehicle’ (RSV) project at Camborne School of Mines. The joint remote telemetry and RSV application was successfully tested out at the CSM Test Mine.

Another potential sensor network application is monitoring the vital signs of personnel; this could be mine workers or even rescue personnel. This type of application in regard to rescue team members has been given careful examination in this thesis. Emergency rescue teams, such as mines rescue or firefighters, are subjected to extreme conditions during rescue operations. Monitoring core vital signs, either locally by the team captain, or at a ground base, would be highly beneficial. Tests were carried out in conjunction with the London Fire Service as part of a feasibility study into the use of wireless mesh sensors to gather vital signs. It was demonstrated that this type of technology could provide a rugged means of monitoring vital signs, with other added advantages including rapid deployment, and reducing the size/weight of the monitoring equipment in regard to a wired sensor approach.

Zonal location information has been a key potential application identified within this research, offering a number of advantages as discussed earlier. Low power mesh wireless networking technology could feasibly provide a lower cost alternative to expensive RFID (or tag) reader stations, with added functionality e.g. dual sensor and tracking applications. A proof-of-concept ‘zonal tracking’ application, using a ‘beaconing’ technique, has been proposed, along with a review of more accurate ‘positional’ tracking techniques as consideration for future work.

9.6 Further Work

Further to both the study of subsurface propagation and mesh networking characteristics in wireless sensor networks (WSN), potential further work has been examined in Chapter 8. This could include developing routing algorithms specifically tailored and optimised for high integrity (i.e. safety and emergency) underground applications. 'Mine friendly' antennas are another factor which has been given careful examination. Further consideration of the types of antenna and potentially developing machine mount and tunnel efficient antennas would be crucial to a successful underground sensor network product. The efficiency of antenna performance could also be enhanced through efficient 'tunnel antenna' designs for a base station (or permanent high gain node). Another proposed future development would be that of a 'hybrid zigbee' with an improved physical layer (PHY) performance. During the underground wireless propagation investigation, it was observed that frequency diversity techniques, for example FHSS employed by technologies such as Bluetooth, offer particularly robust transmission in underground tunnel environments. However, Zigbee is more efficient than Bluetooth in many other respects for the proposed types of applications e.g. DSSS enable faster network discovery and synchronisation than FHSS. A proposed solution would be a Zigbee device, which has an additional adaptive frequency channel selection to mitigate standing waves. The ability to achieve 'true' wireless transmission is another area for further work in terms of power supply, which could include a possible means of energy scavenging for extending or even replacing battery power.

The work in this thesis has presented a novel approach to achieving robust, resilient and survivable data transmission using high frequency mesh wireless networks. Key safety related applications have been examined, some of which have been taken to a 'proof-of-concept' stage. However there is clear further work to be achieved in terms of both research and development to progress these applications. Whilst the research has been primarily targeted at the underground mining industry, the work presented in this thesis could have significant potential in other underground and confined space environments. The challenges of achieving robust underground data communications in mining are certainly representative of other industries and sectors, e.g. military, emergency services, tunnelling and confined space built environments. This thesis has presented a number of interesting results and approaches to robust underground data communications. Future directions will include developing an active underground tracking system using mesh networking technology along with other smart sensor related applications. The results and findings from this thesis could also be applied to enhancing the performance of other wireless technologies in mines and confined space environments including WiFi, Bluetooth, and future technologies such as UWB (ultra wideband) and WiMAX. Therefore, there is certainly significant scope for further research and developments in this field.

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APPENDICES

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A.1: Publications

Kennedy G.A., Foster P.J. and Luke S.P. (2004) Low power Wireless Mesh Networks in Underground Mining. In: *Proceedings of the JKMRC International Student Conference 2004*. Brisbane, Australia, p.361-365.

Kennedy G.A. and Foster P.J. (2005) Low power Wireless Mesh Networks in Underground Mining. *AusIMM Bulletin*, March/April, p 60 – 67.

Foster P.J., Jobling-Purser J., Kennedy G. and Wetherelt A. (2005) Underground Void Visualization using a Low-cost Automated ROV. In: *Proceedings of the 31st Biennial International Conference of Safety in Mines Research Institutes*. Brisbane, Australia, p.285-288.

Kennedy G.A. (2005) Low Power Wireless Mesh Networks in Underground Mining (based on AusIMM paper, with additions from D.Gibson). *The CREG Journal*, **62** p.12-17.

Kennedy G.A. and Foster P.J (2006) High Resilience Networks and Microwave Propagation in Underground Mines. In: *European Conference on Wireless Technology (ECWT 06)*, September, Manchester, UK.

A.2: Detailed Wireless Technology Results

The data presented here was compiled by **Mike Bedford** on behalf of Mines Rescue Service Ltd (MRSL), and is reproduced here with permission of MRSL. The wireless technology test results were collected as part of the collaborative research between CSM and MRSL.

The graphs and information, given below, present more detailed information regarding the wireless technology tests, as opposed to the summary graphs, compiled by myself, in the main body of this thesis. The following data is given:

1. Raw data throughput graphs for each test location (Ashbourne Railway Tunnel, CSM[3] hard rock test mine, MÜZ[4] Coal Mine Test Facility)
    - Figures A.2.1, A.2.3, A.2.7

2. Average throughput for each location
    - Figures A.2.2, A.2.4, A.2.8

3. Additional 'Bend' tests for CSM and MÜZ (Raw and Average)
    - Figures A.2.5, A.2.6, A.2.9, A.2.10

[3] Camborne School of Mines, UK
[4] Maschinenübungszentrum, Germany

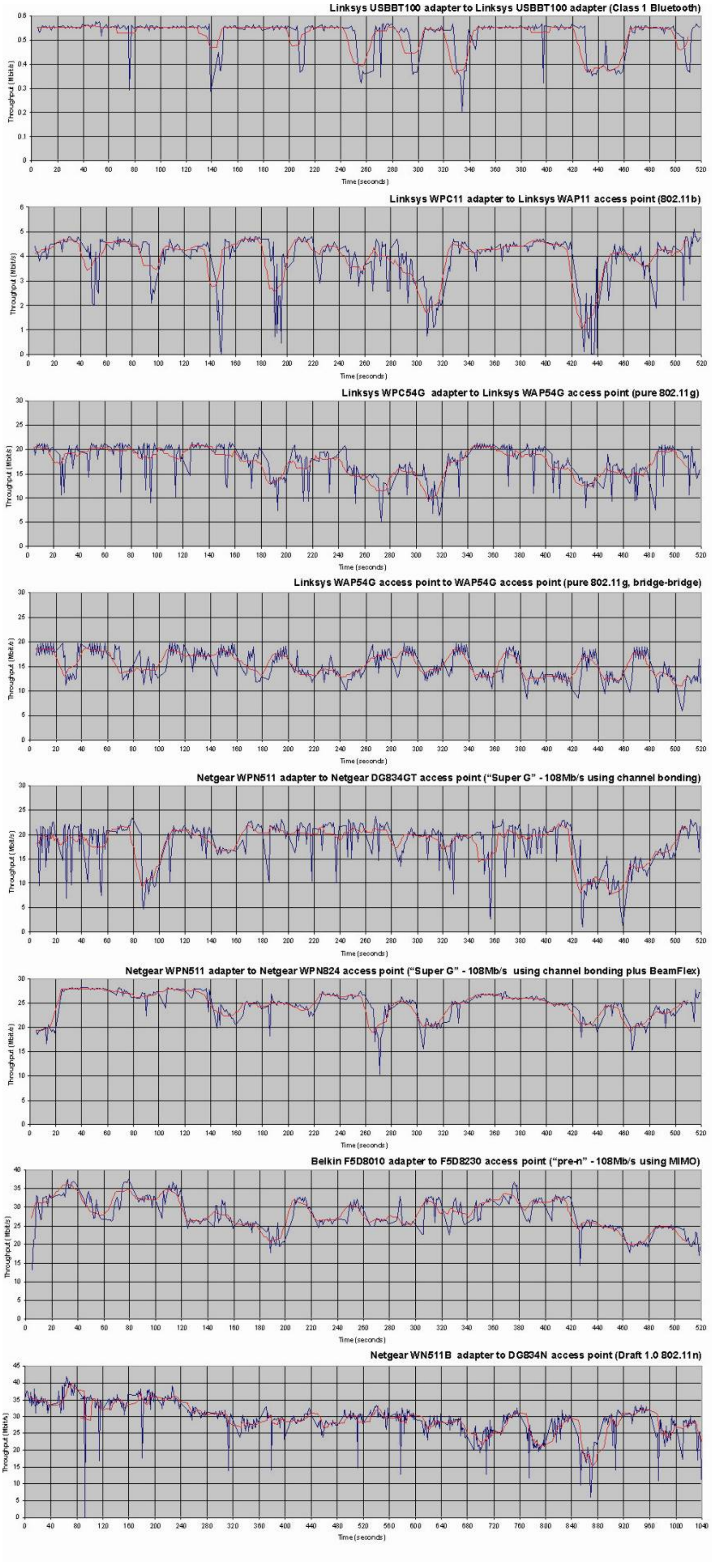

Figure A.2.1: Raw Data for Ashbourne Railway Tunnel

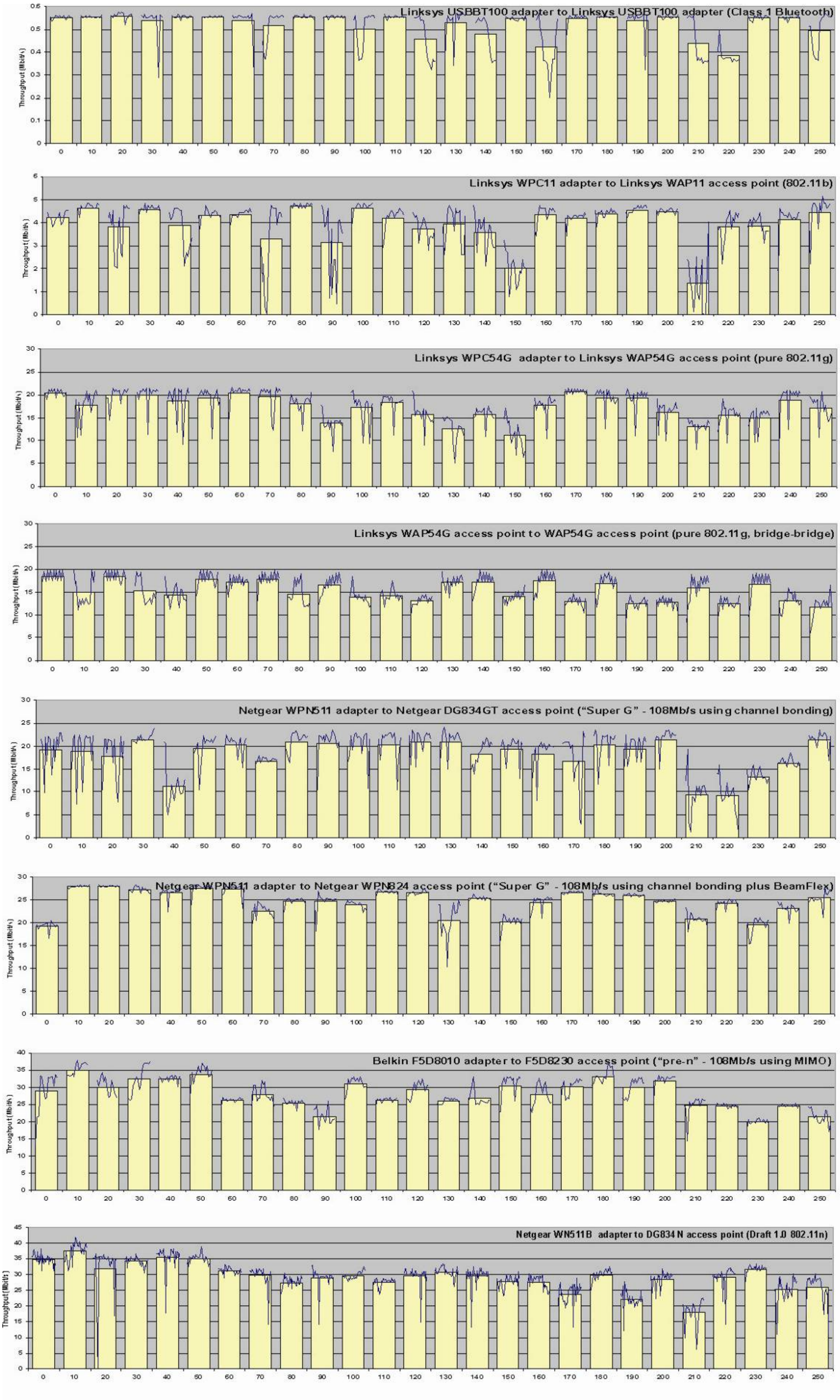

Figure A.2.2: Averaged Data for Ashbourne Railway Tunnel (Distances in metres)

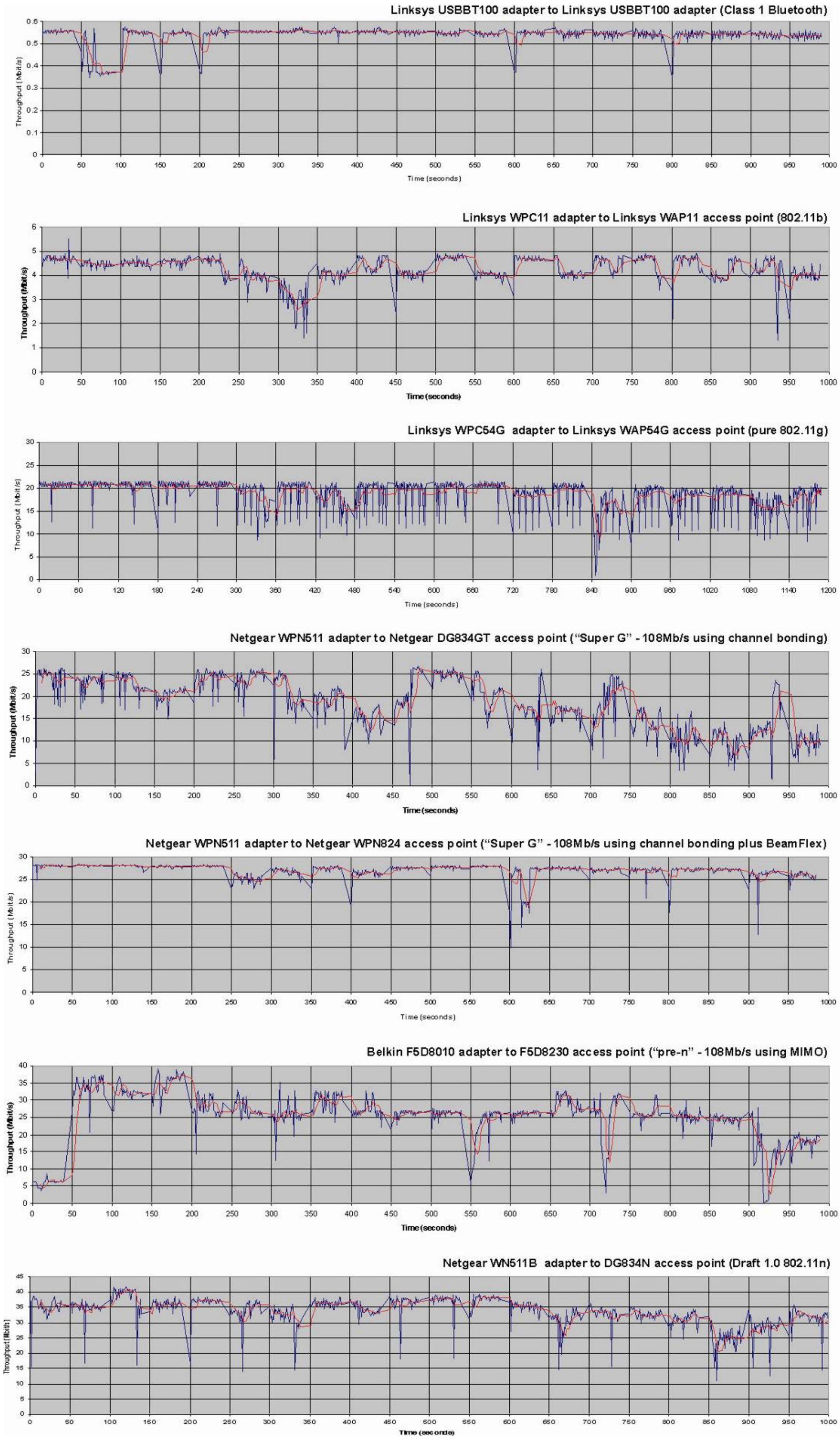

Figure A.2.3: Raw Data for "Tunnel A" (Straight Tunnel) in CSM Test Mine

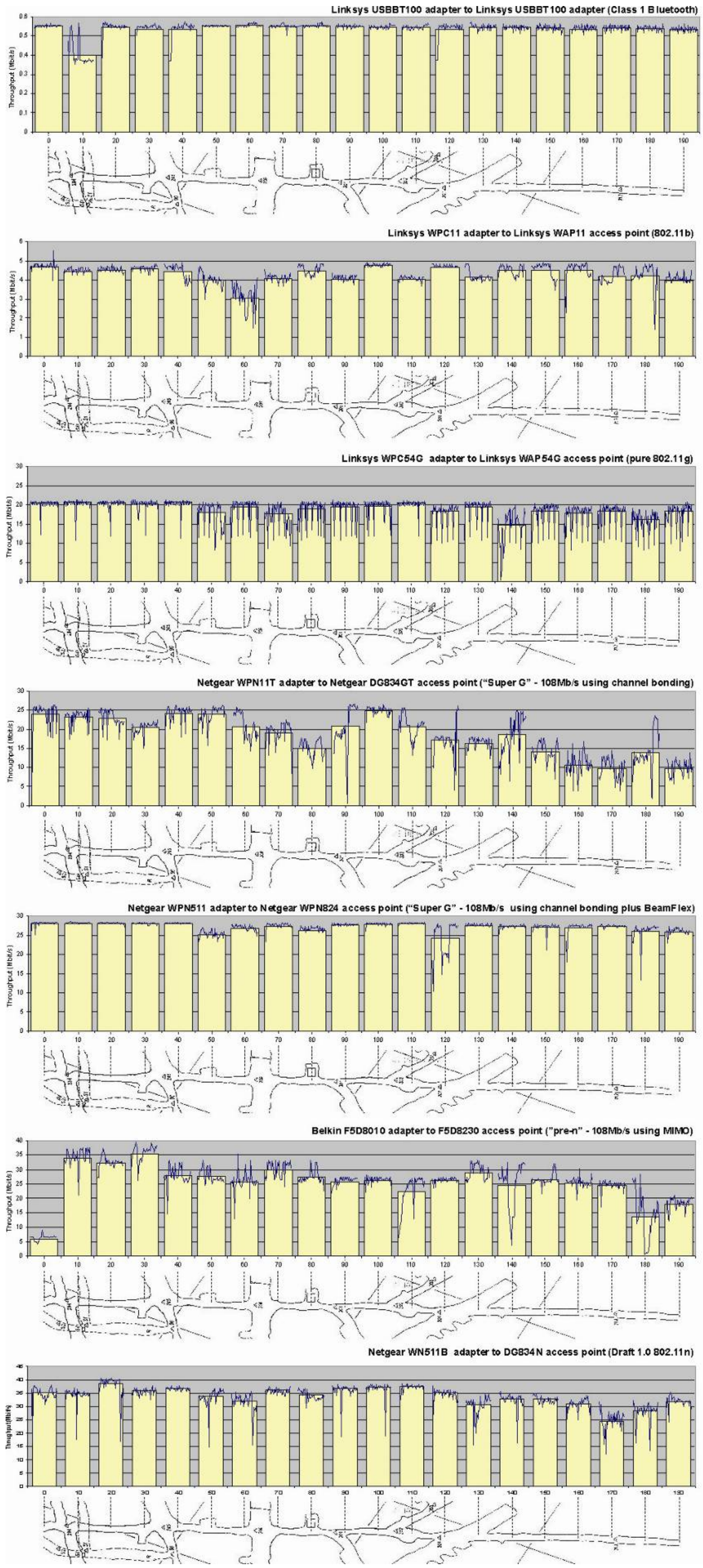

Figure A.2.4: Averaged Data for "Tunnel A" in CSM Test Mine (Distances in metres)

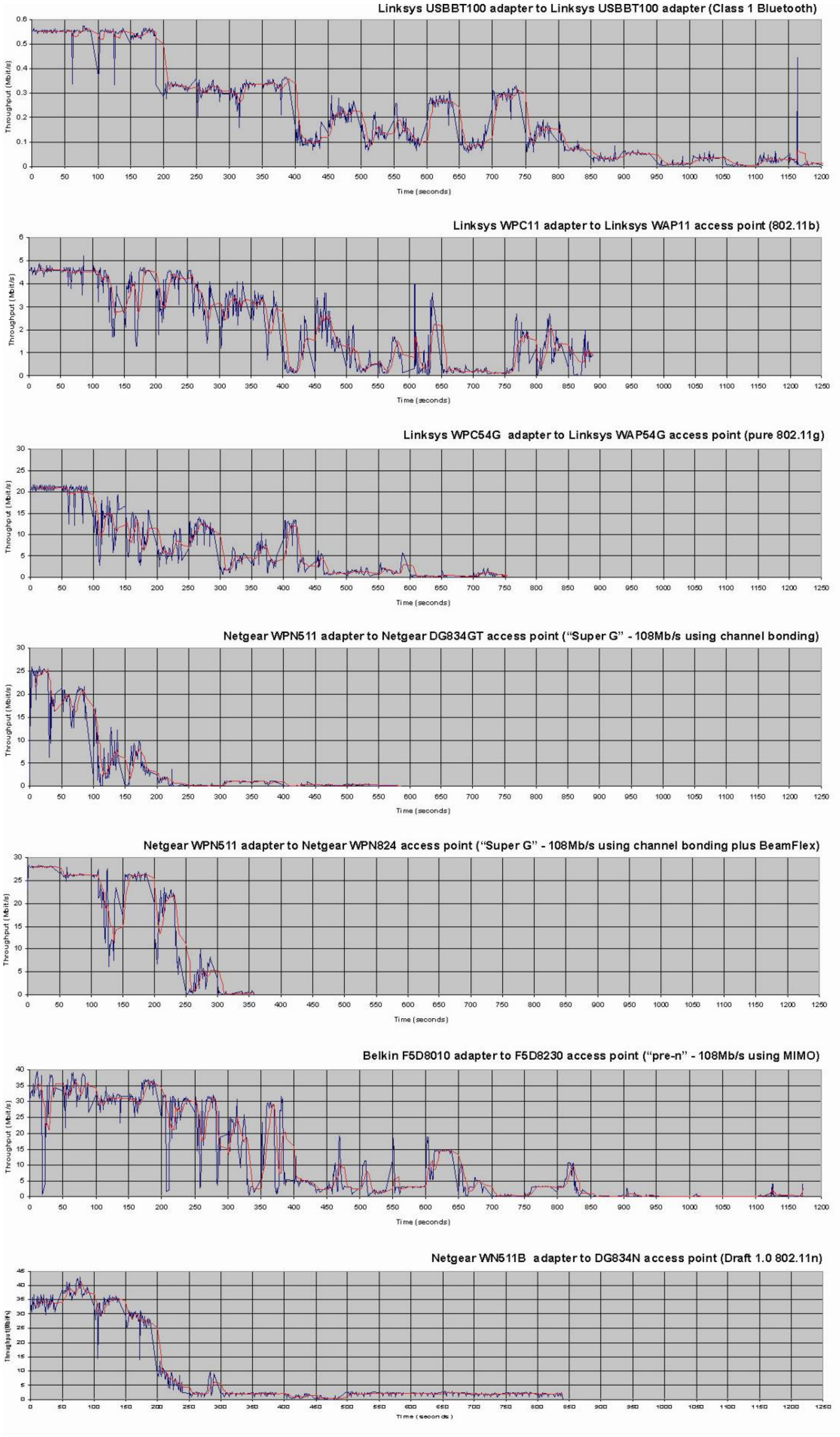

Figure A.2.5: Raw Data for "Tunnel A" into "Tunnel B" (Bend) in CSM Test Mine

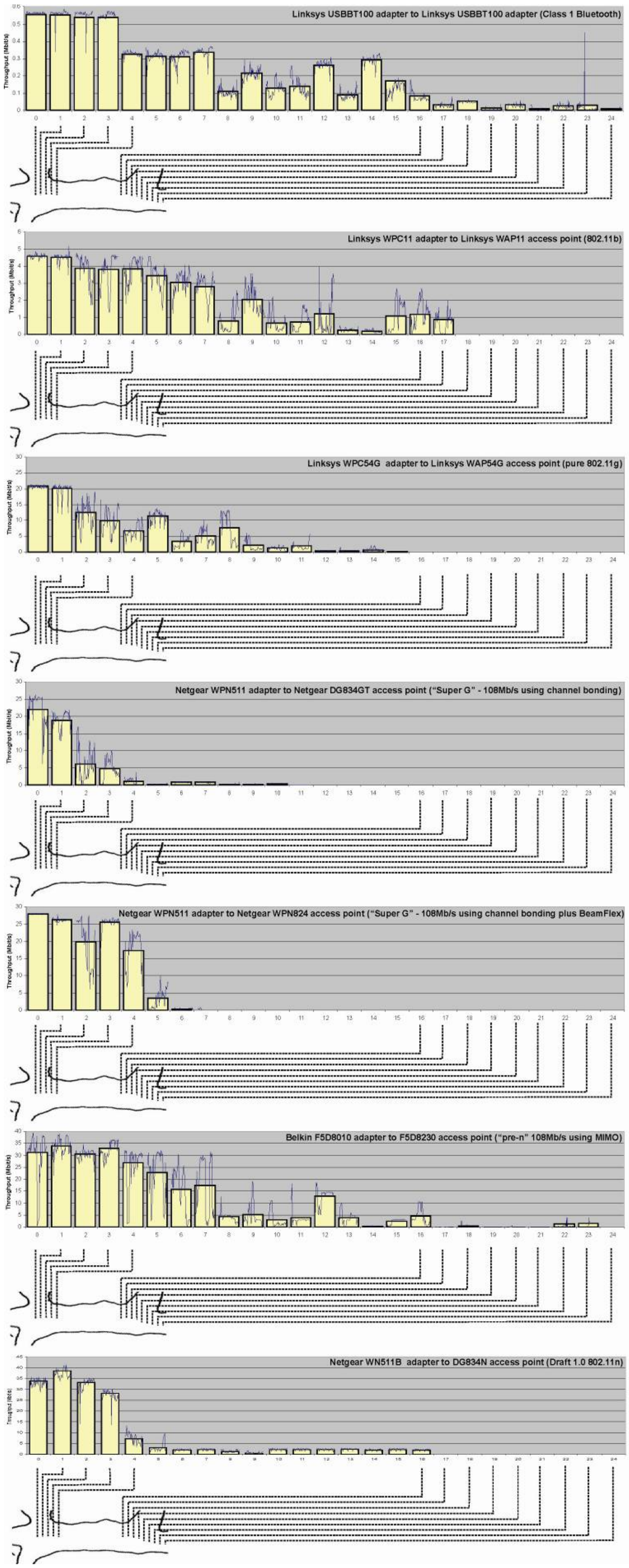

Figure A.2.6: Averaged Data for "Tunnel A" into "Tunnel B" (Bend) in CSM Test Mine (Distances in metres)

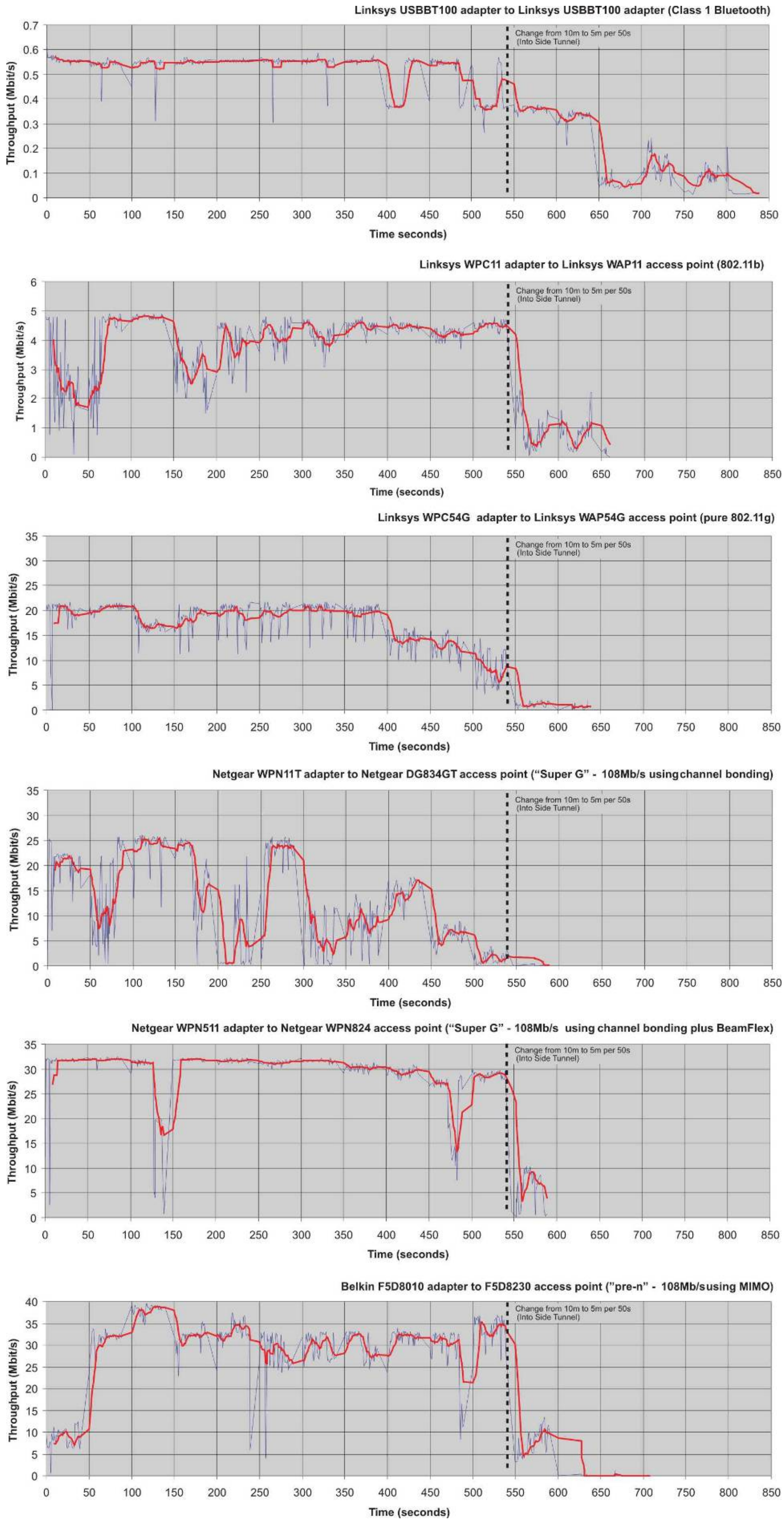

Figure A.2.7: Raw Data for the "Main Tunnel" in Maschinenübungszentrum (Straight Tunnel)

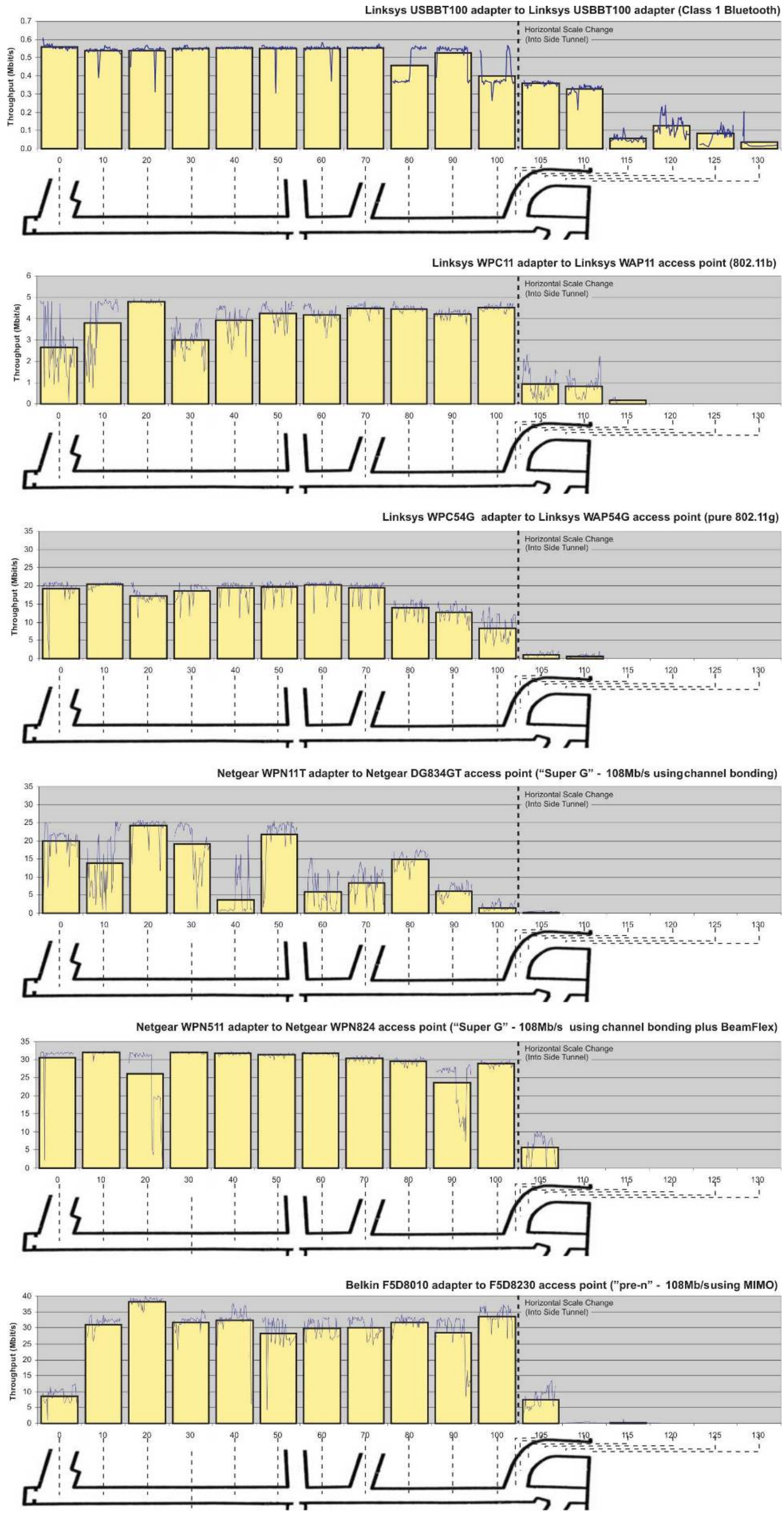

Figure A.2.8: Averaged Data for the "Main Tunnel" in Maschinenübungszentrum (Straight Tunnel)

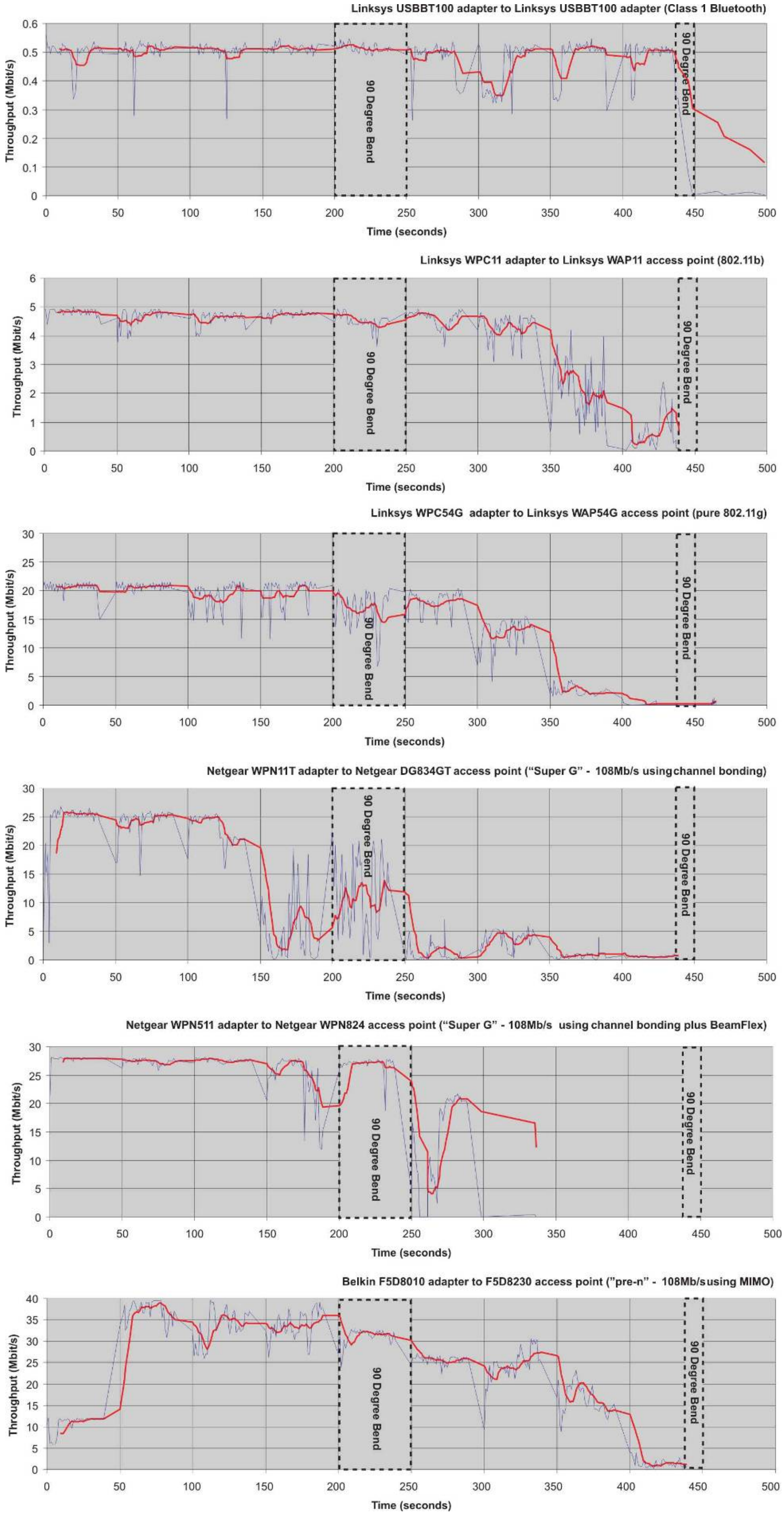

Figure A.2.9: Raw Data for the "East Tunnel" in Maschinenübungszentrum (Gradual Curve Bend)

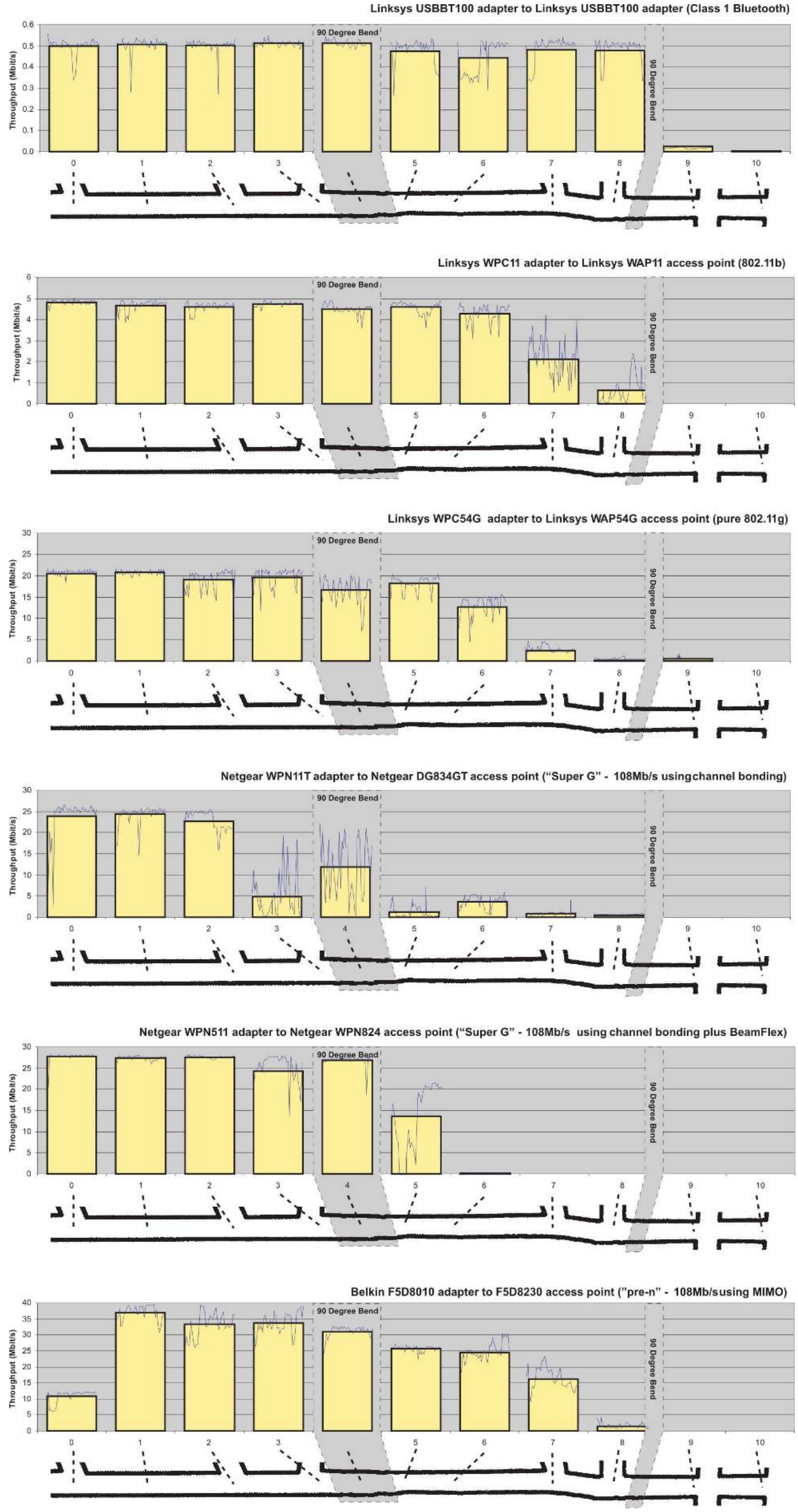

Figure A.2.10: Averaged Data for the "East Tunnel" in Maschinenübungszentrum (Gradual Curve Bend)

A.3: UK Coal Mining Ltd

SCADA Overview

Recently, UK Coal Mining Ltd, which operates the majority of the deep coal mines in the UK, have been upgrading their mine monitoring system to an Ethernet based SCADA (supervisory data acquisition and control. This work has been overseen by **Mr John Ford**, the SCADA development engineer at UK Coal (Ford 2006, UK Coal 2003).

The SCADA system, which is fibre optic Ethernet based, is completely replacing older MINOS (Mine Operating System). The main advantages of the new SCADA system are that it provides 'open' and 'interoperable' infrastructure. The significant increases in bandwidth due to the Ethernet standard provides also allows for other applications including voice/video over IP.

An overview of the SCADA system at a deep colliery is shown below in Figure A.3.1. The system incorporates a ring infrastructure through the mine in order to introduce redundancy. The data is logged in the mine using PLC's, the data is relayed to the surface and various servers and databases. The SCADA system has all the control and monitoring on the same network. Remote access is also available allowing external users to access important data from the mine, or potentially, user's underground can have access to external information e.g. machinery maintenance data. This type of Ethernet backbone is seen as one of the 'core enabling' technologies from this research projects perspective.

Some key features of the SCADA System:

- Open and interoperable – Based on OSI model, this also makes equipment relatively inexpensive.
- ATEX M1 Certified
- Ethernet 10/100 BaseT allows for additional functionality
    - Acts as main backbone data highway
    - Voice/Video over IP
    - Wireless can be used to extend coverage (WiFi, Bluetooth, Zigbee)
    - TCP/IP Interface
- World wide web – External and internal access to information
- Data stored on SQL databases
- Potential future applications with distributed wireless sensor networks

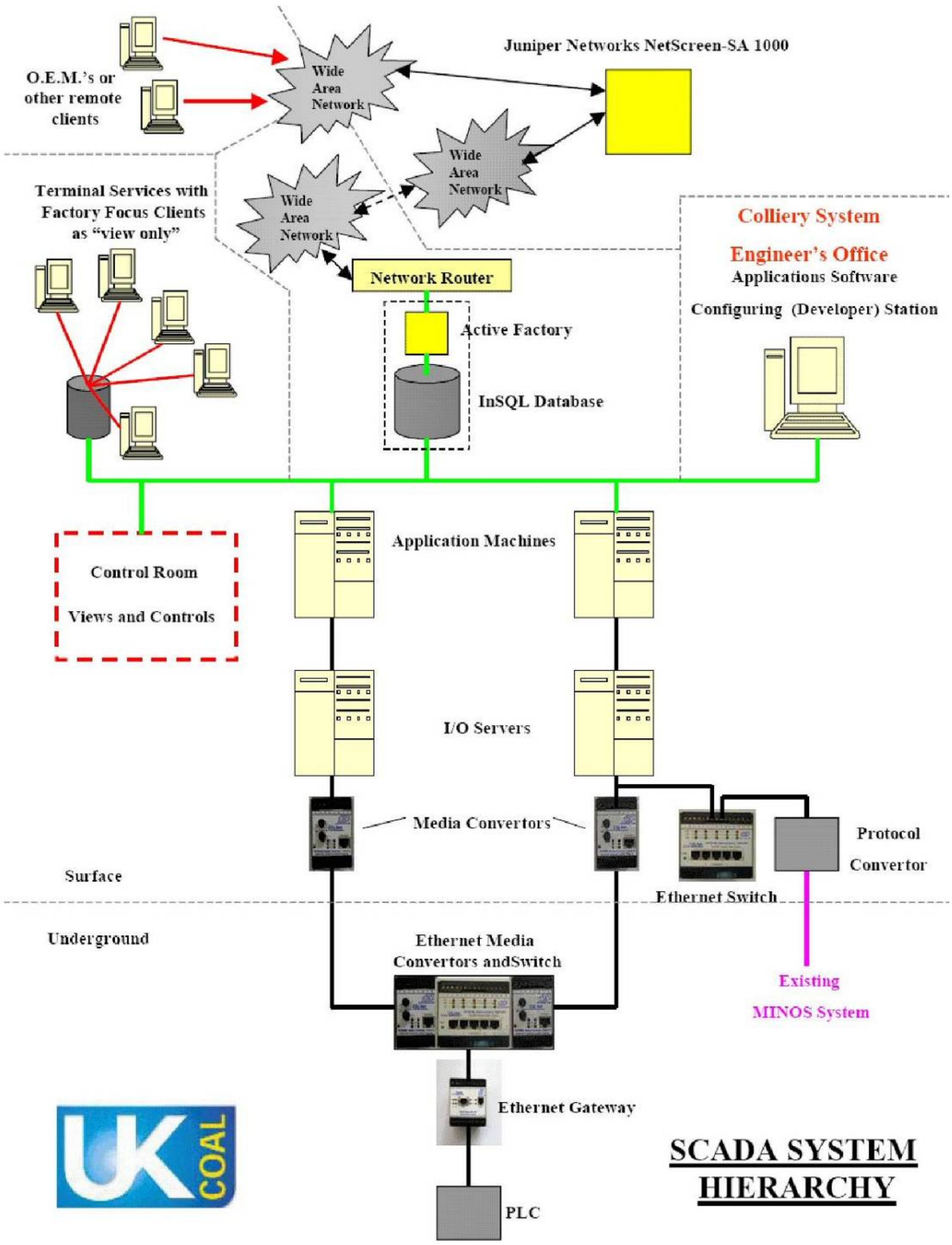

Figure A.3.1: SCADA System Overview

[*Source*: UK Coal (2003)]

Bluetooth Shearer Application

UK Coal Mining Ltd have also been looking into the use of a Bluetooth system for a longwall coalface application. CSL (Controlled Systems Ltd) and Eickhoff have developed a Bluetooth radio controller interface for the Eickhoff SL300 Shearer. The SL300 shearer and Bluetooth radio controller are shown below in Figure A.3.1.

Figure A.3.1: Eickhoff SL300 Shearer and Bluetooth Controller

UK Coal kindly shared unpublished results of field trails using a Bluetooth radio system, these are shown in Figure A.3.3 and Figure A.3.4 below. The field trails were conducted using Class 1 (100 mW) Bluetooth radio devices in two separate collieries: Daw Mill (Coalface A) and Maltby (Coalface B). The number of 'chocks' (self-advancing mechanical roof supports) separating the two Bluetooth devices indicates the range of transmission. The results show the distances in metres, for each power level setting where the received data fell below 100% and 75%.

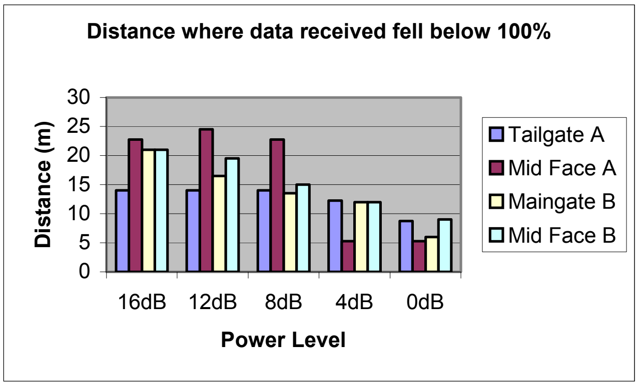

Figure A.3.3: Bluetooth Results: Distance where data fell below 100%

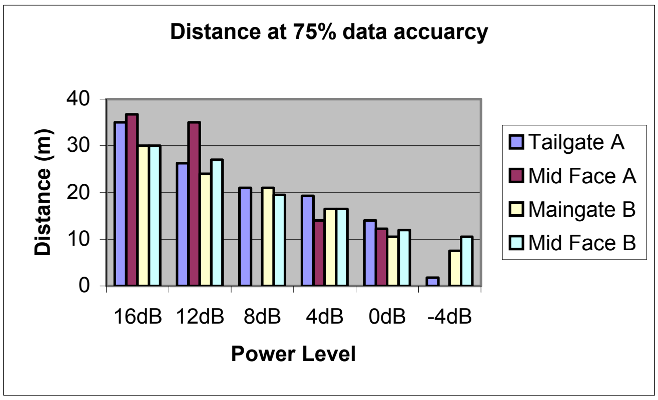

Figure A.3.4: Bluetooth Results: Distance where data fell below 75%

A.4: EmberNet Colliery Trial Preparation

PR-133: Power supply and Exerciser for Ember Beacons

Draft document: These notes are a minimal description for the assembly of this product

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1 Product Description

This power supply and exerciser allows us to operate Ember beacons with an external power pack, and to send serial data to the beacon. The advantages, apart from the ability to send serial data, are a longer battery life and an IP67 sealed unit.

1.1 Operation

1.1.1 Controls and indicators

External rotary switch, SW3	Rotate clockwise for OFF – DATA – ON – OFF. The DATA and ON positions provide power to the beacon. Additionally, the DATA position sends serial data to the beacon. Note that the two extreme positions of the switch are OFF, when the power supply is fully isolated from the rest of the circuit.
Programming link, LK1	If PIC microcontroller is not fitted, this link must be fitted to enable power output to the Ember beacon – ***unless Q1 / Q2 are replaced by a wire link***.
Reset button, SW1	PCB button to reset the PIC microcontroller.
Mode button, SW2	PCB button to allow us to set an operating mode for the PIC microcontroller.
Red LED, L1	Illuminates continuously (0.5mA) to indicate that power is being sent to the Ember beacon.
Yellow LED. L2	Illuminates (0.5mA) when logic zero data is being sent from the serial data output of the PIC
Green LED, L3	High brightness short pulses indicate that the PIC is operating.

1.1.2 Connectors and Maintenance

Battery	A 4.8V NiMH 4xAA battery pack plugs into SK1. The cells are secured in the holder with a cable tie for additional safety. There is no charging facility within the unit, so the cells must be removed for charging. The cells provided are rated at 1600mAh, but it is possible to obtain higher capacity cells. With the Ember beacon drawing 25mA, 1600mAh gives a battery lifetime of 64 hours.
Fuse, FS1	This is in series with the Battery power input
Terminals, SK1	Connects to an external 4.8V NiMH 4xAA battery pack. Lead is strain-relieved by cable tie on PCB. There is no reverse polarity protection. Pin 1 is ground.
Terminals, SK2	Lead is strain-relieved by cable tie on PCB. There is no reverse polarity protection. Pin 1 is ground.
Terminals, SK3	Connects to the RJ45 plug that provides serial input to the Ember beacon. Lead is strain-relieved by cable tie on PCB. There is no reverse polarity protection. Pin 1 is ground.

1.1.3 Software Actions

The main actions of the PIC microcontroller are…

- To blink the high-brightness Green LED
  Codes will indicate operating mode, e.g. "power supply too low for beacon, output power disabled"; "power supply time out" – whatever we need.
- To disable power output to the Ember beacon when the power supply voltage drops below 3V
- To send serial data to the Ember beacon.

1.1.4 Notes

- The PIC software has not yet been implemented
- This circuit does not allow us to read serial data coming from the Ember beacon.
- The serial data output is not true RS-232. It uses 0V for a logic 1 instead of a negative voltage.
- A fully-charged battery pack will probably exceed the rated voltage for the PIC microcontroller (when fitted).

2 Assembly of Unit

2.1 PCB Assembly

Bill of Materials, as extracted from circuit diagram is given in the table on the next page. The following parts need to be added to the BOM.

Ref	Part	Description	Supplier
A1	LED spacer (2 off)	Round 2-pin LED holder, 3mm	300-9130
A2†	Fuse for FS1	20mm 1A quick blow	533-180

2.1.1 Assembly Notes

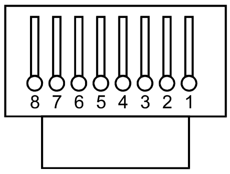
- IC1 is the IC *socket* not the IC itself
- Q2 is not fitted
- If Q1 not used, fit link between pins 1 and 3 of Q2
- SW3 is fitted on reverse of board
- Note PCB error (§5): pins 3 and 4 of SW1 must be joined during assembly.
- C2 is mounted on reverse of board so that it is not fouled whenever IC1 is removed from its socket.
- L1-3 to be bent at right angles to board (possibly fitted using LED spacers, item *BOM1*)
- FS1 is the fuse clips. Mount the fuse in the clips before assembly, and check correct orientation on 'pips' on the clips. Check FS1 does not foul SW1.

2.2 PCB peripheral components

Ref	Part	Description	Supplier
A3	PIC microcontroller	PIC12F675-I/P	413-6883
A4†	Battery connector	PP3 battery connector	536-994
A5†	1.3mm power plug	Maplin	Maplin FK05F
A6	RJ45 lead ***if fitted*** (strip sleeve).	Patch lead, 0.5m	300-6955
A7†–8†	Cable ties for A3, A4	Cable tie red 100mm	151-271 (Uptun stock)
A9	Programming link	Jumper socket 14mm red. Harwin.	321-8442
A10†	Bell Wire		stock

2.2.1 Assembly notes

- Supplier is Farnell, unless shown
- Secure battery connector [A4] to PCB using cable tie [A7]. SK1: Ground (black) is pin 1
- Solder bell wire [A10] to power plug [A5] without using plug housing – Figure 4 below. Secure wire to PCB using cable tie [A8]. Stripe on bell wire is ground: connect to SK2/1 and screen/sleeve of 1.3mm plug.
- SK3: Ground is pin 1, GREEN. The other pin is TXD – it transmits data as if it were coming from a PC. It therefore connects to the Ember pin labelled Rx., BLUE.
- The RJ45 plug, viewed with pins facing is…

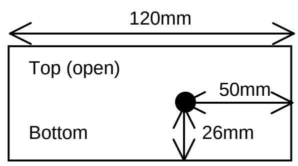


Pin	Farnell 300-6955 wire colour	Ember adapter box: internal wire colour	Ember pin function (from manual)	9D socket, mates with plug on PC
1	White/orange	Blue		
2	Orange	Orange		
3	White/green	Black		
4	**Blue**	Red	Rx	3 TXD
5	White/blue	Green	Tx	2 RXD
6	**Green**	Yellow	Gnd	5 GND
7	White	Brown		
8	Black	White		

2.3 Case Assembly

Ref	Description	Part	Supplier
B1†	Case, drilled with 7mm hole as described below.	Box ABS IP65 clear Lid. CT 662T. Bern	207-858
B2†	Knob for switch	Knob Black	320-640
B3†	Pointer	Pointer Red	321-047
B4†	cap	Cap Red	320-869
B5†	Battery holder	4xAA snap terminal battery holder	599-049
B6†	Cable tie for battery holder	Cable tie black 144mm	592-055 (Uptun stock)
B7†	Foam padding		From scrap
B8	Sealing grommet for Gateway unit only	Grommet, sealing, 12.5mm	417-8968
B9	Sticky Label	Printed label using CIL material.	

2.3.1 Assembly notes

- Drill case with 7mm hole in *short* (120mm) side of box (see diagram below, and photo in Figure 5 below
- 

- Fit sticky label to outside of case – see appropriate disc file for design. See Figure 1 below
- Assemble the rotary switch using nut spinner (nut thread is ¼-40 UNS-2A)
- Cut shaft of switch to suit knob
- Fit knob, pointer, cap
- Position Ember beacon and battery pack using foam padding

2.4 Assembly Without Microprocessor

Fit only items marked †. Fit link to pins 1,3 of Q2.

2.5 Assembly of Gateway Unit

- Drill 13mm hole as shown in photo below (use wood scraper)
- Use Helleman pliers to open up the sealing grommet, and insert the RJ45 lead that comprises the gateway connection, taking care not to tear the grommet.
- Lubricate the grommet and hole using Helleman oil, then press the grommet home from outside the case.
- Gently pull the cable out of the box, to flip the seal on the grommet
- Add a cable tie on the inside of the box as a strain relief. See Figure 2, Figure 3 below

3 Design Problems

3.1 Mechanical Problems

*Extract from email…*I chose to use a particular rotary switch because it was waterproof. (Others did not have a shaft without a flat, so would not have sealed properly against a “hexseal”). However, this particular rotary switch is utterly unsuitable to the use I have put it! (1) Its “rotary stop” will not withstand a “brute force” twist to the knob (I damaged one switch irreparably by this means). (2) It is not suitable as a mounting point for the PCB – if you accidentally bend the PCB slightly, the switch tears apart (I damaged one switch irreparably by this means).

I wonder, in fact, whether the inadequacy of the switch makes the units unsuitable for going underground. For example: it is possible to force the switch against its end-stop; break it; and then not be able to switch the unit off. The short answer to this problem is to make sure that the boxes are under our control all the time.

Second problem: the battery packs are completely useless. They deform when you put the batteries in, causing the batteries to break contact. Each time you insert the batteries you need to fiddle with them to get a good contact. However, I’ll supply the units fully charged, so you shouldnt need to do anything with the batteries. But: this means we cannot guarantee that all the units will work underground, as we cannot open them up and fiddle with them.

3.2 Circuit Problems

Mosfet Q1 doesn’t seem to be operating properly. Pinout or gate voltage problem – needs investigation.

4 Assembly Photos

Figure 1: view of sticky label

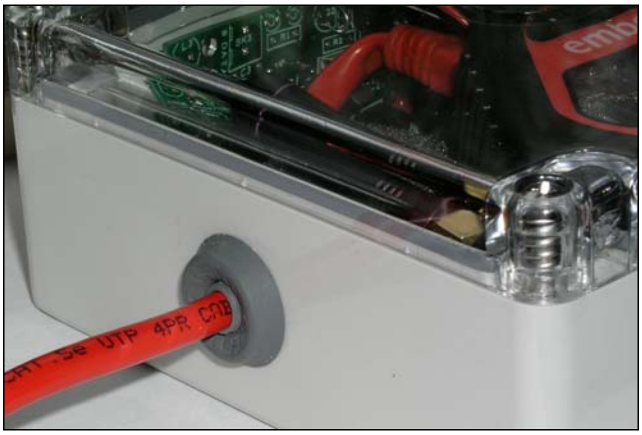


Figure 2: Sealing grommet for Gateway Unit

Figure 3: General assembly of Gateway unit

Figure 4: soldering of bell wire to 1.3mm power plug. Note absence of plug housing – no room in case.

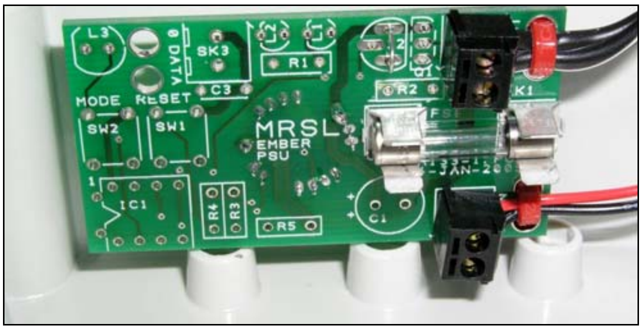


Figure 5: PCB for ‘sparse’ version without any microprocessor components. Note wire link across Q2 and cable ties securing flying leads. Also note the three mounting bushes below the PCB – hole in case must be drilled in the appropriate side of the case.

5 Bill of Materials for PCB

(as extracted automatically from circuit diagram)

Qty	PCB Ident	Schem. Part Name	Farnell Code	Manuf. Part No.	Schem. Comment	Library No.	Sort by
1	C1	RD 330U 16V	769-101	16ZL330...	ELEC CAP 8MM DIA, 3.5MM PINS	L29038	C
1	C2	TN 33U 10V	416-4210	CB	TANTALUM CAPACITOR 10V 0.2"	L32703	C
1	C3	MLC 100N	750-992	MCDR-Z5U	MULTILAYER CERAMIC 63V 0.2"	L32726	C
1	LK1	PINS 2	312-512	035	New part	L29003	CON
3	SK1†, SK2†, SK3	TERM2 3MM5	388-2615	NEW	2W SCREW 3MM5	L29048	CON
1	IC1	PIC12F675	424-2348	SOCKET	8 PIN IC	L1019	IC
1	L1	LED RED 3MM	322-556	HLMP-1700	1.8MCD 2MA 50D F/S CATHODE	L32719	Q
1	L2	LED YELLOW 3MM	322-568	HLMP-1719	1.6MCD 2MA 50D F/S CATHODE	L32719	Q
1	L3	TLGPE159P	325-5621	TLGPE159P	4.00C TYP 20MA 20D F/S CATHODE	L32720	Q
1	Q1	ZVP2106A	352-962	ZVP2106A	P-MOSFET ELINE DGS	L10503	QN
2	R1, R2	4K7	332-136	MRS16-4K7	MF 1% 0W4 0.2"	L5240	R
1	R3	330R	331-995	MRS16-330R	MF 1% 0W4 0.2"	L5240	R
1	R4	33K	332-239	MRS16-33K	MF 1% 0W4 0.2"	L5240	R
2	SW1, SW2	KEY 6MM	176-986	B3W-1050	KEYSWITCH 6MM FLAT	L29009	SW
1	SW3†	ROTARY 3P4W	958-761	TYCO	3 POLE 4 WAY ROTARY SW	L29060	SW
1	FS1†	FUSE 20MM 1A	926-851	HTC210	2 FUSE CLIPS	L29020	Y

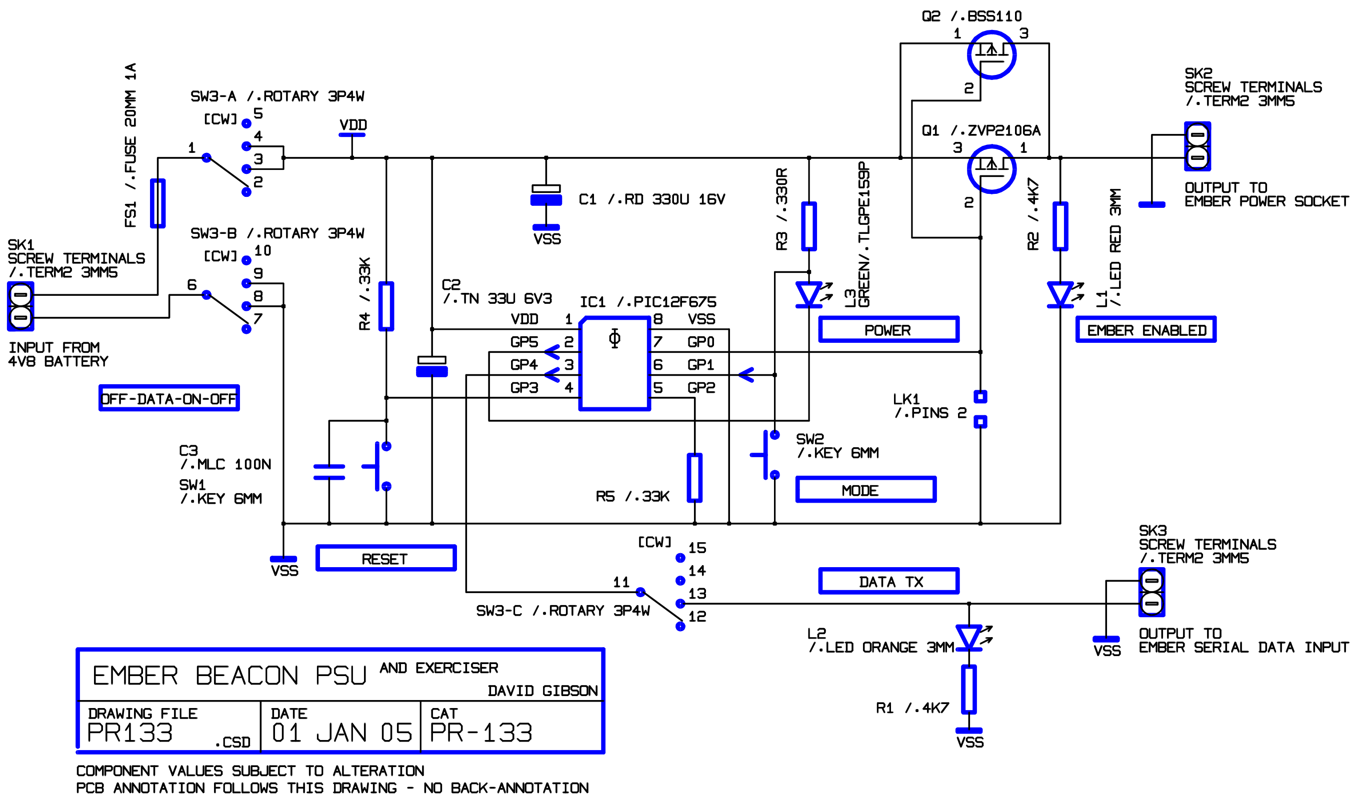
Additional library update:

1	C2	TN 33U 6V3	416-4143	CB	TANTALUM CAPACITOR 6V 0.2"	L32703	C

6 Circuit Diagram

Amendments to be done:

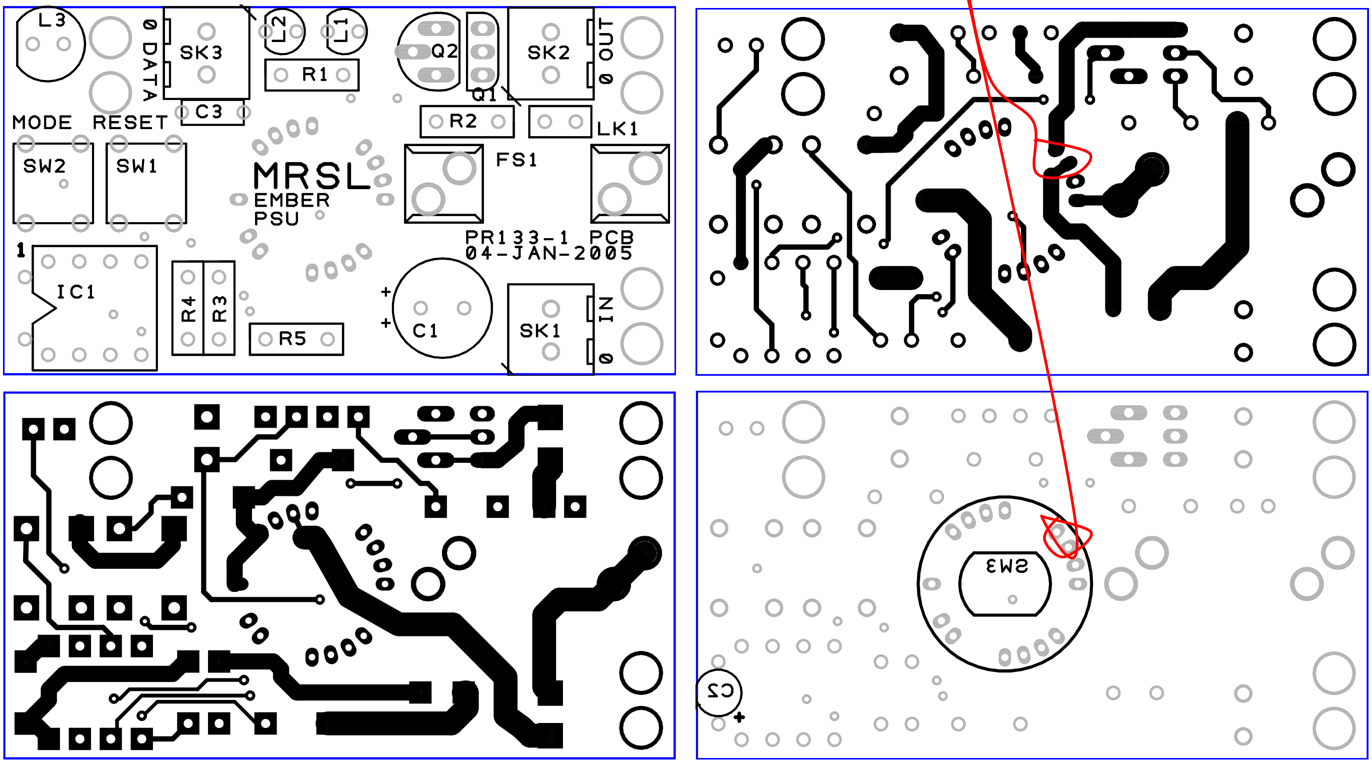
- Ground symbol by SK2 should be VSS. PCB net list was manually altered.
- L2 should be LED YELLOW 3MM
- Amend C2 to be TN 33U 10V
- Change SW1, SW2, LK1 for parts listed on BOM above
- Delete Q2



7 PCB Layout

Board size: 30mm x 55mm

PCB error: Pins 3 and 4 of SW1 must be joined during assembly.



Amendments to be done:

- PCB footprint for SW1 should be amended so that the silkscreen shows the pin 1 position. This is not needed for the correct orientation of the component, but it would be of aid during development work.
- PCB footprint for FS1 shouldbe amended to indicate 'pips' on one side of each fuse clip.
- Why does L1019 come from DIL library, and not USER library?

7.1 PCB Reports

7.1.1 pr133-1.ccr

```
Connectivity Check Status Report
--------------------------------

Report Written : Monday, January 03, 2005
Design Path    : C:\Documents and Settings\Dave\MRSL\project_PR133\pcb\pr133-1.pcb
Design Title   :
Created        : 01/01/2005 13:40:25
Last Saved     : 01/01/2005 16:50:21
Editing Time   : 181 min

Net "N008" is fully connected.
Net "N007" is fully connected.
Net "N001" is fully connected.
Net "N003" is split into 2 sub-nets.
Gap between (5205.0 6468.0) and (5167.0 6517.0).

Net "N009" is fully connected.
Net "N004" is fully connected.
Net "N005" is fully connected.
Net "N006" is fully connected.
Net "N002" is fully connected.
Net "N012" is fully connected.
Net "N016" is fully connected.
Net "N014" is fully connected.
Net "N015" is fully connected.
Net "N011" is fully connected.
Net "N010" is fully connected.

1 split nets found.
0 single pin nets found.
```

Error noted (belatedly).
Amendment made to
Assembly instructions.

```
End Of Report.
```

7.1.2 pr133-1.drr

```
Design Rule Check Report
------------------------

Report Written : Monday, January 03, 2005
Design Path    : C:\Documents and Settings\Dave\MRSL\project_PR133\pcb\pr133-1.pcb
Design Title   :
Created        : 01/01/2005 13:40:25
Last Saved     : 01/01/2005 16:50:21
Editing Time   : 181 min

Pad to Pad Error (P-P) between (4110.0 5865.0) and (4115.0 5865.0) on Layer "Bottom Copper".
Pad to Pad Error (P-P) between (4110.0 6115.0) and (4115.0 6115.0) on Layer "Bottom Copper".
Track to Pad Error (T-P) at (6013.9 6388.9) on Layer "Bottom Copper".
Track to Pad Error (T-P) at (5413.9 6388.9) on Layer "Top Copper".

Number of errors found : 4
End Of Report.
```

Design rule errors acceptable.

7.1.3 pr133-1.upr

```
Unconnected Pins Report
-----------------------

Report Written : Monday, January 03, 2005
Design Path    : C:\Documents and Settings\Dave\MRSL\project_PR133\pcb\pr133-1.pcb
Design Title   :
Created        : 01/01/2005 13:40:25
Last Saved     : 01/01/2005 16:50:21
Editing Time   : 180 min

Component FS1  Pin 3
Component FS1  Pin 4
Component SW1  Pin 3
Component SW1  Pin 4
Component SW2  Pin 3
Component SW2  Pin 4
Component SW3  Pin 2
Component SW3  Pin 5
Component SW3  Pin 7
Component SW3  Pin 10
Component SW3  Pin 12
Component SW3  Pin 14
Component SW3  Pin 15

Unconnected pins found : 13

End Of Report.
```

This is correct.

7.1.4 pr133-1.dsr

```
Design Status Report
--------------------

Report Written : Monday, January 03, 2005
Design Path    : C:\Documents and Settings\Dave\MRSL\project_PR133\pcb\pr133-1.pcb
Design Title   :
Created        : 01/01/2005 13:40:25
Last Saved     : 01/01/2005 16:50:21
Editing Time   : 180 min

Board Area
----------
2557505.1 thou squared

Layers
------
Name            Type            Side     Net

Top Silk        Silk Screen     Top
Top Copper      Electrical      Top
dummy                           Inner
Bottom Copper   Electrical      Bottom
Bottom Silk     Silk Screen     Bottom
Gnd             Electrical      Inner
Vcc             Electrical      Inner

Component List
--------------
Comp Type     Package     Components   Pins

L29038          USER            1       2
L32703          USER            1       2
L32726          USER            1       2
L29020          USER            1       4
L1019           DIL             1       8
L32719          USER            2       4
L32720          USER            1       2
L29003          USER            1       2
L10503          USER            1       3
L10504          USER            1       3
```

```
l5240           USER            5       10
L29048          USER            3       6
L29009          USER            2       8
L29060          USER            1       15

Total:                          22      71

Net List
--------
Net Class     Nets  Track Length  Vias  Connections   Con Length

Signal          81      19964.8      10      0          0.0

Drill List
----------
Drill Diameter  Holes

16.0            10
24.0            15
32.0            38
40.0            14
80.0            4
118.0           6

Total number of drill holes 87.
Total number of free pads 6.


End Of Report.
```

A.5: Application Software Details

[Software on additional CD]

1. Smart Sensor Application Software[1]

    'sink.c' – Smart sensor network gateway and data collection node
    'barometric-sensor.c' – Barometric pressure sensor node.
    'temperature-sensor.c' – Temperature sensor node.

2. Remote Telemetry Application Software (Embedded)[1]

    'theod-control.c' – EmberNet node interface to TCR instrument
    'theod-gateway.c' – Exactly the same as above with added character echo command.

3. Remote Telemetry Application Software (Windows)

    'surlog-tcr.cpp' – Windows Console Application to control and retrieve data from TCR
    'tserial.c & tserial.h' – Non-event driven COM port program (Schneider, 2005)

4. 3D Survey Data using remote telemetry and RSV

    Four text files – two 5 degree resolution scans, two 10 degree resolution scans (one of each resolution using coordinates, one of each in northings, eastings and elevation)

[1] Only the main 'xxx.c' program is given for confidentiality/license reasons. The header files and associated EmberNet stack software is under a strict licensing agreement and therefore not at liberty to make freely available.