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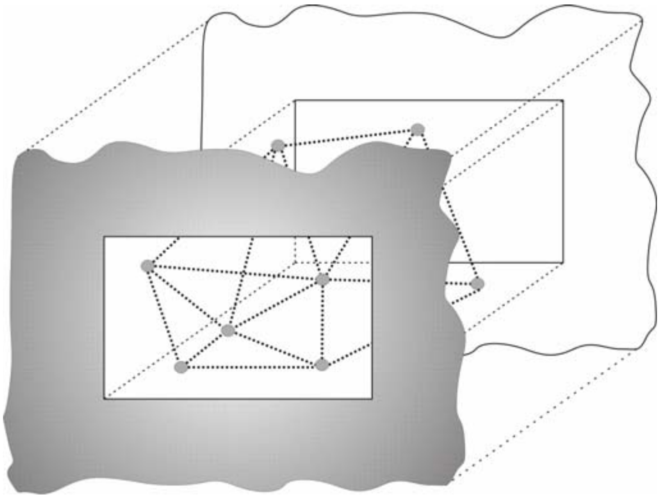

High resilience wireless mesh networking characteristics and safety applications within underground mines

Gareth Allan Kennedy

PhD Thesis

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

Submitted by

Gareth Allan Kennedy

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

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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

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[*] 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, $\pi = 3.14159\ldots$ (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